Aerospace Propulsion

Lecture 21

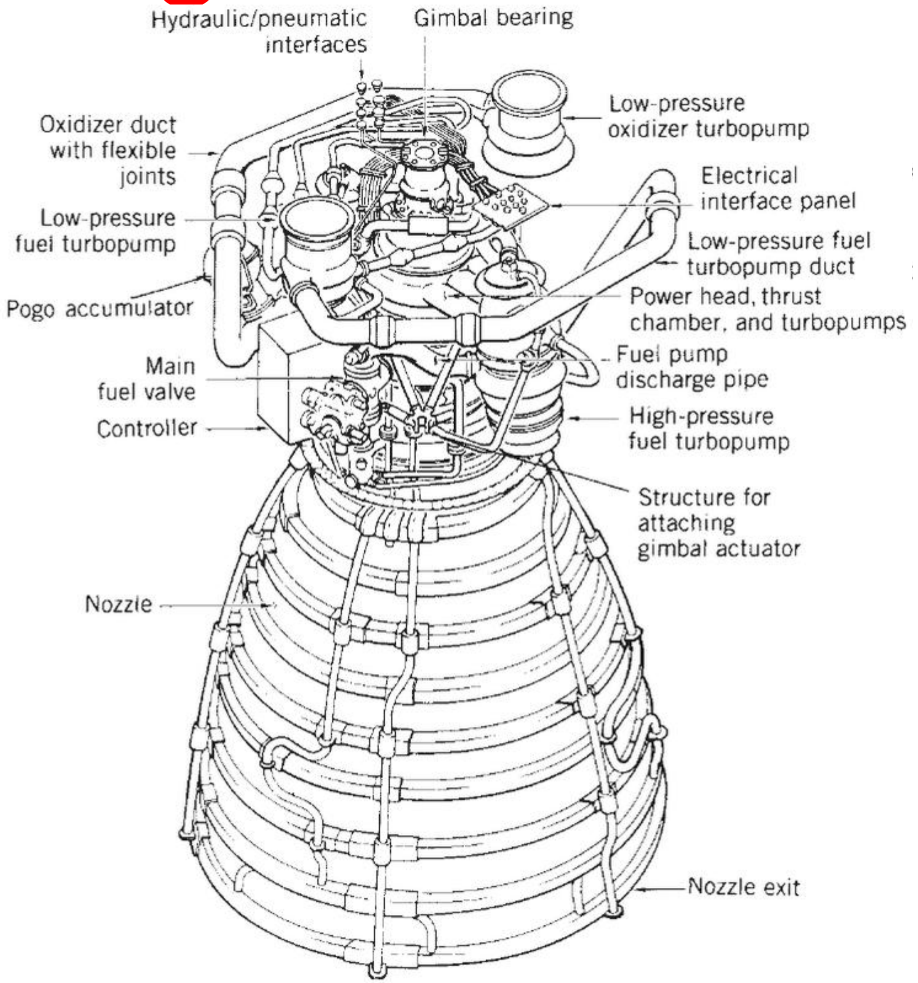
Rocket Propulsion IV

Rocket Propulsion: Part IV

- Liquid Propellant Rocket Engines
- Propellant and Storage
- Feed Systems
- Injectors
- Thrust Chamber Cooling

Liquid Propellant Rocket Engines

- LPRE made from several components
  - Storage tanks (not pictured)
    - Liquid propellant
  - Rocket engine (pictured)
    - Thrust chamber
    - Feed mechanism
      - Supply propellants to thrust chamber
    - Power source
      - Power feed mechanism
    - Plumbing
    - Control devices
      - E.g., valves to control propellent flow



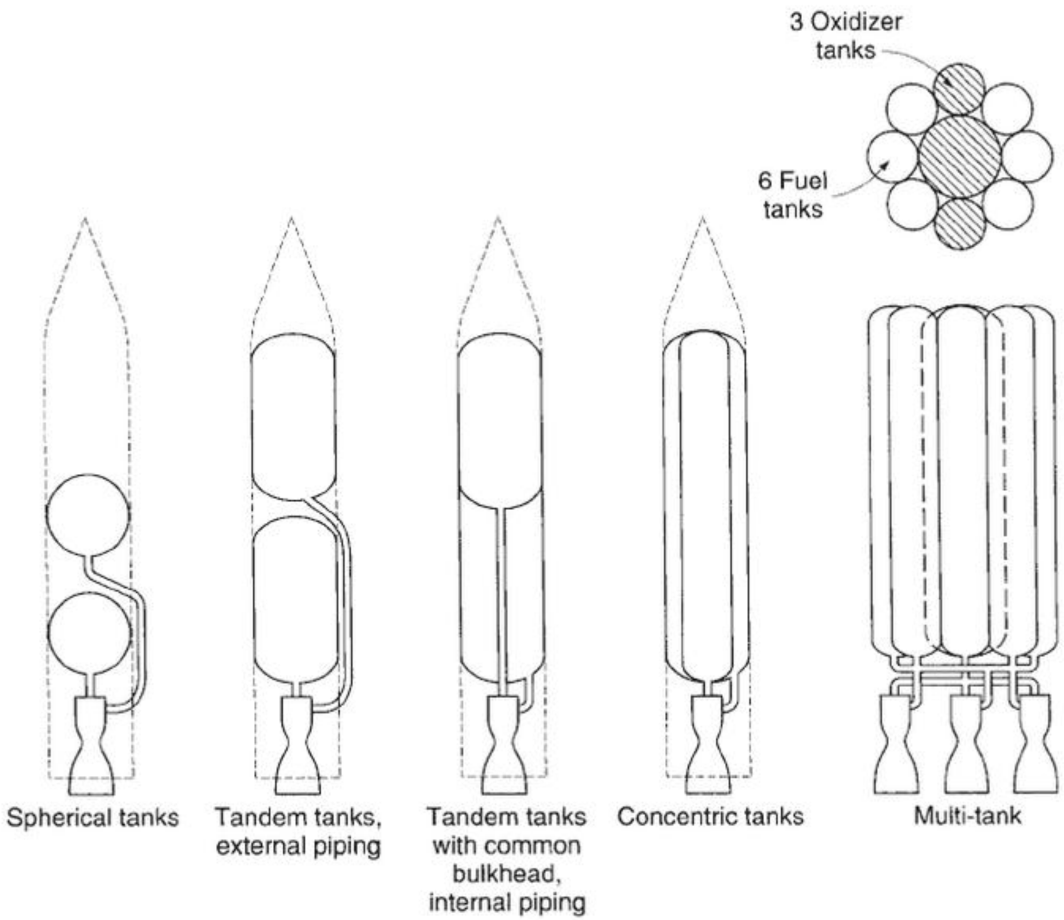
Space Shuttle Main Engine

Propellant and Storage

- Energy source for thrust, which is liquid in a LPRE
  - Types of liquid propellants
    - Bipropellant – Separate liquid oxidizer and fuel mixed in combustion chamber
      - Hypergolic – Self ignites on contact between oxidizer and fuel
      - Non-hypergolic – Requires an ignition source
    - Monopropellant – Fuel + oxidizer in a single liquid substance
      - Can be a mixture of compounds or a single homogenous substance (Lecture 6)
    - Cold gas propellant – Stored at high pressure but non-reacting gas
    - Cryogenic propellant – Liquified gas stored at low temperatures (e.g., LO2/LH2)
    - Storable propellant – Liquid at ambient temperatures and modest pressures
    - Gelled propellant – Liquid with gelling additive (experimental)

Propellant and Storage

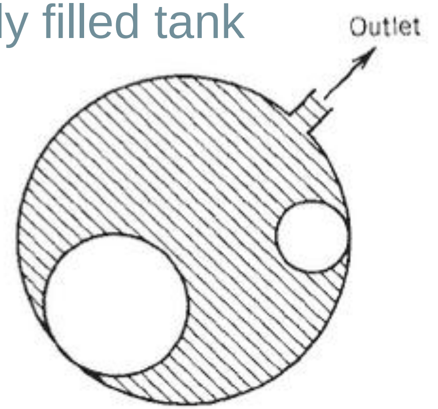
- Propellant Storage
  - Bipropellants stored in separate tanks
  - Monopropellants stored in same tank
  - Tank shape and location is important
    - Rocket center of mass shifts as fuel is used changing its dynamics
  - Tanks are never fully filled
    - Space reserved for propellant thermal expansion (3-10%) and gases
  - Residual (trapped) propellant up to 3%



Propellant and Storage

- Propellant Storage
  - Storing liquids for rapid side acceleration and low gravity is difficult
  - Sloshing
    - Imagine shaking a glass with water
  - Vortexing
    - Imagine the vortex that forms when flushing a toilet
  - Gravity-free environments
    - Gases will no longer be “above” the liquid
  - Issues related to the above:
    - Allowing gas into the combustor affects rocket operation
    - Sudden motion can lead to direction changes and tank failure

Mostly filled tank

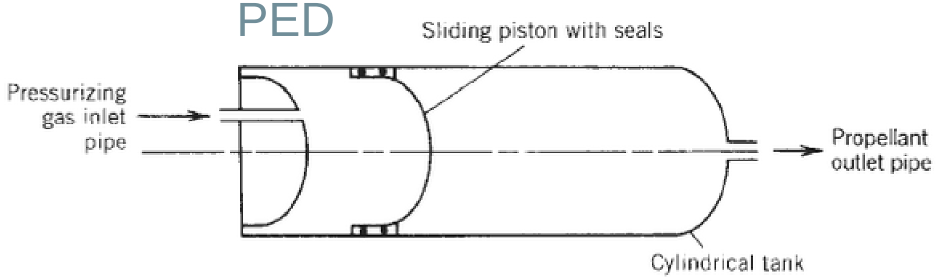


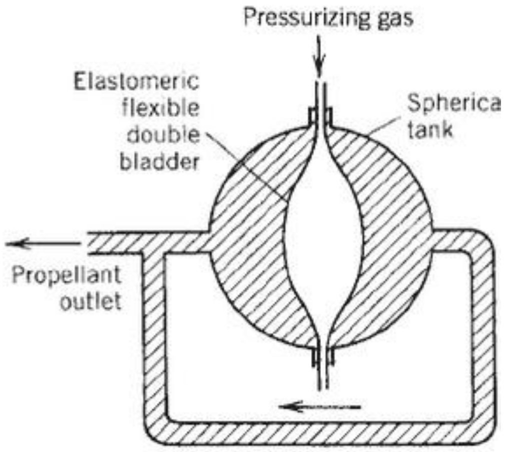
Barely filled tank

Propellant and Storage

- Solutions to these problems
  - Positive expulsion devices
    - Mechanically separate gas from liquids
  - Surface tension devices
    - Woven stainless steel wire that pulls liquid along
    - Only useful at low acceleration where surface tension can overcome inertia
  - Acceleration
    - Brief acceleration can overcome issues with gravity free environments

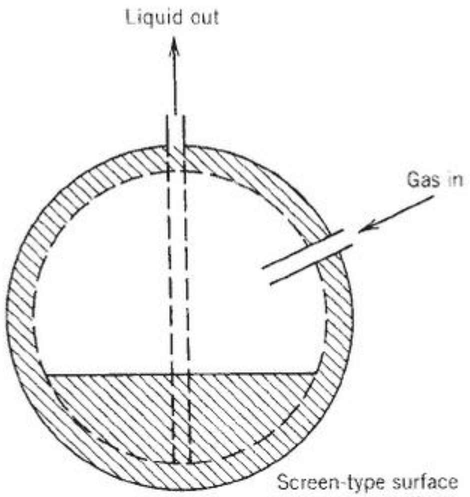
PED





PED

STD

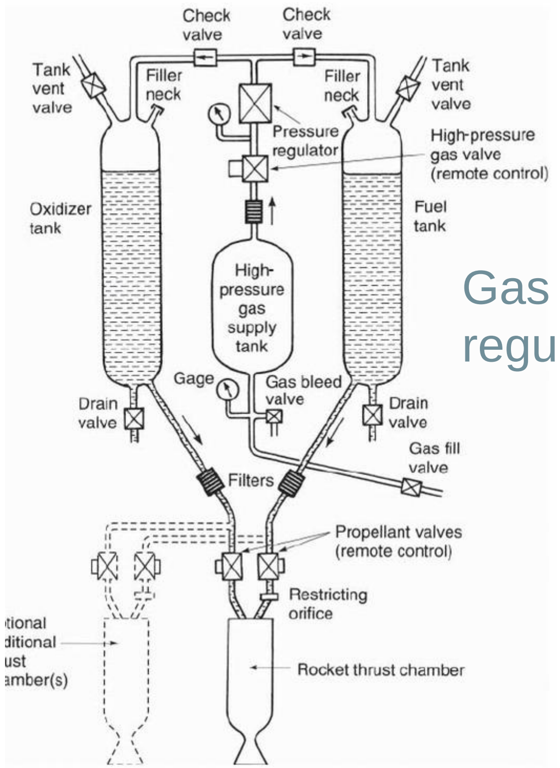


Feed Systems

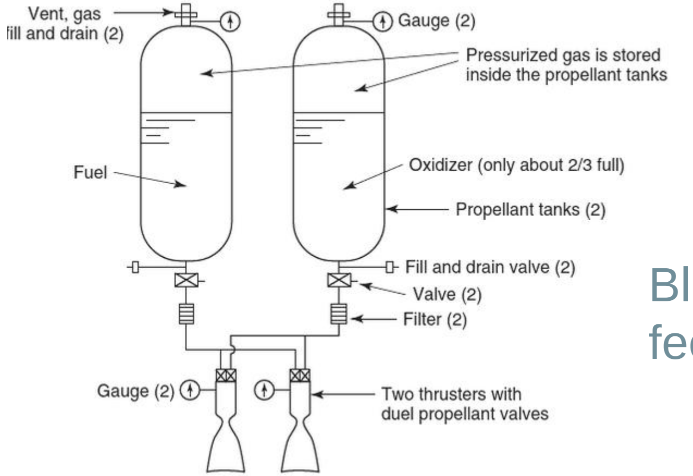
- Liquid propellants are fed to combustion chamber in one of two ways
  - Gas pressure feed system
    - Pressurized gases are used to move propellant
    - Efficient when total impulse, chamber pressure, and mission velocity are low
  - Turbopump feed system
    - Turbine + pump are used to move propellant
    - Efficient when total impulse, chamber pressure, and mission velocity are high

Feed Systems

- Gas pressure feed system
  - Uses gases to feed liquid through piping
  - Gas pressure regulator feed
    - Additional high-pressure gas supply tank onboard
    - Supply tank connected to propellant tanks
    - Constant pressure applied to propellants
    - Heavy additional tank
  - Blow-down feed system
    - Propellant tanks are only filled ~2/3rds
    - Remaining space is filled with pressured gas
    - Gas pressure decreases as propellants expelled



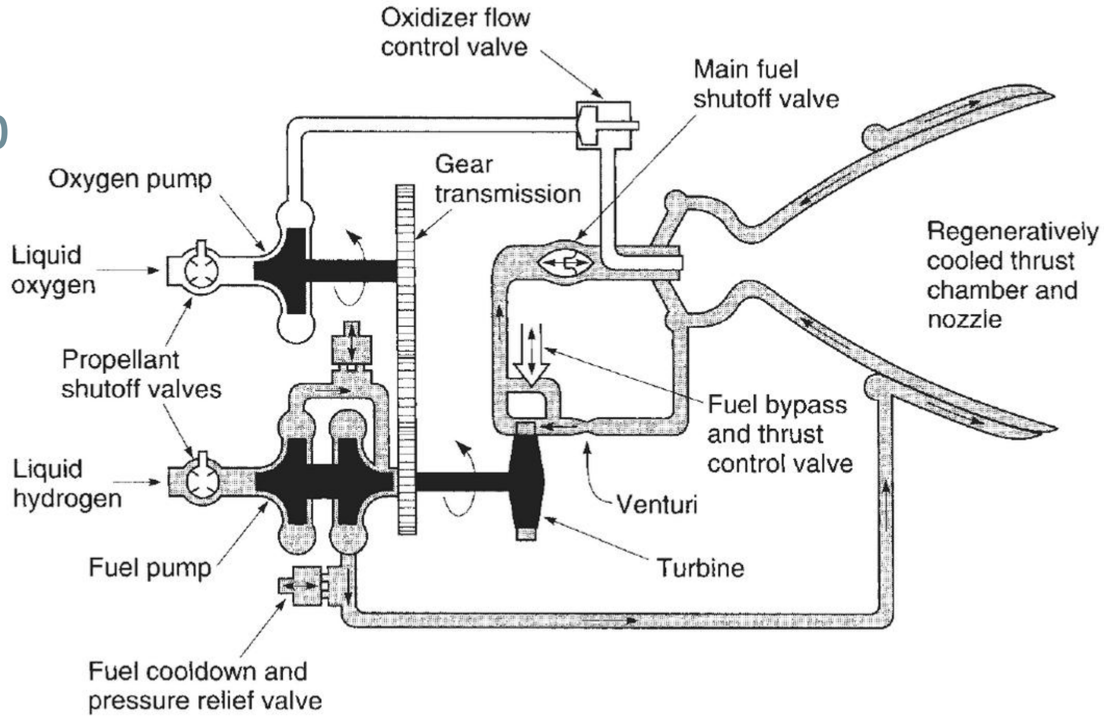
Gas pressure regulator



Blow-down feed system

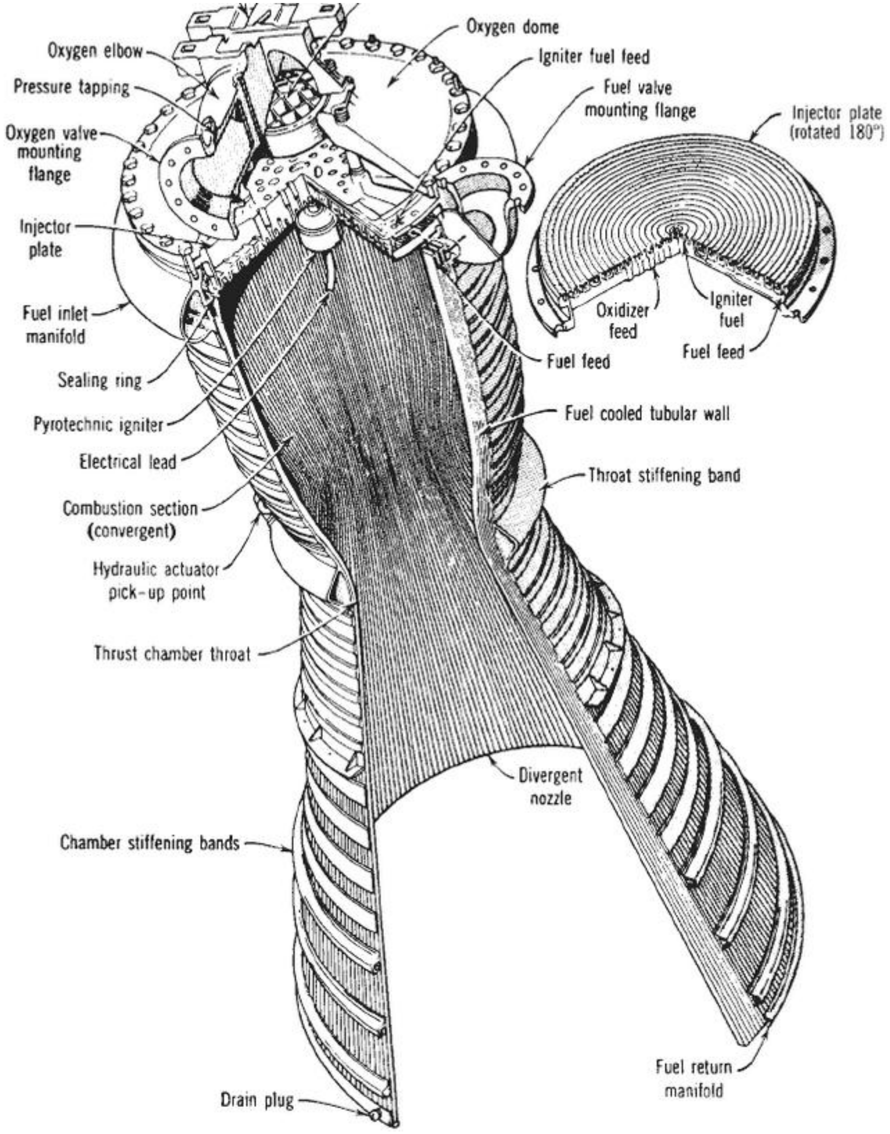
Feed Systems

- Turbopump feed system
  - Liquid propellants are fed using a pump
  - Pumps are powered by turbine(s)
    - Turbine exhaust fed to nozzle or expelled
  - Turbine start/stop is relatively slow so not great for rapid changes in flow rate
  - Remember, energy used to power turbine is energy not used for thrust!



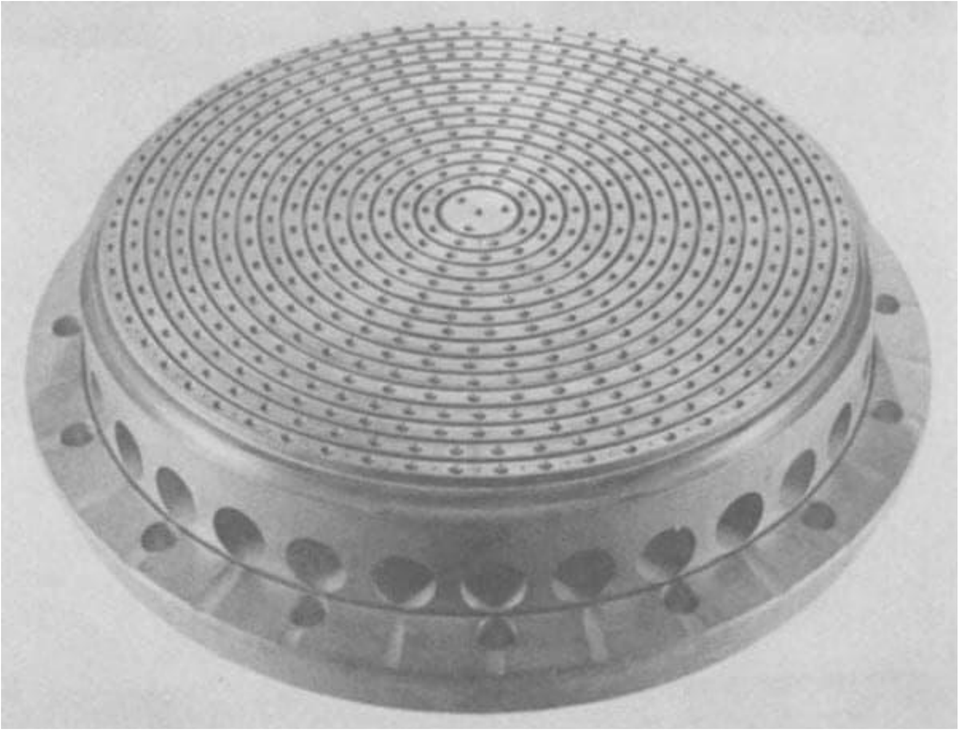
Injectors

- Three major components in a standard thrust chamber
  - Injector
    - Efficiently inject propellants for combustion
    - Liquids are being injected
  - Combustor
    - Efficiently burn propellent
    - Liquids converted to gases
  - Nozzle
    - Efficiently accelerate high energy exhaust
    - Gases are exhausted



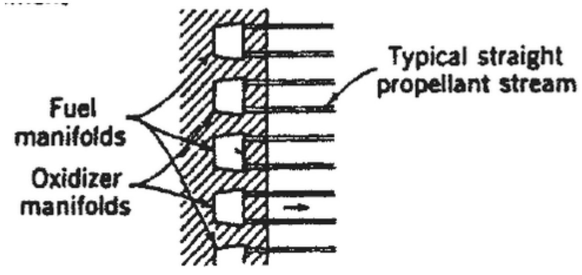
Injectors

- Injector
  - Three main goals of injector
    - Introduce propellant into thrust chamber
    - Break up liquid into small droplets
      - Droplets are pure fuel/oxidizer so don't burn
    - Mix propellants before combustion
      - Unmixed propellants will ultimately lead to incomplete combustion
  - Liquid rocket injectors generally utilize many holes to inject propellants

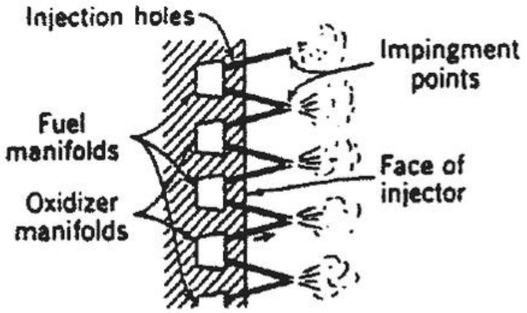


Injectors

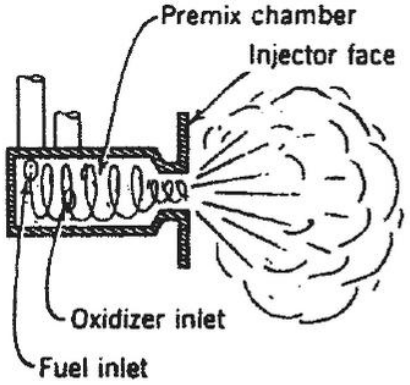
- Injector
  - Straight propellant stream is bad
    - Slow droplet breakdown
    - Poor mixing of propellants
  - Multiple strategies for improving droplet breakdown and mixing
    - Impinging propellent jets
      - Improves breakdown and mixing
    - Swirling injector flow
      - Improves mixing
    - Splash plate
      - Improves breakdown and mixing

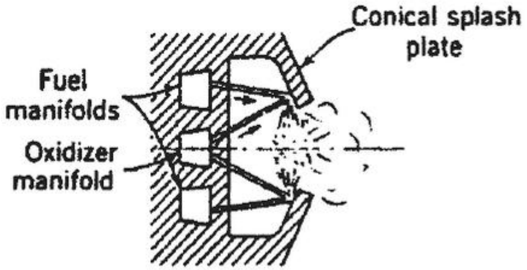


Shower head stream pattern



Doublet impinging stream pattern

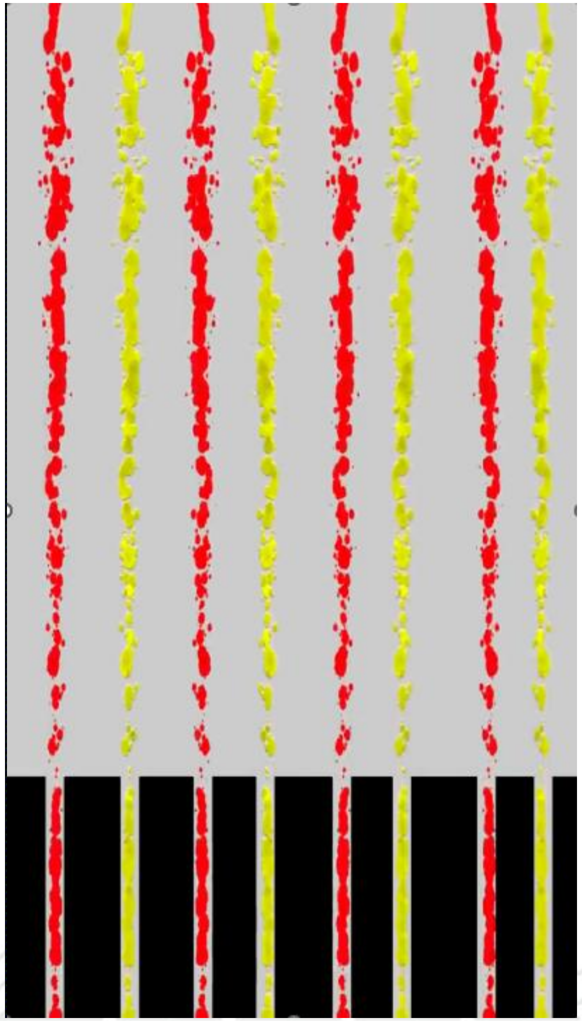




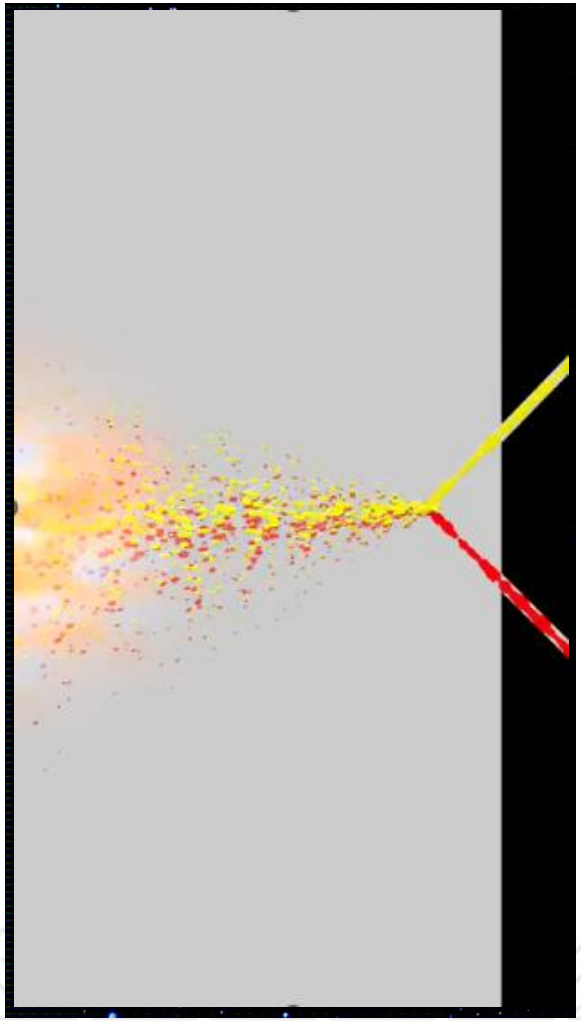
Splash plate pattern

Injectors

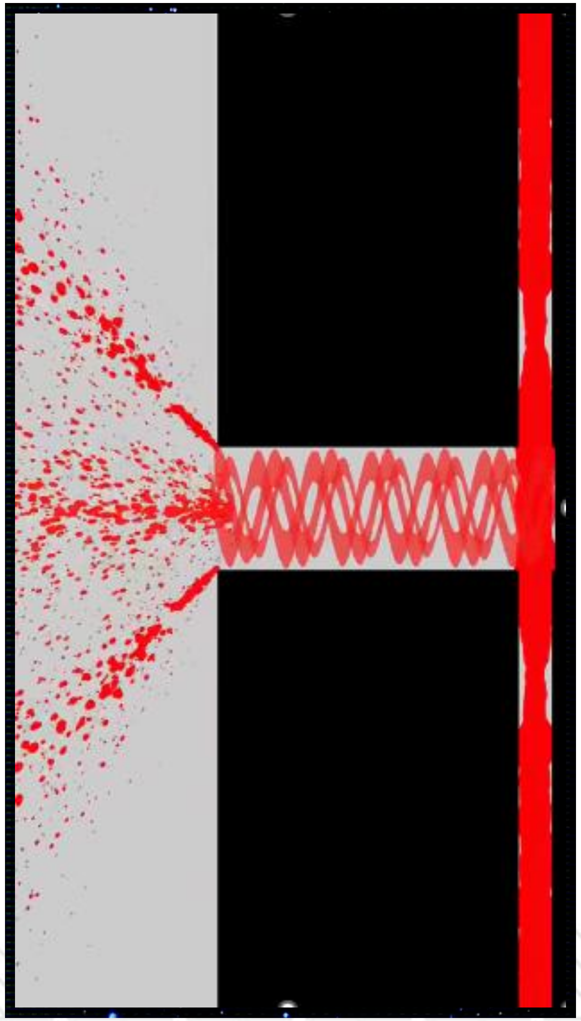
Straight



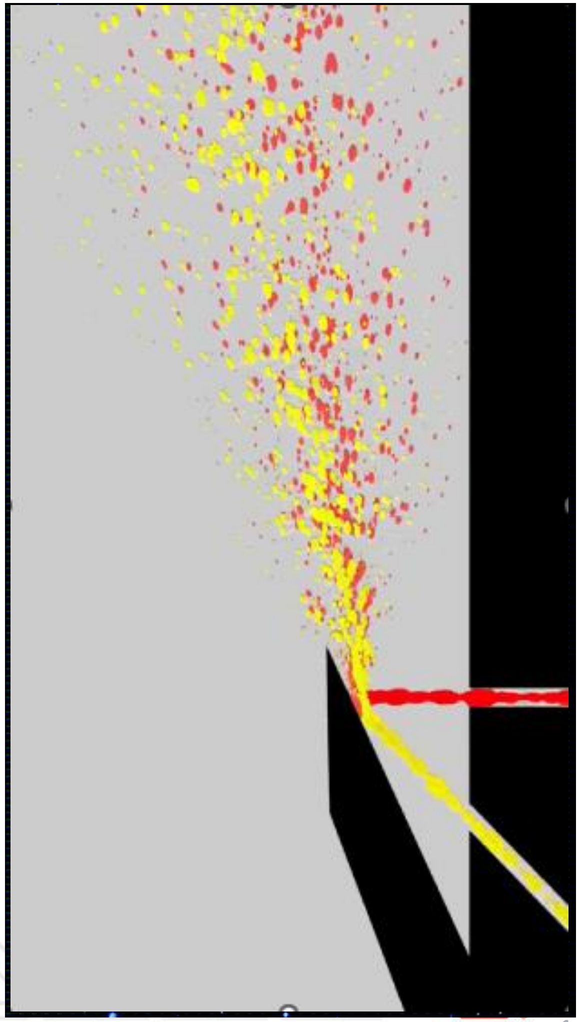
Impinging



Swirling



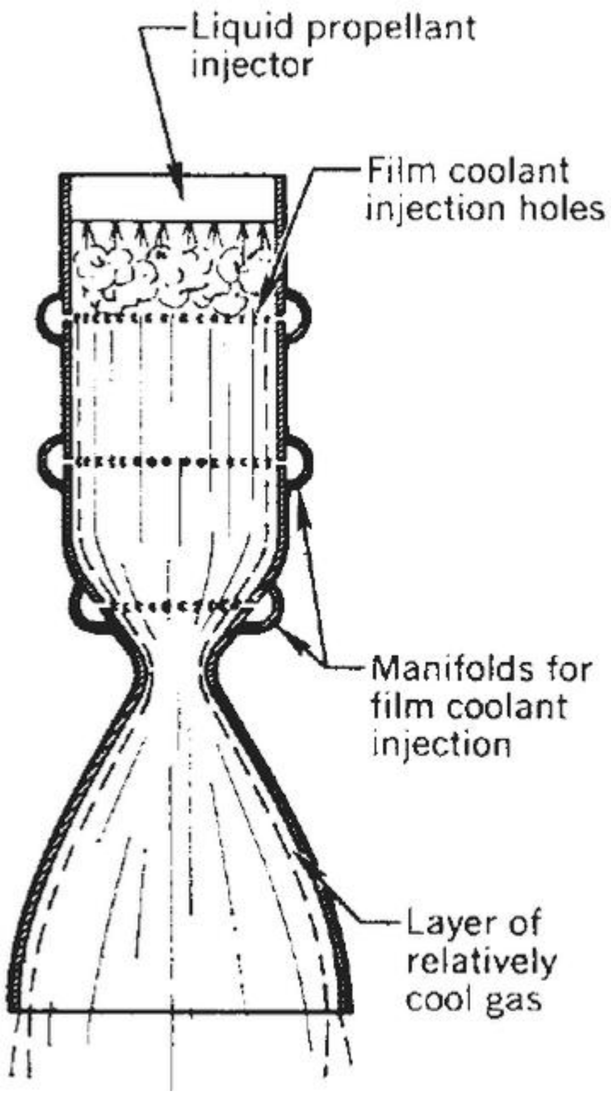
Splash



Thrust Chamber Cooling

- Rocket thrust chambers need to be cooled
  - Rockets usually operate near stoichiometric for maximum performance, massive temperatures
    - Combustion temperatures up to 4000 K possible
  - Many cooling techniques will be familiar from airbreathing engines

  - Film cooling is used extensively
    - However, air is no longer “free”
    - More common to inject fuel through holes in nozzle
      - With good design, this fuel still reacts and contributes energy to the fluid



Thrust Chamber Cooling

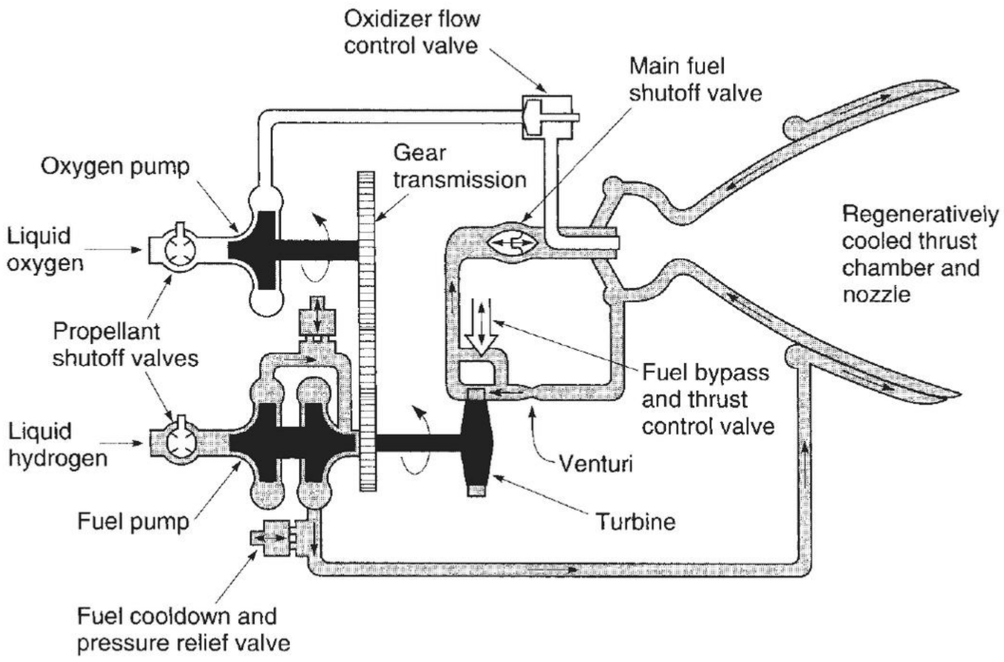
- Internal ceramic coatings are <u>not</u> used commonly
    - Temperatures are so high that thermal expansion of materials leads to cracking and separation

    - Asbestos was used for some time but no longer
        - Cancer causing

    - Ongoing research efforts
        - E.g., Rhenium coatings

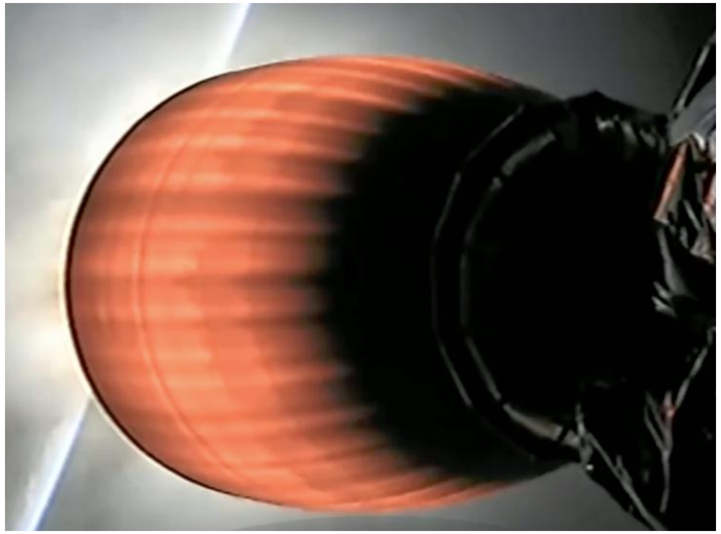
Thrust Chamber Cooling

- Regenerative cooling
  - Before entering the combustion chamber, fuel is circulated along the nozzle
    - Cold (cryogenic) fuel is warmed up
      - This provides more energy to the flow
    - Outside of hot nozzle is cooled down
  - Injectors often also regeneratively cooled
  - Note that this technique is also often used in Ram/Scramjets operating with LH2



Thrust Chamber Cooling

- Radiative Cooling
  - Radiation
    - Electromagnetic energy exchanged by a substance with its environment mostly in the infrared range
    - Occurs most efficiently in a vacuum (no absorbing media in the way)
    - $E \propto AT^4$
      - Increasing area increases energy lost to radiation
      - Increasing temperature dramatically increases energy lost to radiation
  - Rocket thrust chambers are extremely hot (often glowing), meaning effect of radiation is strong
    - At 4000 K, about 40% of heat loss is through radiation



SpaceX Merlin in space