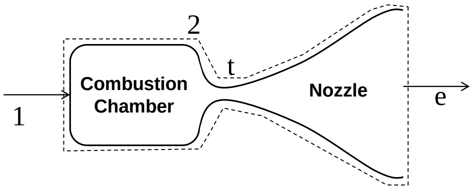
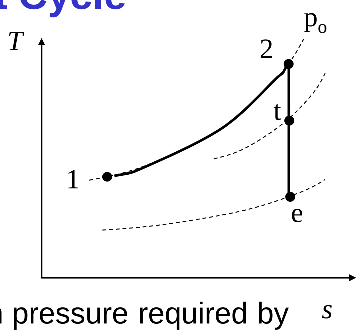
Rocket Propulsion

Liquid Propellant Cycles: Gas Feed and Turbopump Systems

Ideal Rocket Cycle

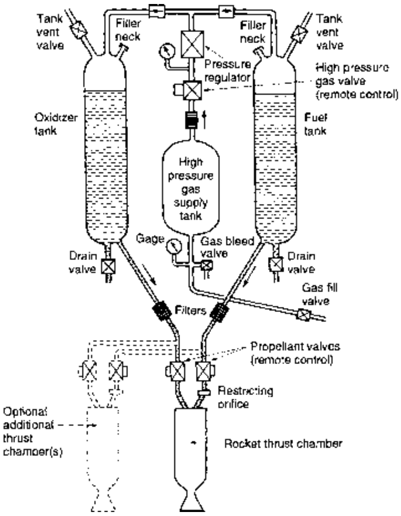




- How do propellants reach high pressure required by C.C. (i.e., p_o)
  - gravity fed
    - only for low pressure applications in well-defined g field
  - pressure fed
  - turbopump fed

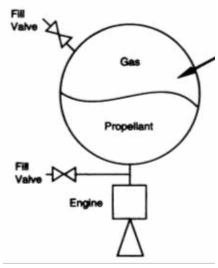
Pressure Feed

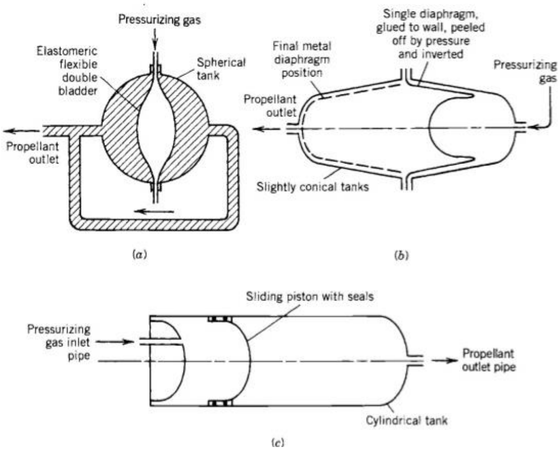
- Use high pressure gas to pressurize liquid propellant tanks
- Primary controls are
  - gas pressure regulator
  - gas on/off control valve
  - liquid propellant valves



Positive Expulsion Tank Management

- Barrier required to prevent pressurant gas entering thrust chamber assembly





Turbopump Cycles

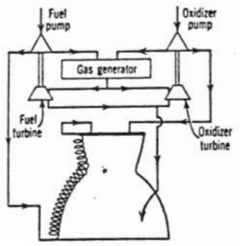
- Use pump to pressurize liquid propellants
  - – steady flow pumps run with shaft power input
- Shaft power source ??
  - – electric motor
    - usually insufficient onboard electrical power
  - – turbine
    - need to expand high pressure, heated gas

Liquid (Bipropellant) Cycles

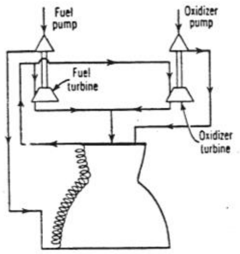
- Various rocket cycles have been developed that differ on how hot gas is supplied to the turbines
- Most common are variations of:

Open Cycle

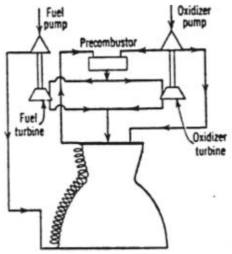
Closed Cycles



Gas Generator Cycle



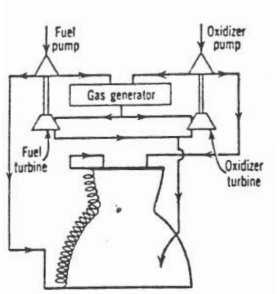
Expander Cycle



Staged Combustion Cycle

LRE Pump-Fed Open Cycles

- Turbine exhaust gas can't be re-injected into comb. 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

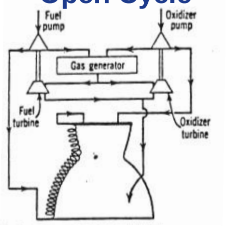


Gas Generator Cycle

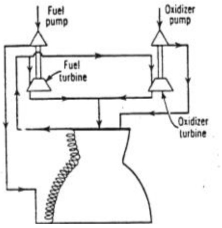
Comparison of Liquid Turbopump Cycles

Open Cycle

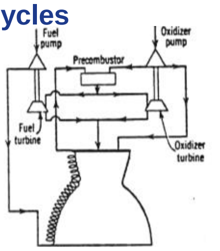
Closed Cycles



Gas Generator Cycle



Expander Cycle

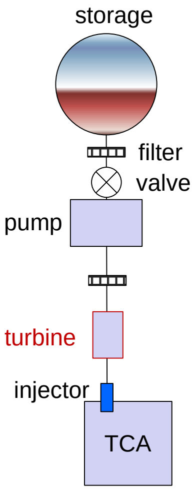


Staged Combustion Cycle

Isp	low	medium	high
Complex	medium	low	high
Thrust	high	Low	high
P_r Turbine	high	Medium	low
Examples	V2, F-1/J-2 (SaturnV), Vulcain (Arianne 5), RS-68 (Delta IV), Merlin 1 (Falcon)	Upper Stages: RL-10 (Saturn IV, Delta III, IV), Vinci (Arianne 6)	RS-25 (SSME), NK-33 (N-1, Soyuz), RD-170 (Energia), RD-180 (Atlas V), BE-4 (Atlas V?), AR1 (Atlas V?), Raptor (ITS?)

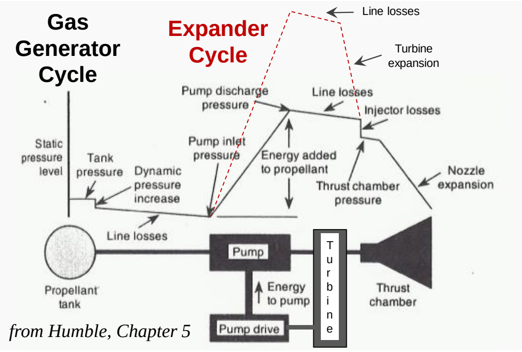
Pressure Losses in Propellant Path

1. Storage pressure
2. Dynamic pressure loss
   - static pressure drops as flow moves
3. Line losses between storage and pump
   - friction losses in piping
   - pressure drops in flow restrictions (orifices, filters, valves, etc.)
4. Pump increase
5. Line losses
6. Turbine pressure drop
7. Injector pressure drop



Pressure Requirements

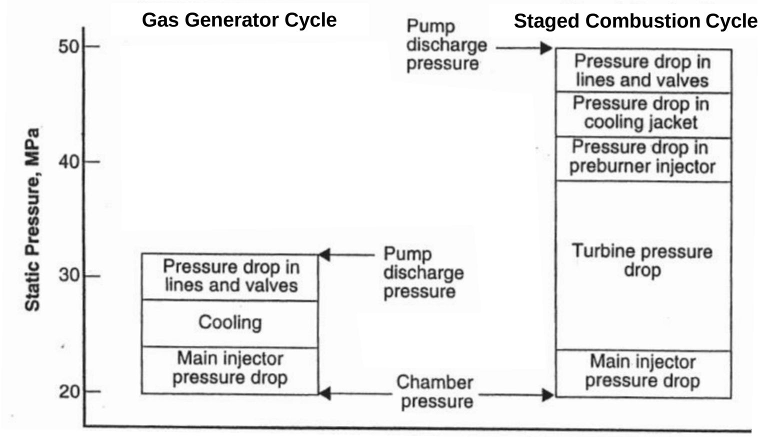
- Significant difference between cycles is the pump pressure requirement
  - for example, an open vs. a closed cycle
  - higher pump pressure required if propellant stream passes through turbine before entering combustion chamber



from Humble, Chapter 5

Example Pump Pressure Requirements

- Pump must produce an additional 180 bar for the closed cycle in this comparison with a c.c. pressure of 200 bar



Pressure Modeling – "Rules of Thumb"

- **Dynamic pressure** $\boxed{\Delta p = \tfrac{1}{2}\rho u^2}$ **(IV.20)**
- **Line losses: piping**
  - various modeling approaches, e.g., friction factor
  - traditional expression

pipe length

$$\Delta p_f = \rho g_o H_f \qquad H_f = f\,\frac{L}{d}\,\frac{u^2}{2g_o}$$

Head Loss (height) (Darcy) friction factor pipe diameter

  - or $\boxed{\Delta p_f = f\,\rho\left(L/d\right)\left(u^2/2\right)}$ **(IV.21)**
  - f is function of Re_d, pipe material, surface finish
    - find values from Moody diagrams, empirical models

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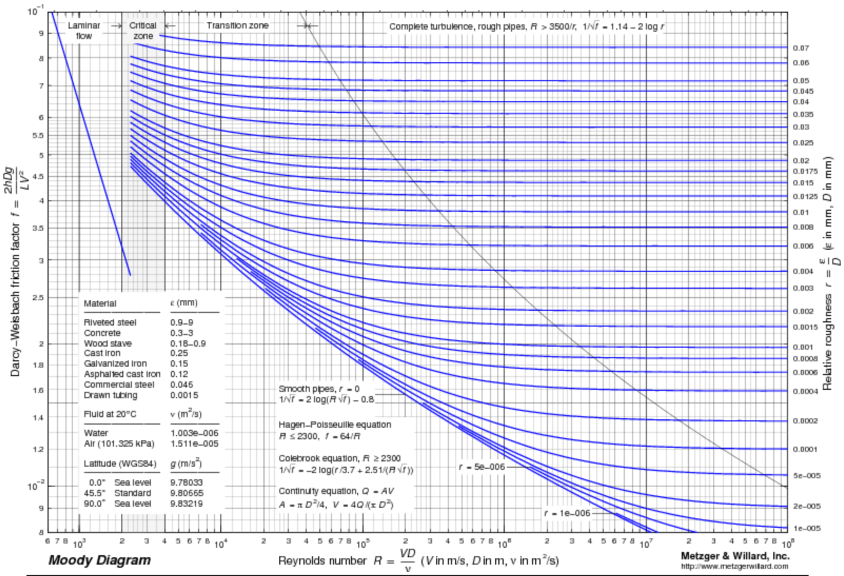
Moody Diagram



Material	ε (mm)
Riveted steel	0.9–9
Concrete	0.3–3
Wood stave	0.18–0.9
Cast iron	0.25
Galvanized iron	0.15
Asphalted cast iron	0.12
Commercial steel	0.046
Drawn tubing	0.0015

Fluid at 20°C	ν (m²/s)
Water	1.003e–006
Air (101.325 kPa)	1.511e–005

Latitude (WGS84)		g (m/s²)
0.0°	Sea level	9.78033
45.5°	Standard	9.80665
90.0°	Sea level	9.83219

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Pressure Modeling – “Rules of Thumb”

- **Line losses: orifices**
  - flow restrictors, valves, etc.
  - typically use discharge coefficient

volumetric flowrate

(IV.22a)
$$\boxed{C_d = \frac{Q}{A\sqrt{2\Delta p/\rho}} = \frac{\dot{m}/\rho}{A\sqrt{2\Delta p/\rho}}}$$

orifice area

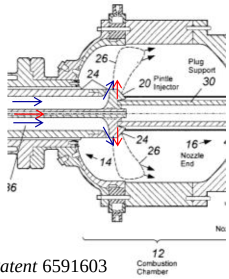
alternate definition
$$C_d = \frac{Q}{A\sqrt{\Delta p/\rho}}$$

  - essentially ratio of actual flow rate to flow rate through ideal “nozzle” that produces same expansion
  - so pressure drop given by $\boxed{\Delta p = \frac{\left(\dot{m}/AC_d\right)^2}{2\rho}}$ **(IV.22b)**

$$\Delta p = \frac{\left(\dot{m}/AC_d\right)^2}{\rho}$$

Pressure Modeling – “Rules of Thumb”

- **Typical line losses**
  - feed system: Δp_{loss}=10’s kPa (4-8 psi)
  - regenerative cooling (of TCA): Δp_{loss}~10-20% of p_{cc}
- **Injector pressure drops**
  - required to produce required dispersion and mixing of propellant, isolation, etc.
  - depends on engine operational requirements and propellant type
    - Δp_{loss}~20% p_{cc} for unthrottled engines
    - Δp_{loss}~30% p_{cc} for throttled engines
    - as low as Δp_{loss}~5% p_{cc} for some pintle injectors



US Patent 6591603

Pressure Modeling – “Rules of Thumb”

- **Turbine pressure drops**
  - amount based on the required pressure ratio across turbine to supply pump power
  - gas generator cycle: Pr_t up to ~20
    - low flow rate so large expansion requirement
  - staged, expander cycles: lower Pr_t ~1.3-1.7
    - often includes complete flow from one of the propellant streams

$$Pr_t = \frac{P_{t_{inlet}}}{P_{t_{exit}}}$$

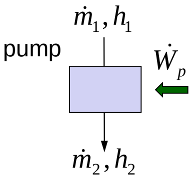
- **Pump requirements**
  - pump supply pressure
  - pump inlet pressure

(IV.23)

$$\boxed{\begin{aligned} p_{pump,exit} &= p_{cc} + \Delta p_{inj} + \Delta p_{lines} \\ p_{pump,inlet} &= p_{storage} - \Delta p_{dyn} - \Delta p_{lines} \\ \Delta p_{pump} &= p_{pump,exit} - p_{pump,inlet} \end{aligned}}$$

pump power requirement ⬅

Pump Power Requirements



- **Conservation equations**
  - assume steady flow, adiabatic
  - mass: $\dot m_1 = \dot m_2 \equiv \dot m$
  - energy $\dot m h_1 + \dot W_p = \dot m h_2$

$$\dot W_p = \dot m\left(h_2 - h_1\right) \overset{?}{=} \cancel{\dot m c_p\left(T_2 - T_1\right)}$$

NO, not perfect gas

- **State equations**

$$h \equiv e + p/\rho \qquad dh = de + d\left(p/\rho\right)$$

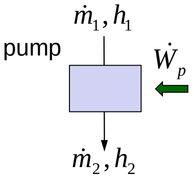
$$\boxed{dh = c\,dT + \frac{dp}{\rho}}$$

assume incompressible liquid $\rho \neq \rho(p)$ → $\underline{dT = 0}$

Gibbs' Eqn.

$$Tds = dh - \frac{dp}{\rho} \quad \underline{\text{if isentropic}} \Rightarrow dh = \frac{dp}{\rho}$$ →

Pump Power Requirements



- **Ideal pump power**
  - so for incompressible liquid undergoing ideal (adiabatic, isentropic) pumping

$$\dot W_{p,ideal} = \dot m \Delta h_{ideal} = \dot m \frac{\Delta p_{pump}}{\rho_l}$$

- **Pump efficiency**

for same Δp across both

$$\eta_p \equiv \frac{\dot W_{p,ideal}}{\dot W_{p,actual}} = \frac{\Delta h_{ideal}}{\Delta h_{actual}}$$

typical ~70-90%

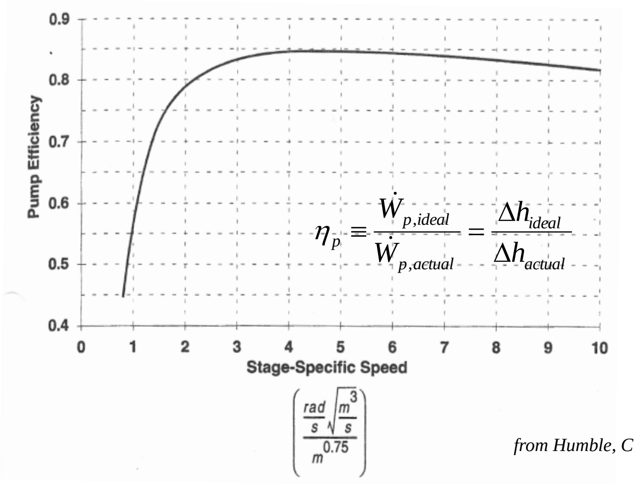
- **Pump power**

in terms of pump head

$$\boxed{\dot W_p = \frac{\dot m \Delta p_{pump}}{\eta_p \rho}} = \frac{\dot m g_o H_{pump}}{\eta_p}$$

(IV.24)

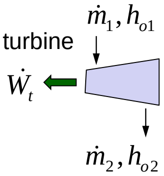
Example Pump Characteristics



$$\eta_p \equiv \frac{\dot{W}_{p,ideal}}{\dot{W}_{p,actual}} = \frac{\Delta h_{ideal}}{\Delta h_{actual}}$$

from Humble, Chapter 5

Turbine Power Requirements



- **Power output needed**
  - depending on shaft/gear box efficiency

$$\dot{W}_t \geq \dot{W}_p$$

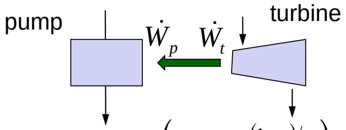
- **Conservation equations** (steady, adiabatic)
  - mass: $\dot{m}_1 = \dot{m}_2 \equiv \dot{m}$
  - energy $\dot{m}h_{o1} = \dot{m}h_{o2} + \dot{W}_t \quad \Rightarrow \dot{W}_t = \dot{m}\left(h_{o1} - h_{o2}\right)$
    - for cal. perfect gas $\dot{W}_t = \dot{m}c_p\left(T_{o1} - T_{o2}\right)$
- **Turbine efficiency**
  - if also reversible (so isen.) $Pr_t = p_{o1}/p_{o2} = \left(T_{o1}/T_{o2s}\right)^{\gamma/(\gamma-1)}$

$$\eta_t \equiv \frac{\Delta h_{actual}}{\Delta h_{ideall}} \Rightarrow \boxed{\dot{W}_t = \dot{m}c_p T_{o1}\eta_t\left(1 - Pr_t^{(1-\gamma)/\gamma}\right)} \quad \textbf{(IV.25)}$$

for same pressure ratio

$$\dot{W}_{t,ideal} = \dot{m}c_p\left(T_{o1} - T_{o2s}\right)$$

Power Summary



- **Power requirements**

$$\dot{W}_p = \frac{\dot{m}_l \Delta p_{pump}}{\eta_p \rho_l} = \eta_{trans} \dot{W}_t = \eta_{trans} \dot{m}_t c_p T_{o,t_{inlet}} \eta_t \left(1 - Pr_t^{(1-\gamma)/\gamma}\right)$$

shaft or gear transmission efficiency

- so given
  - pump flow rate
  - pump pressure rise
  - pump and turbine efficiencies
- have relation between
  - turbine inlet temperature
  - turbine pressure ratio
  - turbine flow rate

can be linked