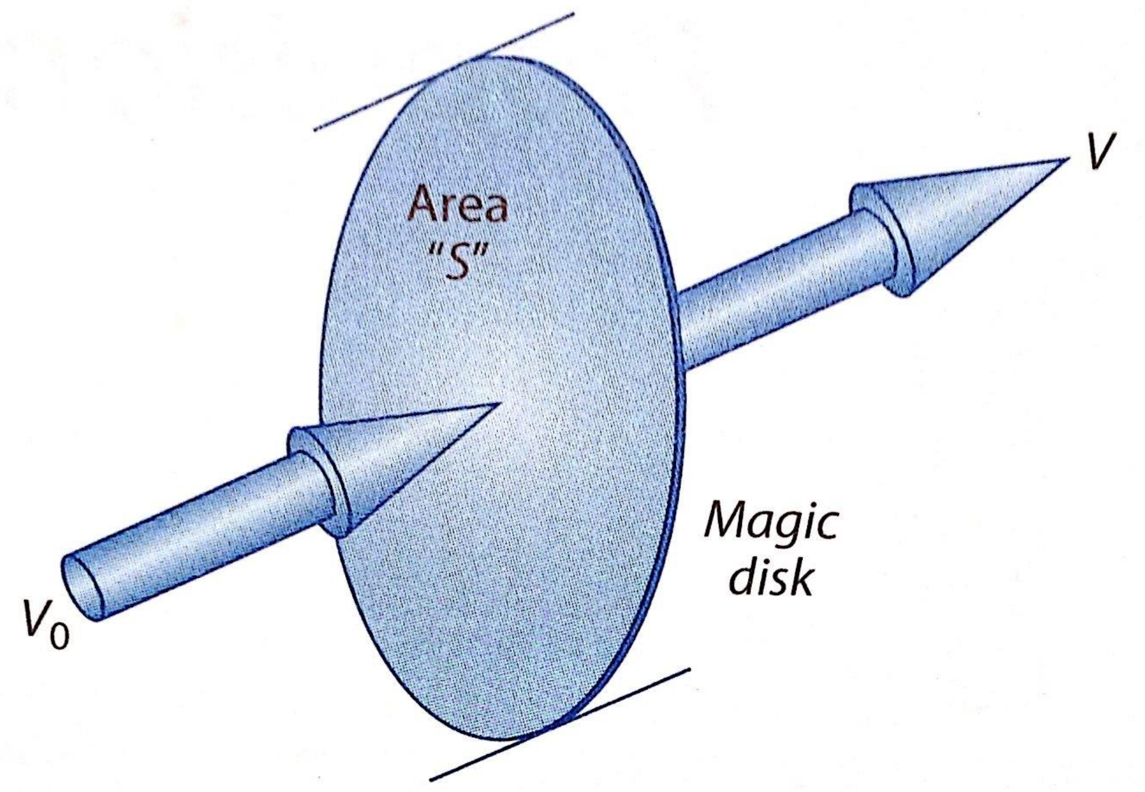
ME4932 Aircraft Performance & Design

Propulsion (Chapter 13)



$$F = ma = \dot{m}\Delta V = (\rho V s)(V - V_0) = \rho s V(V - V_0)$$

$$P_t = FV_0 = \rho s V(V - V_0)V_0$$

$$P_{t_{\text{expended}}} = \frac{\partial \Delta E}{\partial t} = \frac{1}{2}\dot{m}V^2 - \frac{1}{2}\dot{m}V_0^2 = \frac{1}{2}\rho V s(V^2 - V_0^2)$$

$$= \frac{\rho s}{2}V(V^2 - V_0^2)$$

Source: Aircraft Design by Daniel P. Raymer

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$$\eta_{PE} = \frac{P_t}{P_{t_{\text{expended}}}} = \frac{2}{V/V_0 + 1}$$

Propulsive Efficiency = Maximum = 1.0 , when V0 = V !

But No Acceleration of the Fluid = No Thrust!

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Propulsion

- So, if you want to maximize Propulsive Efficiency, you want to get the most thrust with the smallest change in fluid velocity!
- A very large area S is conducive to this (helicopter's rotor, propeller's, or turbofan's....)

For a turbojet, typically V/V0 = 3; Eff = 0.5

For a propeller, V/V0 = 1.5; Eff = 0.8

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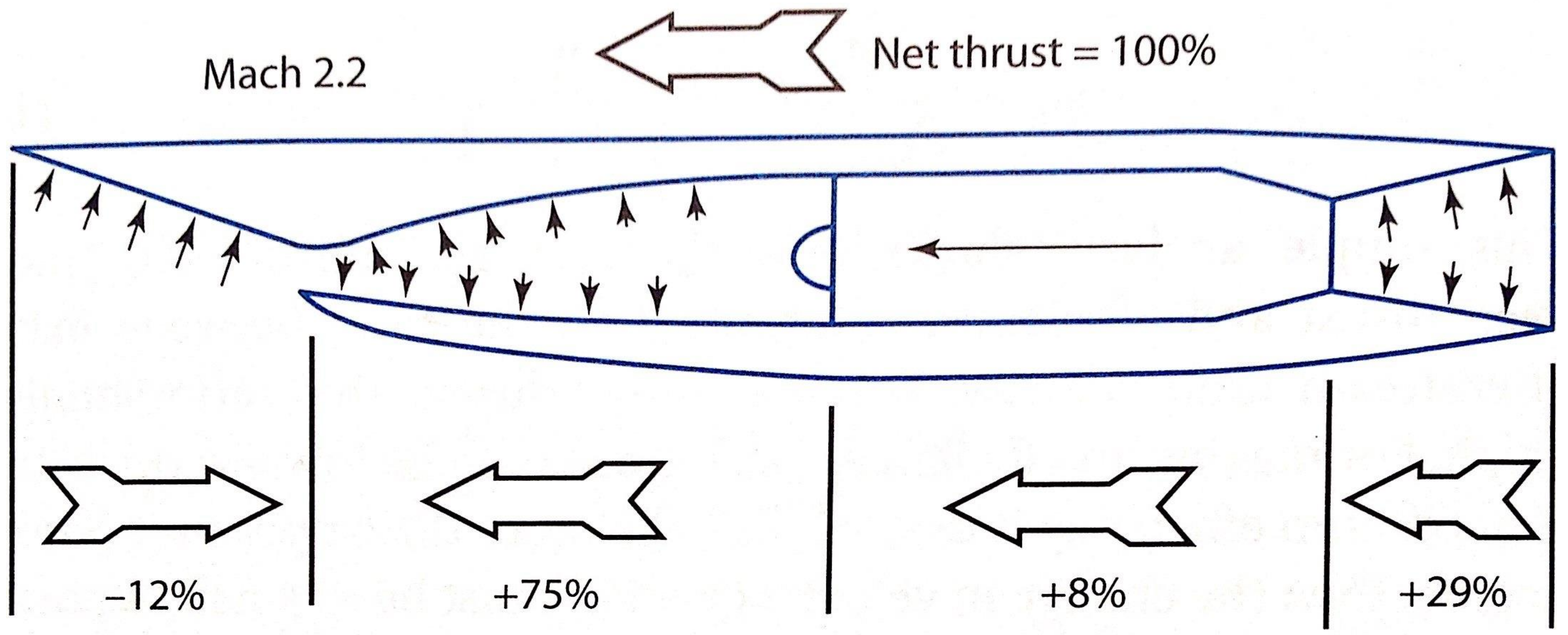
Propulsion

- For a propeller, all the thrust is passed from the shaft to the engine mounts.
- For a jet aircraft, the force through the engine mounts may be 1/3 of the total propulsive force!



- At Mach=2.2, this inlet expands the air from sonic to about 0.45M,; a massive convertion of dynamic pressure into static pressure. This pressures acting on inlet walls pull the aircraft!

Source: Aircraft Design by Daniel P. Raymer

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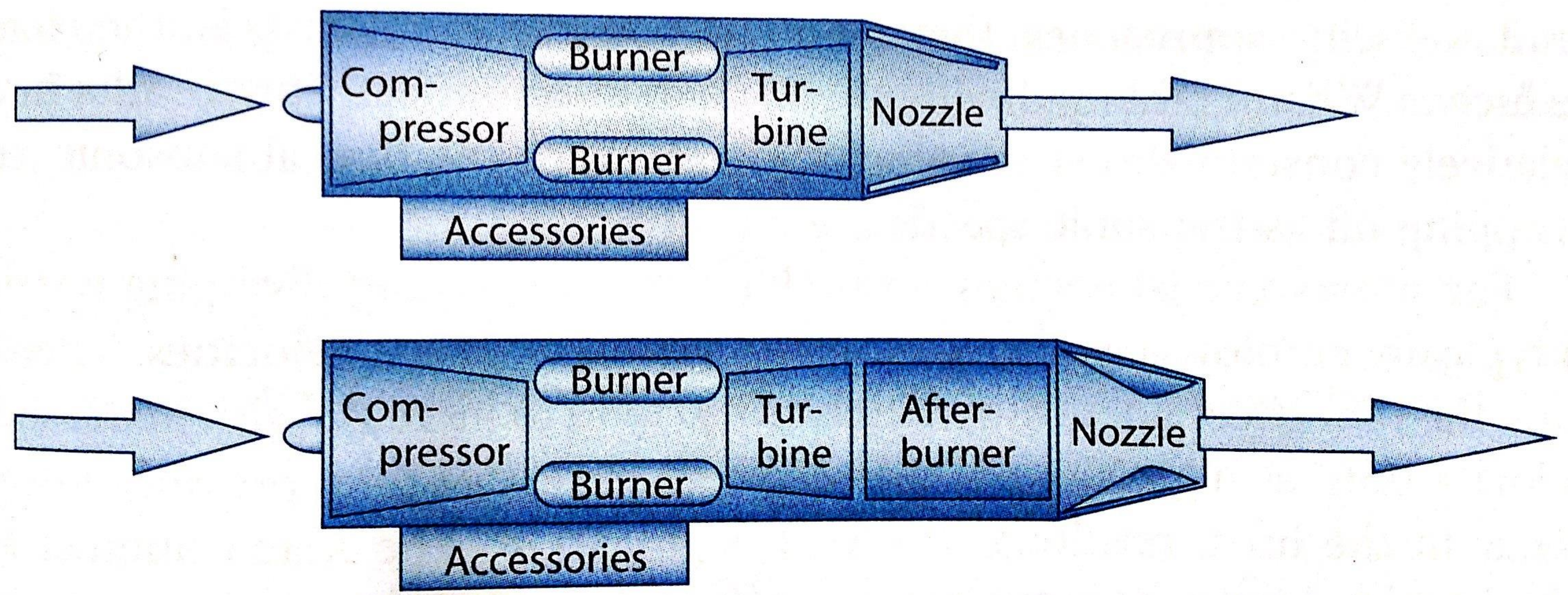
Propulsion



Gross Thrust = Results from the total momentum in the exhaust stream
Ram Drag = Results from the total momentum in the inlet stream
Net Thrust = Gross Thrust - Ram Drag

Source: Aircraft Design by Daniel P. Raymer

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Propulsion

- Thrust is proportional to the mass flow rate of air going through a jet engine, benefiting from ram air as it gains speed.

- Subsonic jet aircraft have approximately constant thrust with velocity up to transonic speeds. Subsonic turbofans can generate 30# per #/sec of airflow.

- Supersonic jets, because of their converging/diverging nozzle can fully use the ram effect up to supersonic speeds! Afterburning turbojets can generate 130# per #/sec of airflow.

- For a propeller-piston engine, shaft power is constant with velocity, so thrust is reduced as the aircraft speeds up! (P=TV)

- At altitude, thrust is reduced because of the low air density

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- OPR = Overall Pressure Ratio of Exhaust Pressure to Inlet Pressure. Measure of the engine's ability to accelerate flow (thrust). OPR = 15-30

- TIT = Turbine Inlet Temperature. The higher it is, the more stoichiometric the fuel/air mix is (more thrust). Technology-limited.

- BPR = Bypass Ratio. Ratio of bypassed mass flow to the flow that goes through the engine’s core and therefore used for combustion. A high BPR increases efficiency (more S, lower change in V). Works well at lower velocities but the ram drag makes turbofans suitable for M<<2.0

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- Thrust - Drag Bookkeeping.- In general, changes in drag that have to do with engine operation/power setting are accounted for in engine data.

- Tremendously important as aerodynamics and propulsion teams could easily fail to account for a significant force or could duplicate it!

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Propulsion - Installed Thrust

- Engine companies provide UNINSTALLED engine data
- Aircraft companies correct data for inlet efficiency/distortion, engine bleed, power extraction, nozzle performance. This is INSTALLED ENGINE THRUST.
- Drag items are calculated and coordinated with aerodynamics analysis team. For example, aerodynamics data may assume nozzle is wide-open so max. is going through engine, so engine data should correct at all power settings. If engine creates a moment, aerodynamic data may be trimmed for example at max power so the propulsion data should also be corrected!
- The end result is the net propulsive force or NET THRUST

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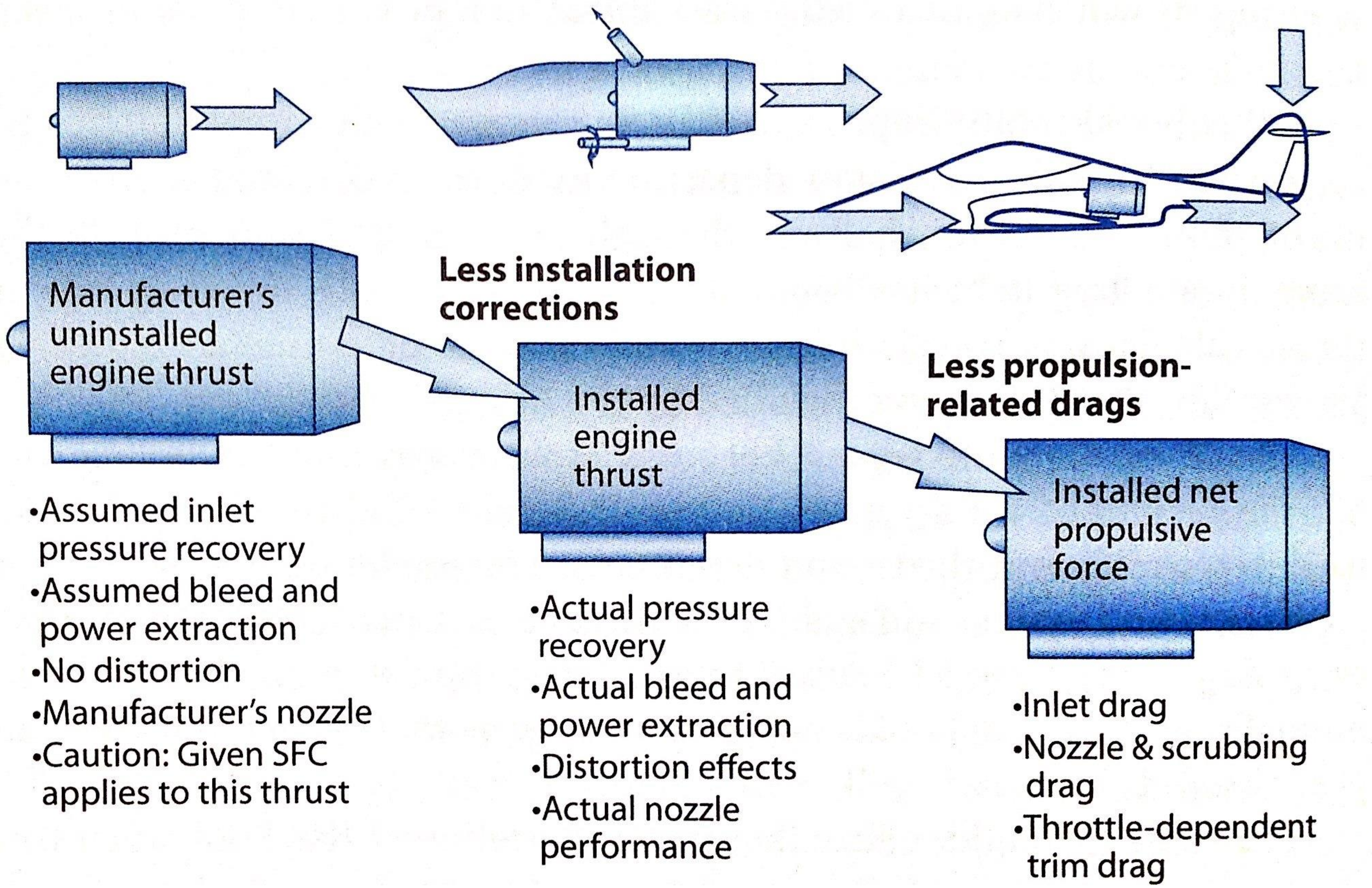
Propulsion - Installed Thrust



Source: Aircraft Design by Daniel P. Raymer

Propulsion - Installed Thrust

- Losses inside inlet duct.- Pressure recovery is about 0.94-0.98, but can be much lower at very low speeds, as inlet is sized for design conditions and has to "suck in" airflow at the lower speeds.

- Bleed losses.- high pressure air is bled from the compressor for cabin air, anti-icing, etc. % of thrust loss is about twice the % of bled mass flow.

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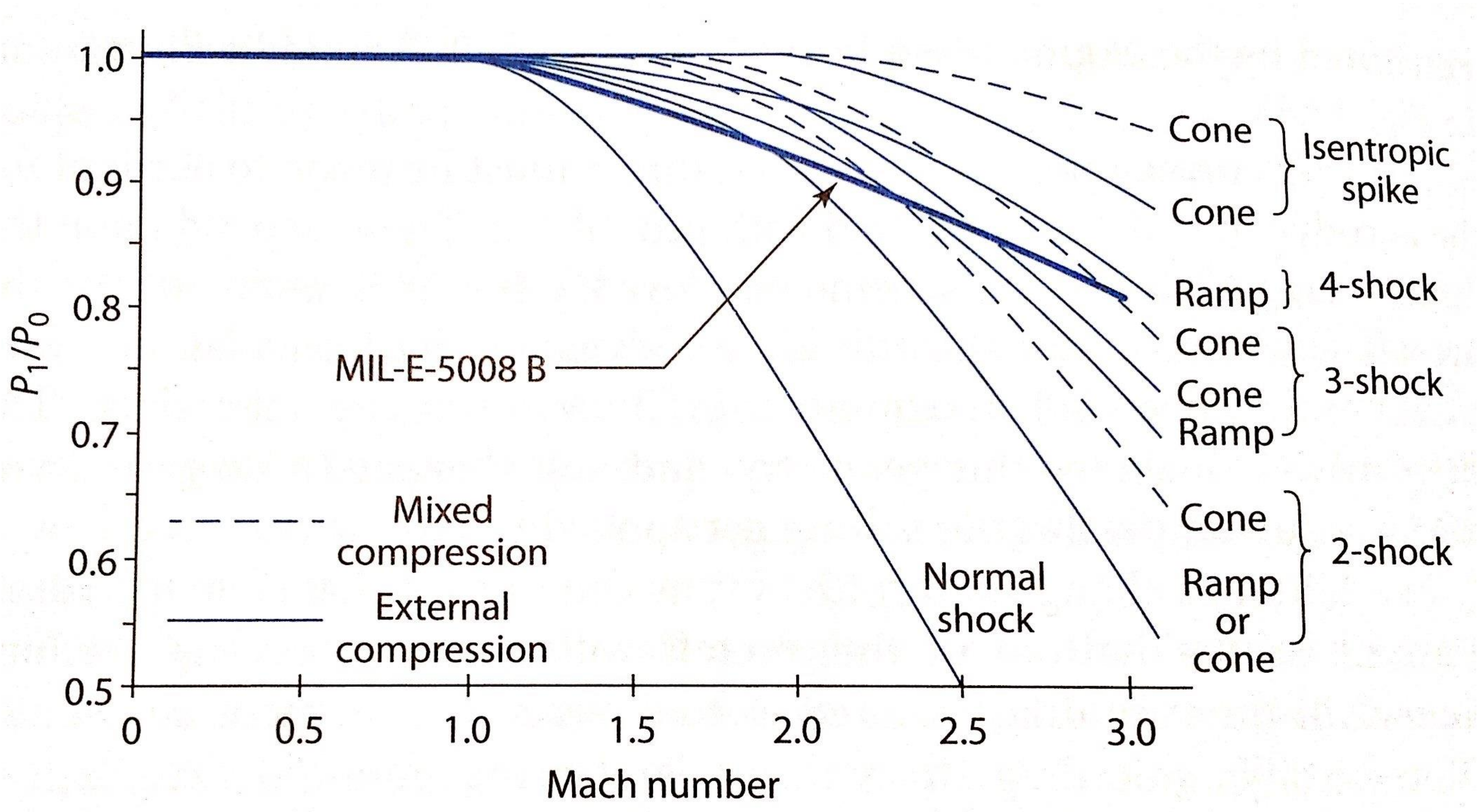
Propulsion - Installed Thrust



$$\left(\frac{P_1}{P_0}\right)_{\text{ref}} = 1 - 0.075(M_\infty - 1)^{1.35}$$

Source: Aircraft Design by Daniel P. Raymer

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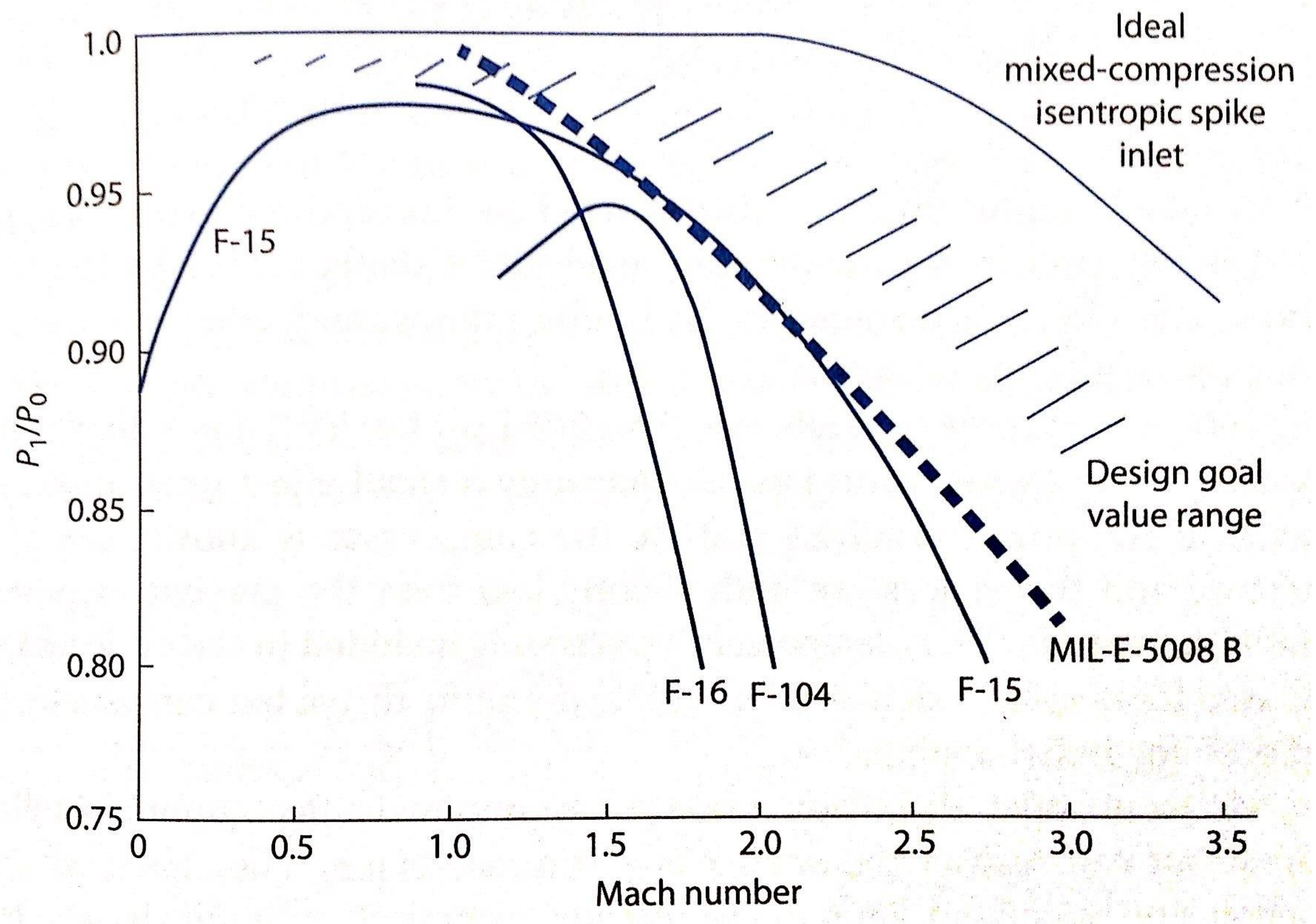
Propulsion - Installed Thrust



$$\text{Percent thrust loss} = C_{ram}\left[\left(\frac{P_1}{P_0}\right)_{ref} - \left(\frac{P_1}{P_0}\right)_{actual}\right] \times [100]$$

Supersonic:

$$C_{ram} \cong 1.35 - 0.15(M_\infty - 1)$$

Source: Aircraft Design by Daniel P. Raymer

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Propulsion - Installed Thrust

- Most of the ram drag is caused by a mismatch between engine air demand and and inlet area. Inlets are sized for the largest demand.
- The drag from air spilled before entering the inlet is "spillage drag". This air is compressed by the external part of the inlet but never reaches the engine. Resulting cowl-lip suction is a "thrust" that reduces the spillage drag significantly. In flight conditions where spillage drag becomes prohibitive, a bypass door is used to allow the air go through the inlet to then be ejected before reaching the engine. The resulting bypass drag is lower than what the spillage drag would have been.
- Inlet boundary layer bleed is used to prevent a formation of a thick boundary layer and shock induced separation within the inlet. The B.L. is bled through holes in the ramps and inlet surface and dumped overboard. This momentum loss is accounted as a propulsion drag.

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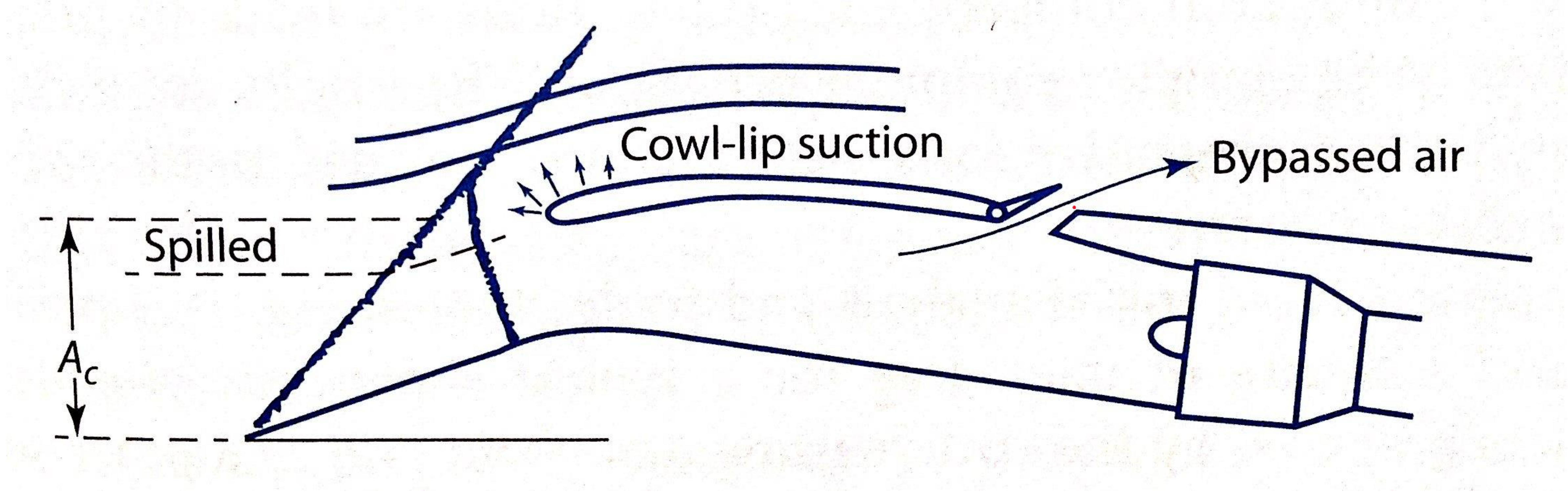
Propulsion - Installed Thrust



Source: Aircraft Design by Daniel P. Raymer

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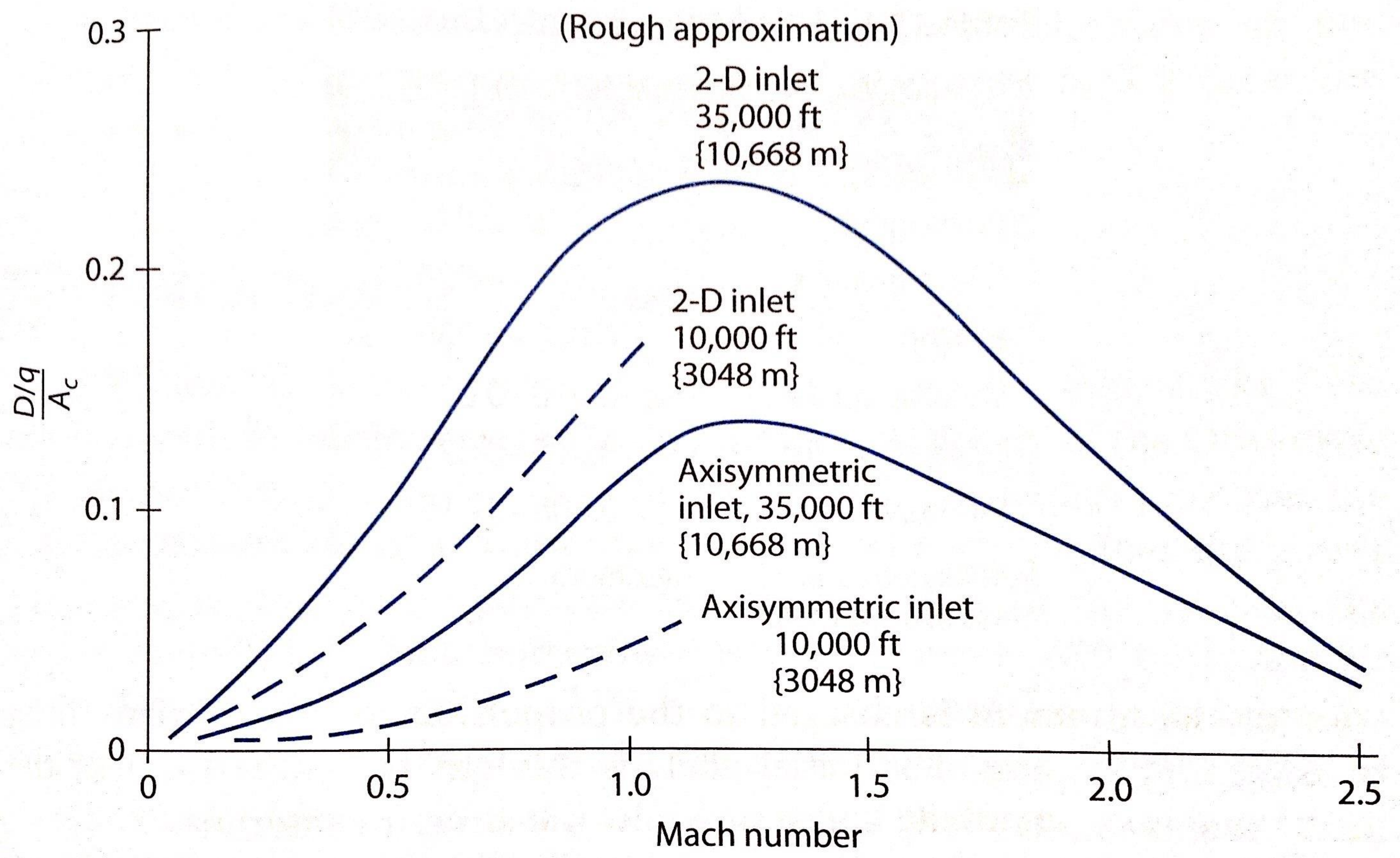
Propulsion - Installed Thrust



Source: Aircraft Design by Daniel P. Raymer

Propulsion - Installed Thrust

- Nozzle drags are a function of Mach number, nozzle geometry change with power setting, etc.

- As an approximation, use the subsonic (worst case) estimated drags (negligible for podded nacelle):

Nozzle type	Subsonic $\frac{D/q}{A_{fuselage}}$
Convergent	0.036–0.042
Convergent iris	0.001–0.020
Ejector	0.025–0.035
Variable ejector	0.010–0.020
Translating plug	0.015–0.020
2-D nozzle	0.005–0.015

Referenced to fuselage maximum cross-section area.

Source: Aircraft Design by Daniel P. Raymer

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Propulsion - Part Power Operation

- When they are throttled back, jet engines exhibit worse specific fuel consumption (C or SFC) because the resulting reduction in thrust (#) is more than proportional to the reduction in fuel flow (#/hr).

- Engine companies provide part-power table for fuel flow or SFC (fuel flow hooks).

- Approximation:

$$\frac{c}{c_{\text{max dry}}} = \frac{0.1}{\left(T/T_{\text{max dry}}\right)} + \frac{0.24}{\left(T/T_{\text{max dry}}\right)^{0.8}} + 0.66\left(\frac{T}{T_{\text{max dry}}}\right)^{0.8} + 0.1M\left[\frac{1}{\left(T/T_{\text{max dry}}\right)} - \left(\frac{T}{T_{\text{max dry}}}\right)\right]$$

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Propulsion - Piston Engines

- Engine Power is a function of air mass flow into the engine manifold. Basically, power is constant at the various velocities but it decreases with the reduction in air density at altitude.

$$\text{power} = \text{power}_{SL}\left(\frac{\rho}{\rho_0} - \frac{1-\rho/\rho_0}{7.55}\right)$$

- Piston engines can be supercharged or turbo-supercharged so they maintain sea level power to about 20,000 ft altitude.

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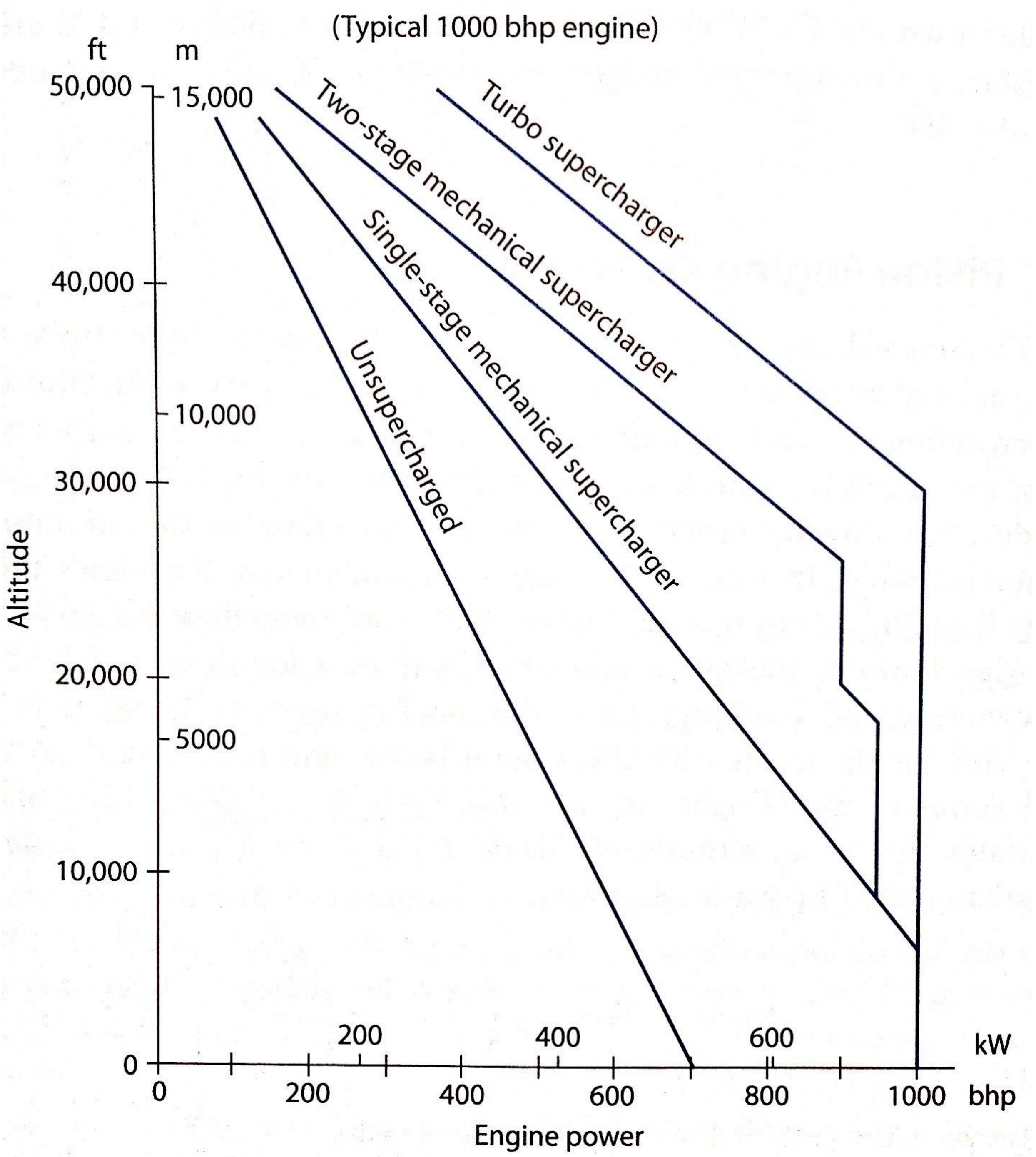
Propulsion - Piston Engines



Source: Aircraft Design by Daniel P. Raymer

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Propulsion - Propeller Analysis

- We define propeller efficiency as the way a propeller converts Shaft Power into Thrust Power (useful)

$$\eta_p = \frac{ThrustPower}{EngineShaftPower} = \frac{TV}{P_s} \sim 0.8$$

- A fixed pitch (usually referenced to 75% radius) propeller will exhibit its highest efficiency (like a blade effective L/D w.r.t. aircraft V) at a particular speed. Variable pitch propellers exhibit top efficiency at various velocities, making possible the achievement of the best climb and best cruise with the same equipment.

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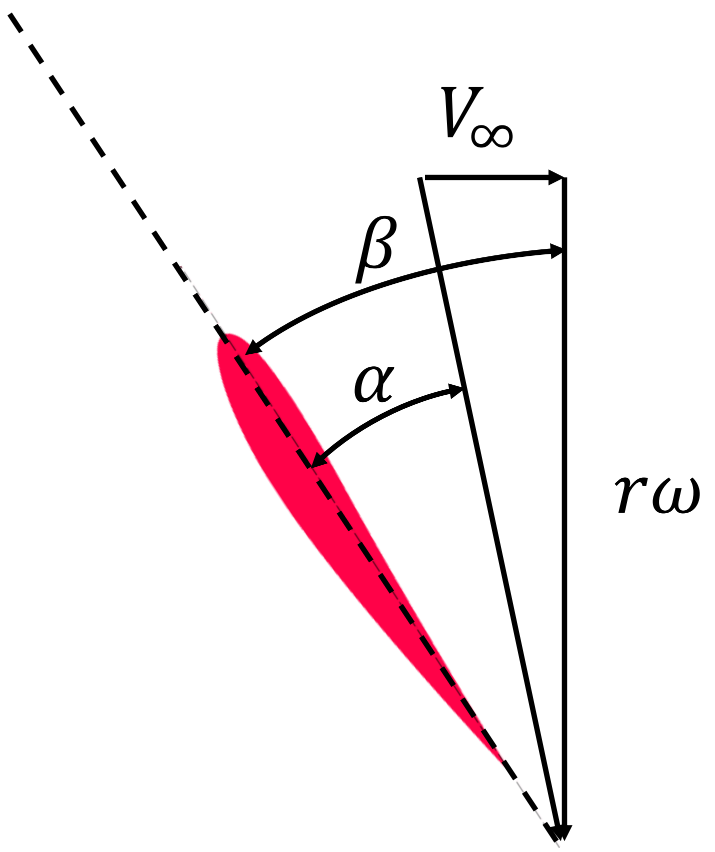
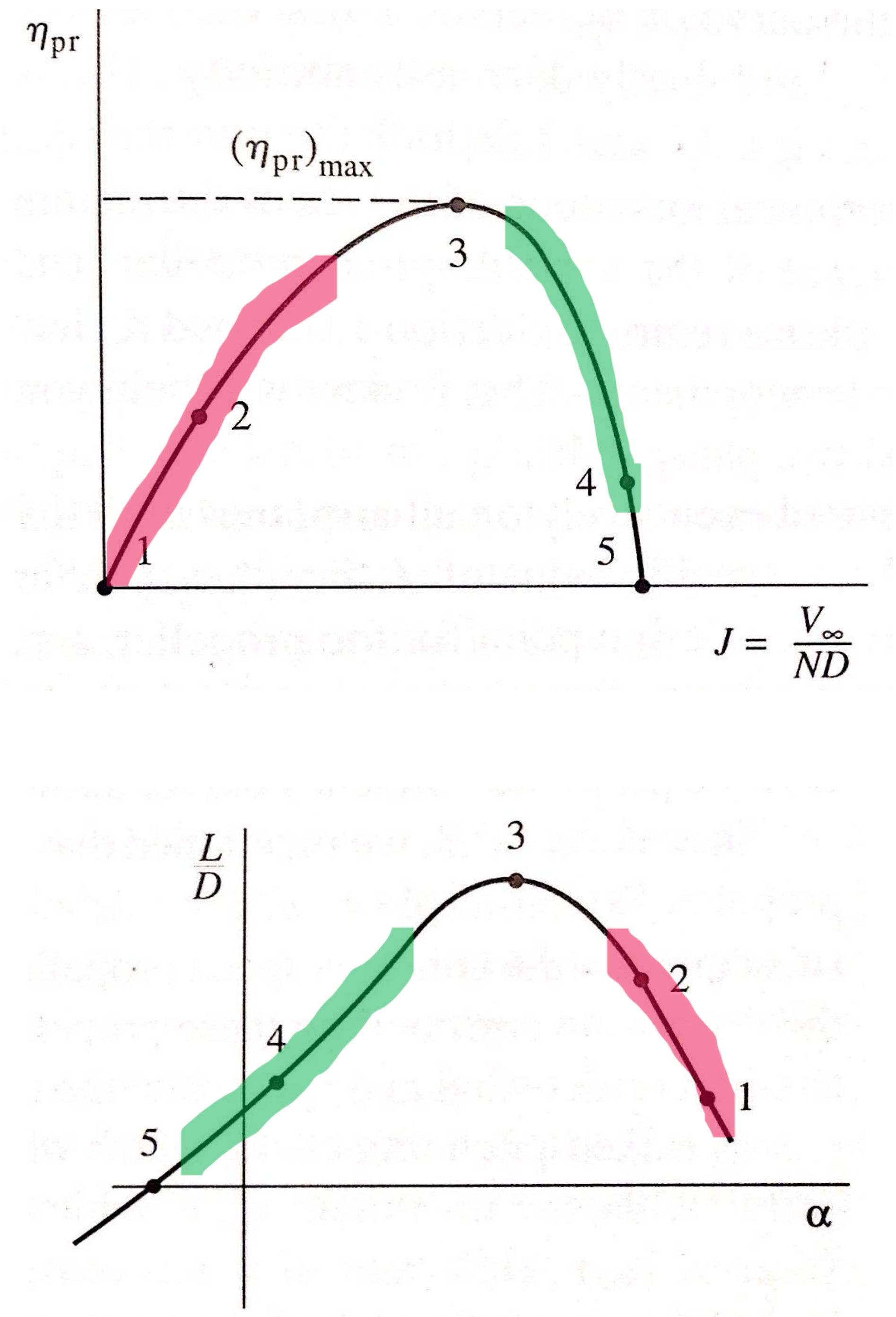
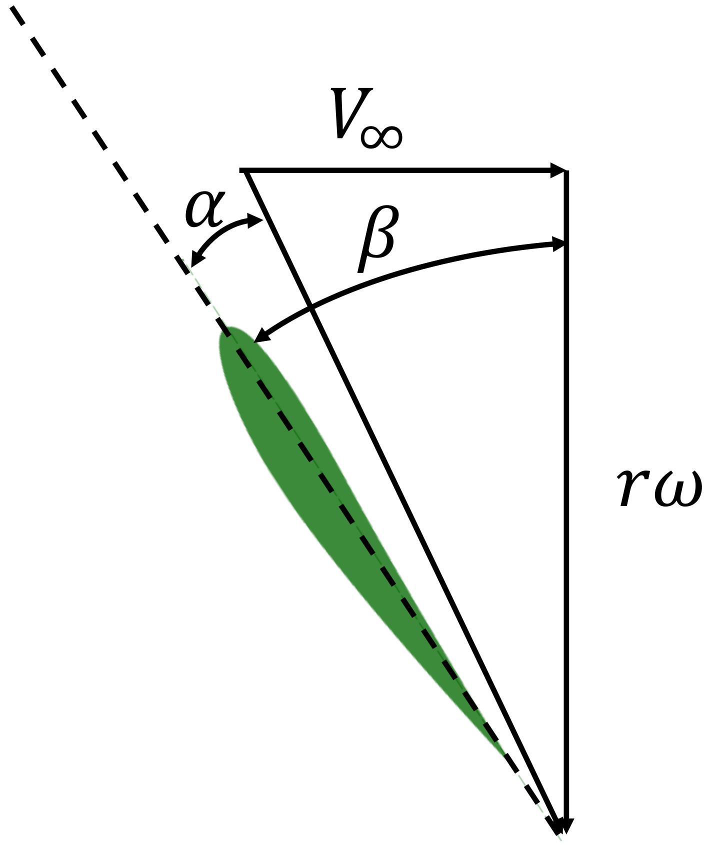
Propulsion - Propeller Analysis



Aircraft at **low speed**





Aircraft at **high speed**

Source: Aircraft Performance and Design by John D. Anderson

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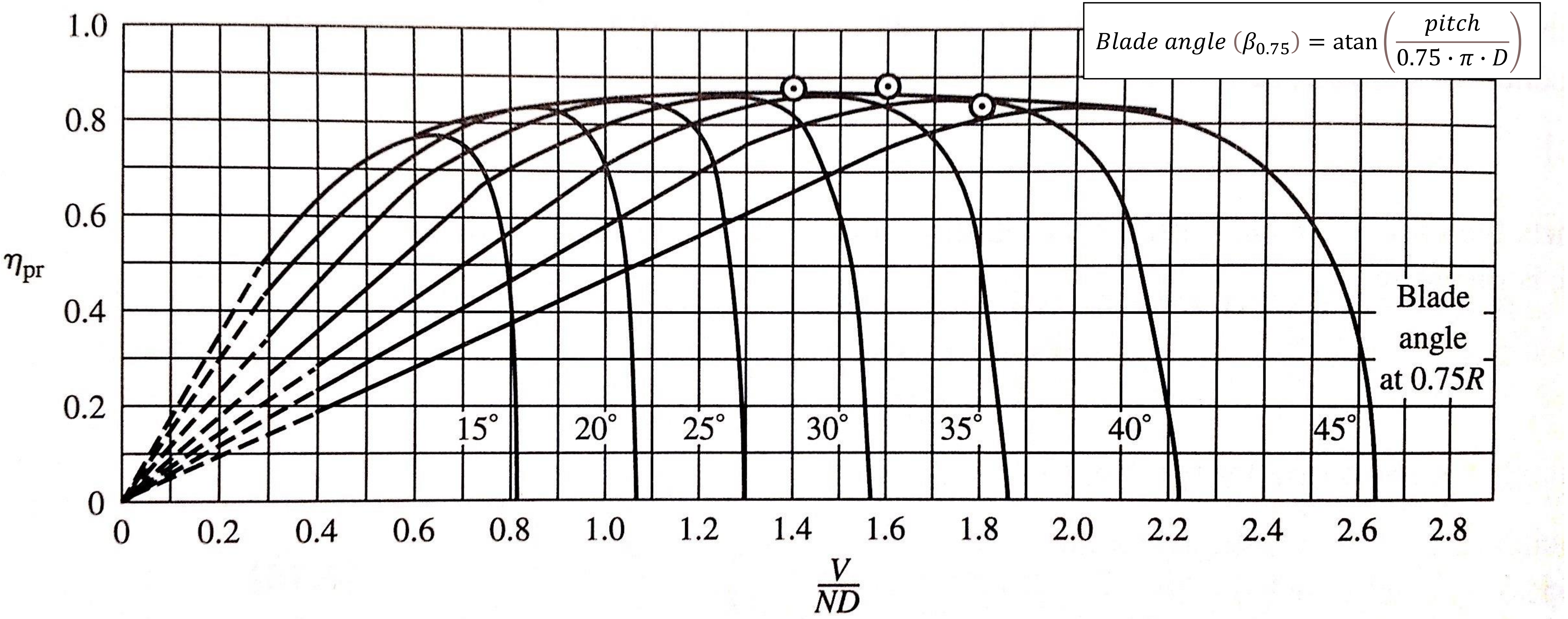
Propulsion - Propeller Analysis

Propeller pitch (p) is the distance that a propeller theoretically advances during one revolution.

$$Blade\ angle\ (\beta_{0.75}) = \text{atan}\left(\frac{pitch}{0.75 \cdot \pi \cdot D}\right)$$



Source: Aircraft Performance and Design by John D. Anderson

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Propulsion - Propeller Analysis

Advance ratio:

$$J = V/nD$$

Power coefficient:

$$c_P = \frac{P}{\rho n^3 D^5} = \frac{550\,\text{bhp}}{\rho n^3 D^5}$$

Thrust coefficient:

$$c_T = T/\rho n^2 D^4$$

Speed-power coefficient:

$$c_S = V^5 \sqrt{\rho / P n^2}$$

$$AF_{\text{per blade}} = \frac{10^5}{D^5} \int_{0.15R}^{R} cr^3$$

$$= \frac{10^5 c_{\text{root}}}{16D} [0.25 - (1 - \lambda)0.2]$$

Propeller efficiency:

$$\eta_P = \frac{TV}{P} = \frac{TV}{550\,\text{bhp}}$$

Thrust:

$$T = P\eta_p / V = \frac{550\,\text{bhp}\ \eta_P}{V} \quad \text{(forward flight)}$$

or

$$T = \frac{c_T}{c_p} \frac{P}{nD} = \frac{c_T}{c_P} \frac{550\,\text{bhp}}{nD} \quad \text{(static)}$$

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Propulsion - Propeller Analysis

- Blockage by nacelle slows down the flow before it reaches the propeller. This is good, because it reduces advance ratio and increases the high speed performance.

$$J \text{ corrected} = J(1 - 0.329\, S_c/D^2)$$

- Tips of propellers of high speed propeller airplanes may encounter sonic speeds and therefore a reduction of thrust. Propulsion efficiency may be reduced by the following:

$$\eta_{p_{\text{corrected}}} = \eta_p - (M_{\text{tip}} - 0.89)\left(\frac{0.16}{0.48 - 3t/c}\right) \quad \text{for } M_{\text{tip}} > 0.89$$

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Propulsion - Propeller Analysis

- Scrubbing drag is caused in conventional tractor configurations by the propwash flow around the aircraft. Again, accounted for by reducing propeller efficiency (on pushers, it is the aircraft wake that reduces thrust!):

$$\eta_{p_{\text{effective}}} = \eta_p \left[1 - \frac{1.558}{D^2} \frac{\rho}{\rho_0} \sum (C_{f_e} S_{\text{wet}})_{\text{washed}} \right]$$

- Cooling drag is due to the momentum loss of air taken into the cowling to be passed over the engine.

$$(D/q)_{\text{cooling}} = (4.9 \times 10^{-7}) \frac{\text{bhp} \cdot T^2}{\sigma V}$$

$$= 6 \times 10^{-8} \frac{P T^2}{\sigma V}$$

Propulsion - Propeller Analysis

- Miscellaneous engine drag includes the drag of the oil cooler, air intake, exhaust pipes, and other parts. Usually equivalent to a 6-10% reduction in thrust or as the following drag impact:

$$
\begin{aligned}
(D/q)_{\text{misc}} &= (2 \times 10^{-4})\,\text{bhp} \\
&= 2.5 \times 10^{-5} P
\end{aligned}
$$

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Propulsion - Turboprops

- Turboprop aircraft have a jet engine that drives a propeller. The jet exhaust itself may provide 20% more thrust!
- This residual thrust provides better efficiency than piston/propeller systems at higher speeds, but never like a turbofan.

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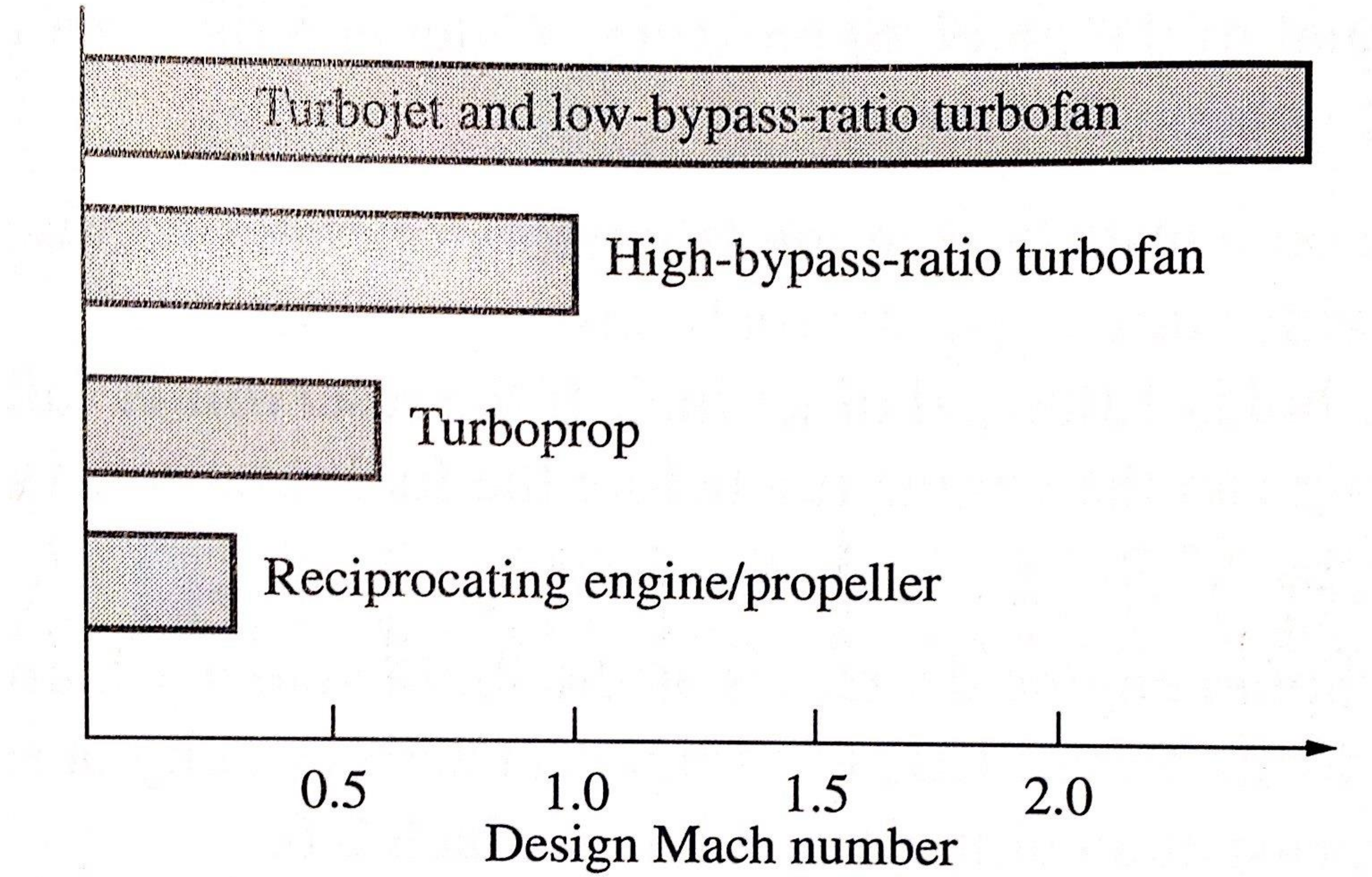
Propulsion



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