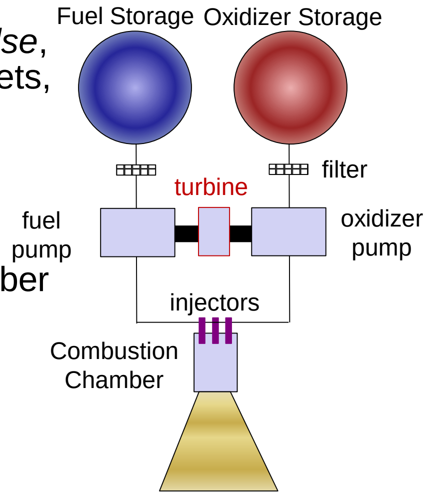
Liquid (Bipropellant) Rockets Engines

Overview

- Can characterize liquid rocket engines in number of ways
- Application
  - launch/boost, upper stage, RCS, …
- Propellants used
  - monopropellants (already covered); **bipropellants** (e.g., fuel+oxidizer); tripropellants
  - hypergolic (self-igniting on contact) or forced ignition
- Pressurization approach
  - gas (and self-pressurized)
  - **pump-fed**

Propellant Pressurization

- For large, high *total impulse*, high thrust to weight rockets, can't rely on gas-pressurization systems
  - lower tank weights
  - high feed rates
  - high combustion chamber pressures
- Use pump-feed
- What drives pumps?
- What drives turbine(s)?
  - need hot, "high" p gas



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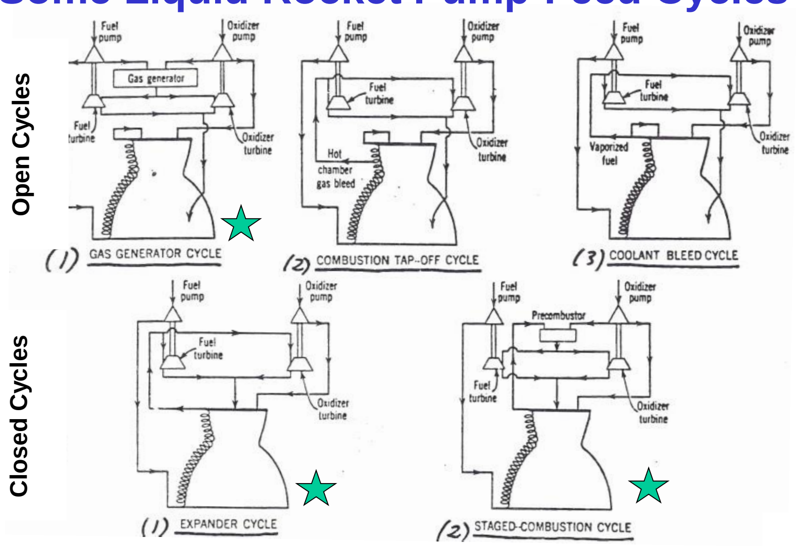
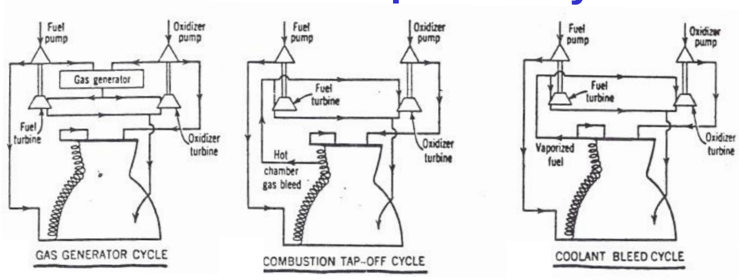
Some Liquid Rocket Pump-Feed Cycles



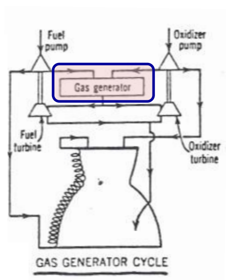
Liquid Rocket Pump-Feed Cycles



- **Open Cycles**
  - turbine exhaust gas that can't be re-injected into combustion chamber (pressure too low) ⇒ lower I_{sp}
  - turbine exhaust dumped through separate nozzle or injected in downstream part of main nozzle (where pressure is low)
  - generally rely on low flow rate, few % of total propellant flow (less wasted propellant mass) and high pressure drop across turbine

Gas Generator Cycle

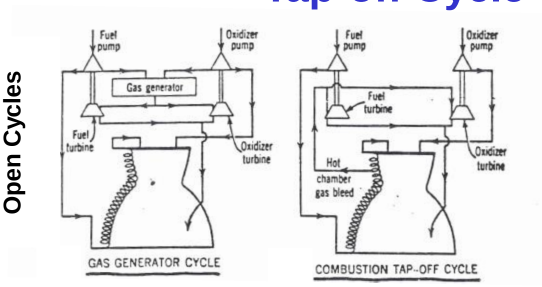
Open Cycles



- Most common open cycle
  - typically lower development costs
  - uses separate combustor(s): gas generator(s) to run turbine(s)
  - gas generators operated very fuel-rich or fuel-lean ("low" temperature) to prevent damage to turbine blades
  - use main or separate propellants
- Examples
  - V-2 separate H_2O_2 gas generator
  - Saturn V: F-1 RP/LOX and J-2 LH2/LOX (Rocketdyne)
  - Arianne 5: Vulcain LH2/LOX (Snecma)
  - Delta IV: RS-68 LH2/LOX (Aerojet Rocketdyne) (362-415s, 660-760klbf: largest LH2/LOX engine)
  - Falcon: Merlin 1 RP/LOX (SpaceX)

Tap-off Cycle

Open Cycles

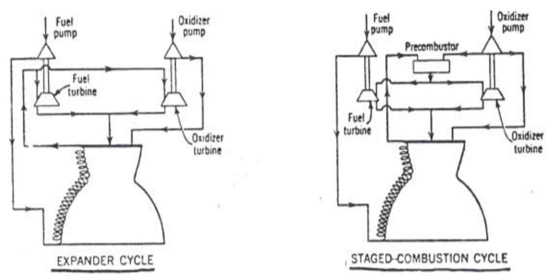


- Turbines operated by small amount of (high pressure) gases from main combustor
- J-2S (Rocketdyne)
  - upgrade of J-2, LH2/LOX
  - 6 preproduction models tested

at one time, plan for 5 J-2S engines to power Space Shuttle

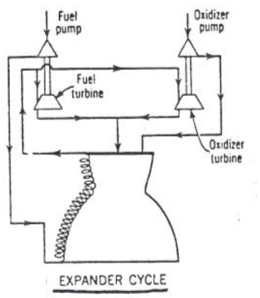
- BE-3 (Blue Origin)
  - LH2/LOX, 490 kN/110klb$_f$ (vacuum)
  - flight tested in 2015

Liquid Rocket Pump-Feed Cycles



- **Closed Cycles**
  - no wasted propellant – turbine exhaust injected into combustion chamber (requires higher pressure) ⇒ higher I_{sp}
  - generally rely on high flow rates and low pressure drop across turbine

Expander Cycles



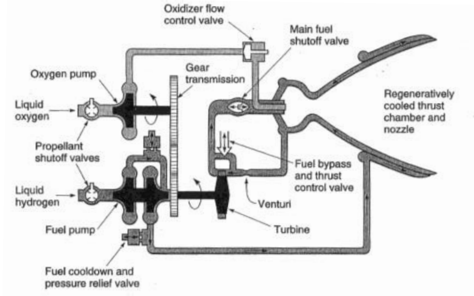
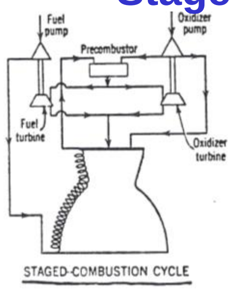


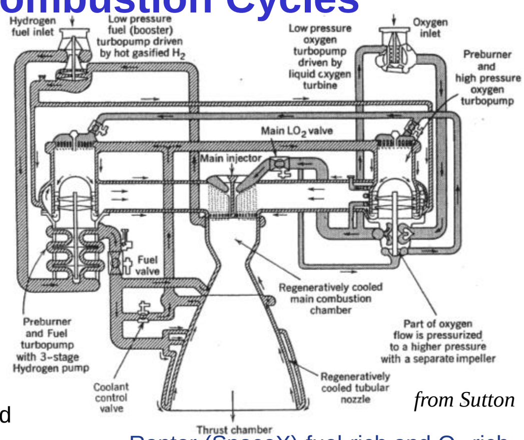
FIGURE 6–11. Schematic flow diagram of the RL10B-2 upper stage rocket engine. For data see Table 8–1. (Courtesy of Pratt & Whitney, a division of United Technologies.)

from Sutton

- Use propellant evaporated in cooling circuit
  - power limited
- RL-10 (Rocketdyne)
  - LH2/LOX, only 25 klb$_f$, but 467 s (vacuum)
  - uses single turbine to drive fuel and oxidizer pumps

Staged-Combustion Cycles



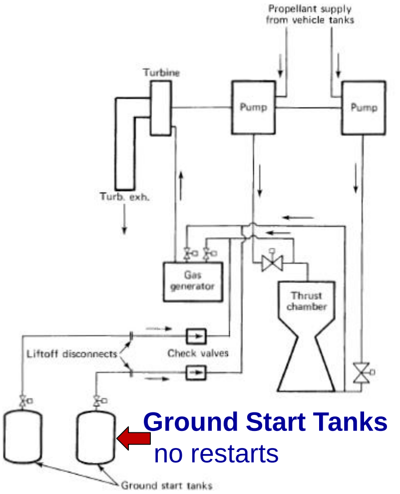


from Sutton

- RS-25 (SSME) (Rocketdyne)
  - LH2/LOX,
    491 klb$_f$, 453 s (vacuum)
  - separate turbopumps and preburners (fuel-rich)
- RD-180 (NPO Energomash) (Atlas V)
  - RP/LOX, 4150 kN, 338 s (vacuum)
  - oxygen-rich preburner

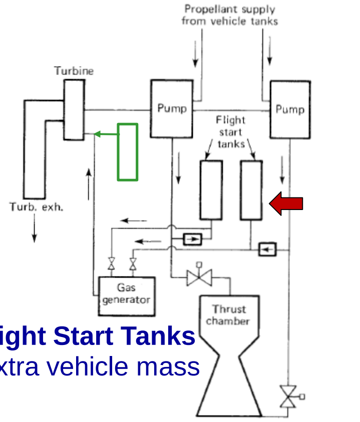
- Raptor (SpaceX) fuel-rich and O_2-rich preburners and BE-4 (Blue Origin) O_2-rich preburners, both LCH_4/LOX,
- AR1 (Aerojet Rocketdyne), RP/LOX, O_2-rich preburners

Starting Pump-Fed Systems



Ground Start Tanks
no restarts

Fig. 5.7 Rocket engine diagram—gas generator cycle with ground start tanks.



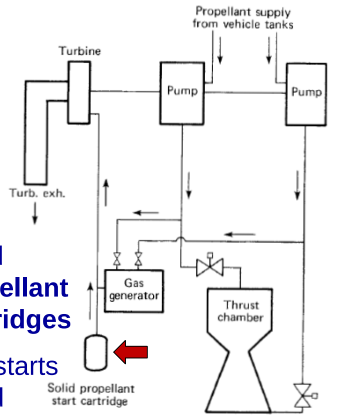
Flight Start Tanks
extra vehicle mass

Fig. 5.8 Rocket engine diagram—gas generator cycle with flight start tanks.

can also spin turbine directly

from AIAA *Space Vehicle Design*, M. Griffin (2004)

Starting Pump-Fed Systems

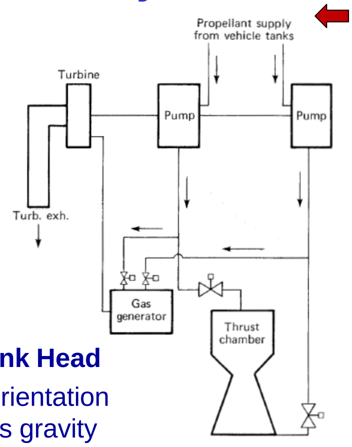


Solid Propellant Cartridges

restarts fixed

Fig. 5.9 Rocket engine diagram with solid propellant start cartridge.

sometimes separate turbine



Tank Head

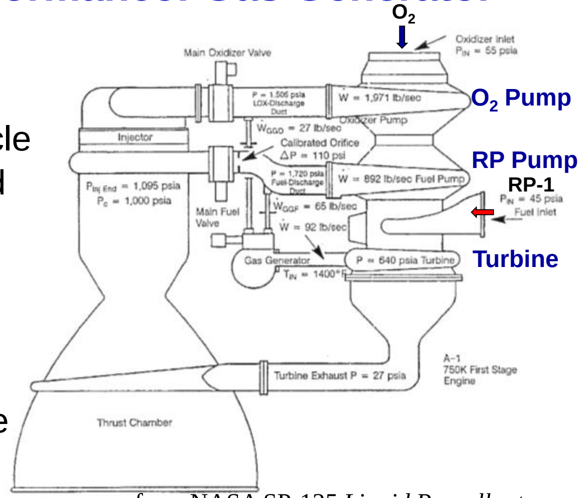
orientation
vs gravity

Fig. 5.10 Rocket engine diagram—gas generator with tank head start.

from AIAA *Space Vehicle Design*, M. Griffin (2004)

Example Performance: Gas Generator

- A-1 booster (1st stage) engine for hypothetical vehicle
  - from Huzel and Huang (Rocketdyne)
- RP-1/Liquid O_2
- 750,000 lb_f thrust (sea-level)
- Examine pressure drops and flow splits



from NASA SP-125 *Liquid Propellant Rocket Engines*, Huzel and Huang (1967)

Example Performance: Gas Generator

- **Engine O/F**

$$\dot{m}_O/\dot{m}_F\big|_{tot} = \frac{1968\,lb_m/s}{892\,lb_m/s} = 2.21 \quad \textit{Rich}$$

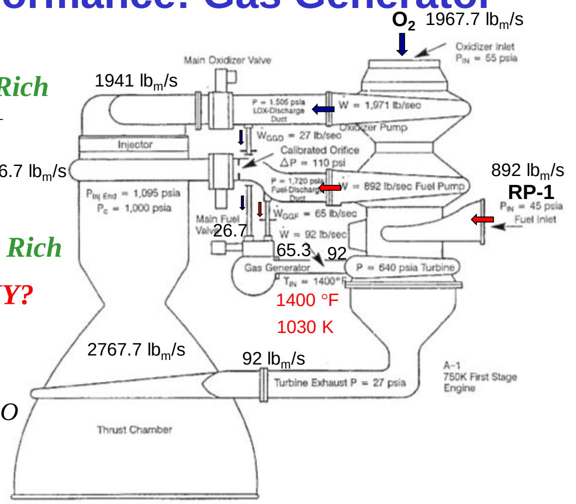
$$\dot{m}_O/\dot{m}_F\big|_{main} = \frac{1941}{827} = 2.34 \quad \textit{Rich}$$

$$\dot{m}_O/\dot{m}_F\big|_{gg} = \frac{26.7}{65.3} = 0.41 \quad \textit{Very Rich}$$

- Rich/lean? ***WHY?***
  - RP-1 $\frac{C}{H} = \frac{1}{1.9}$

$$CH_{1.9} + 1.475O_2 \rightarrow CO_2 + 0.95H_2O$$

$$\frac{O}{F}\bigg|_{stoich} = \frac{1.475(32)}{12+1.9} = 3.4$$



Also note m_{gg}/m_{total} = 92/2860 ~ 3%

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Example Performance: Gas Generator

- **Specific Impulse**

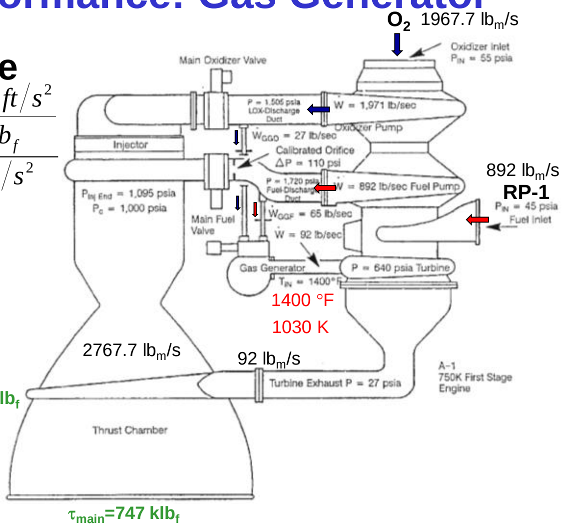
$$I_{sp,main} = \frac{747{,}000\,lb_f}{2768\,lb_m/s}\;\frac{32.2\dfrac{lb_m\ ft/s^2}{lb_f}}{32.2\ ft/s^2} = 270s$$

$$I_{sp,gg} = \frac{3000}{92} = 32.6s$$

$$I_{sp,tot} = \frac{750{,}000}{2860} = 262s$$

  – note

$$\frac{I_{sp,tot}}{I_{sp,main}} = \frac{262}{270} = 97\%$$



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Example Performance: Gas Generator

- **Pressure Changes**
  – low supply pressures (3-4 atm)
  – large Δp drops
    - injectors
    - calibrated orifices
    - manifolds
    - cooling jacket
    - **turbine**
  – small Δp drops
    - valves
    - lines