



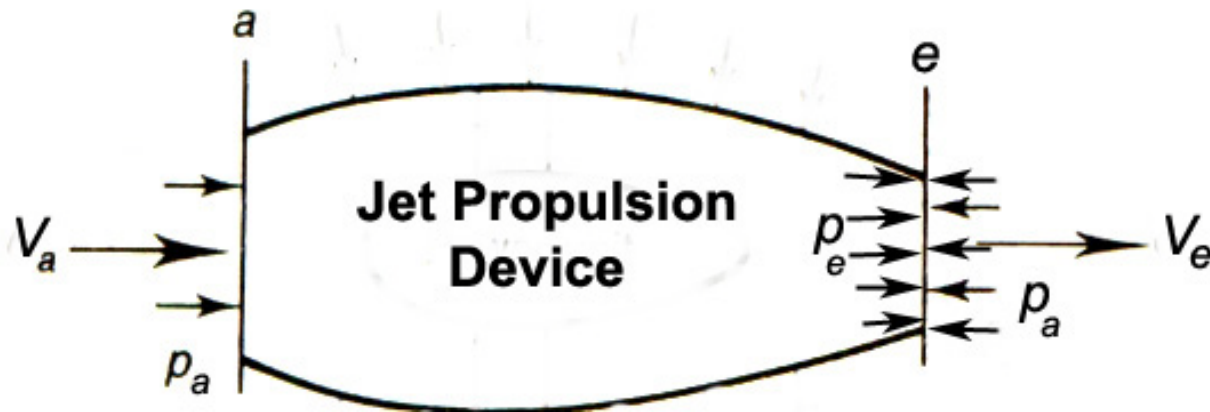
# Jet Aircraft Propulsion

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Lecture - 3

## Jet Engine Thrust and Other Performance Parameters



Consider the above propulsive duct in which the inflow air is at pressure  $p_a$  and, velocity  $V_a$  and, leaves the exhaust nozzle with a velocity of  $V_e$ . The pressure with which the air/gas leaves the exhaust nozzle is  $P_e$ .

The net thrust  $F_n$  due to change in momentum is

$$F_n = \underset{\substack{\uparrow \\ \text{Gross Momentum} \\ \text{Thrust}}}{\dot{m} \cdot V_e} - \overset{\substack{\text{Intake Ram drag} \\ \downarrow}}{\dot{m} \cdot V_a} + \underset{\substack{\uparrow \\ \text{Pressure} \\ \text{Thrust}}}{A_e \cdot (P_e - P_a)}$$

The thrust relation shown in the last slide is of general nature and is valid for cases where a residual exit static pressure exists in the exhaust flow.

If it is assumed that the expansion in the nozzle is completed to  $P_a$ , and hence the 2<sup>nd</sup> term, pressure thrust, can be neglected. Thus net thrust is:

$$\text{Then, } F_n = \dot{m} \cdot (V_e - V_a)$$

For a net thrust  $F_n$ , the thrust power may be written as:

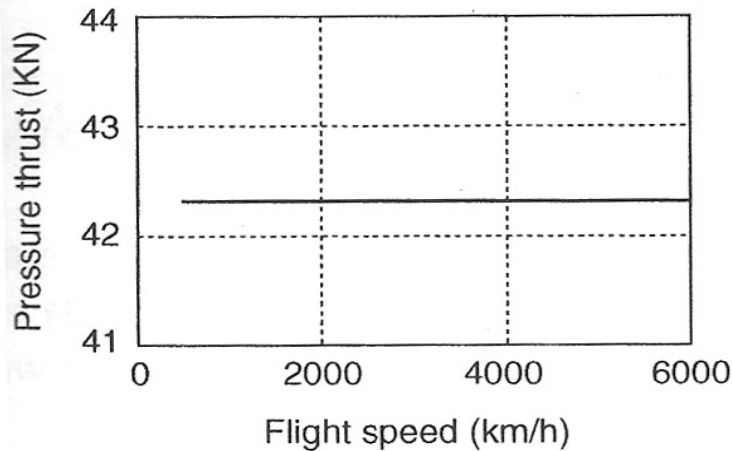
$$\text{THP} = F_n \cdot V_a$$

- The basic thrust equation indicates that as forward speed  $V_a$  increases it is necessary to increase either the mass flow, or exit velocity  $V_{ex}$ , or both, in order to hold the thrust,  $F$ , constant.
- The near-constant thrust characteristics at any altitude a desirable and attractive feature of jet engines (flat rated engines)
- A near-constant  $F_n$  results in almost direct increase in thrust horsepower with forward speed.
- This characteristic of turbojet engines exists well up into the high subsonic speed range, and with a properly designed inlet diffuser, extends into the supersonic range.

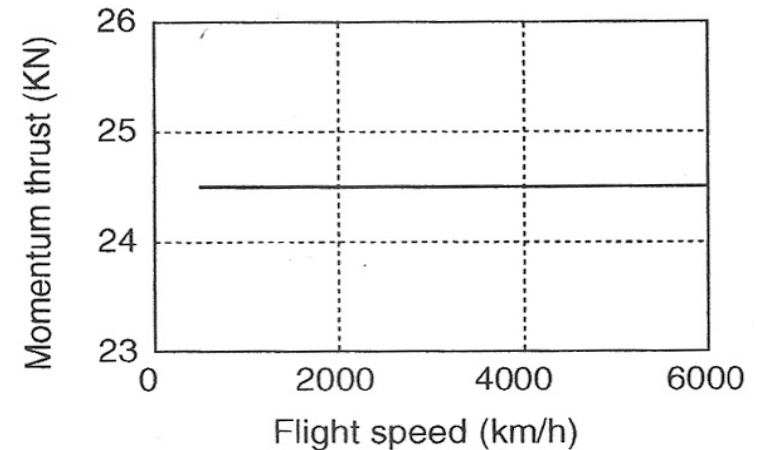
- In the supersonic region afterburner equipped engines enable large increase in thrust with Mach number.
- This is possible from  $M=0$  to  $M>3.0$  . At high flight speeds (Mach 1 and above), an appreciable proportion of the air compression is accomplished by inlet diffuser ram effect.
- In fact, at a Mach number well above 3.0, due to enormous ram effect it is economical to dispense with the compressor, and hence, also the turbine.
- This has given rise to ramjet engines.

## Typical thrust variation at constant air mass flow

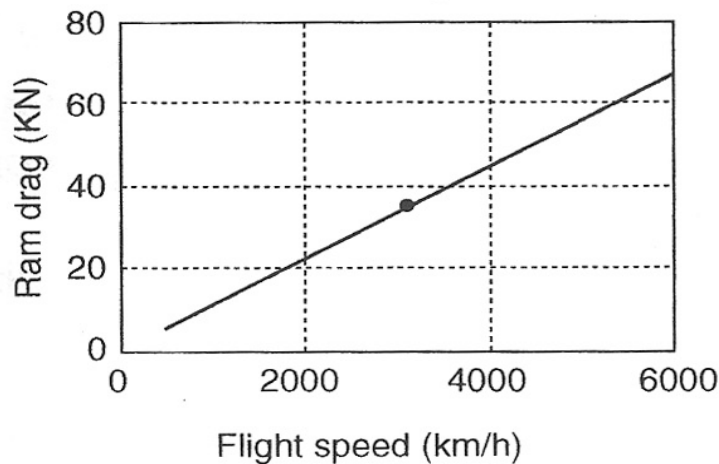
Pressure thrust versus flight speed at 9 km



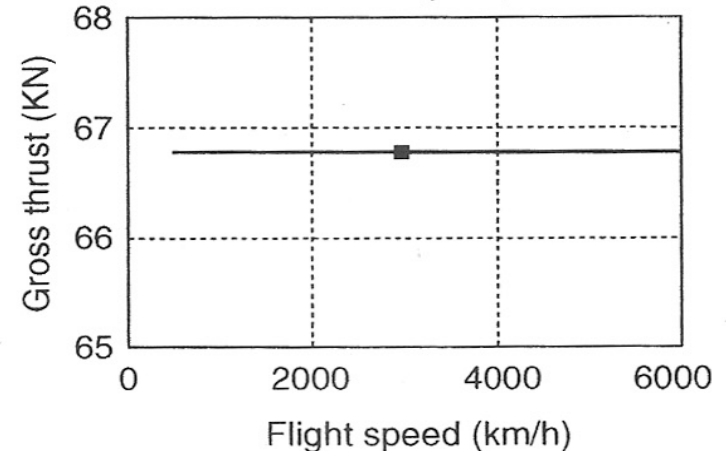
Momentum thrust versus flight speed at 9 km



Ram Drag versus flight speed at 9 km

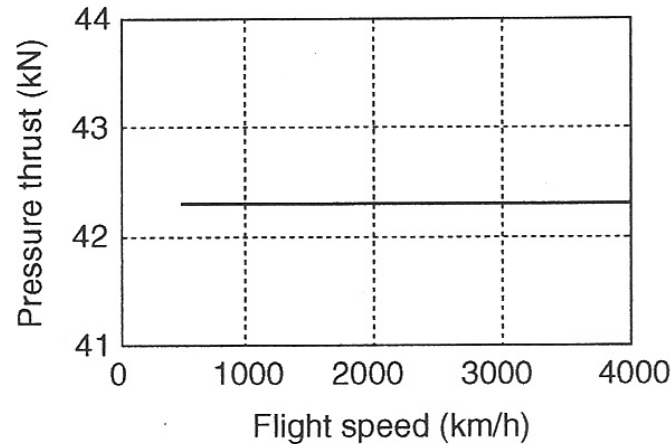


Gross thrust versus flight speed at 9 km

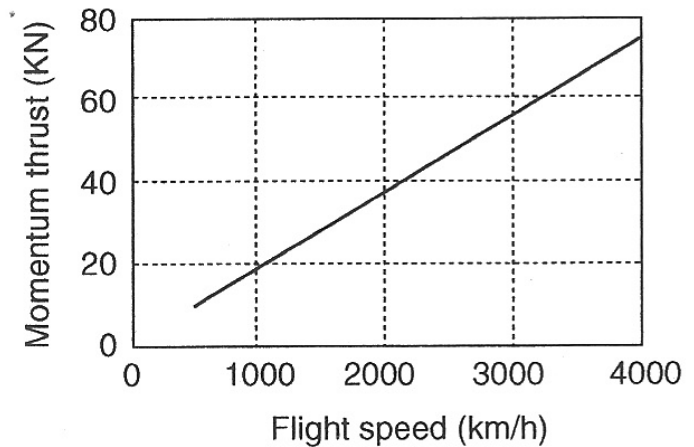


## Typical thrust variation with variable air mass flow

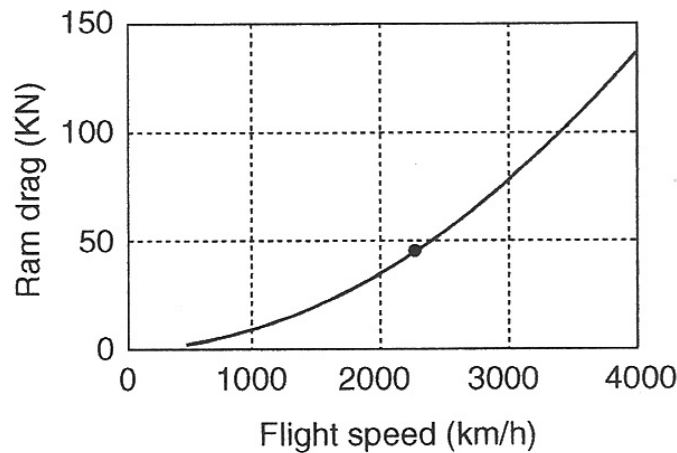
Pressure thrust versus flight speed at 9 km



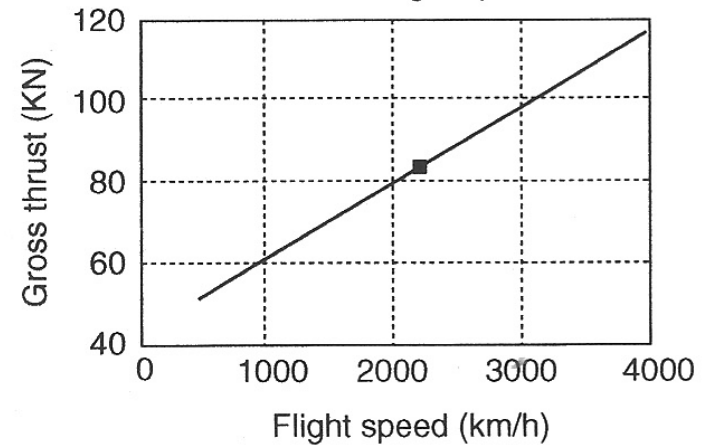
Momentum thrust versus flight speed at 9 km



Ram drag versus flight speed at 9 km



Gross thrust versus flight speed at 9 km





The propulsive efficiency  $\eta_p$  can be defined as the ratio of the **useful propulsive energy or thrust power** ( $F.V_a$ ) to the sum of **that energy and the unused kinetic energy of the jet**. This is the kinetic energy relative to the earth, and may be written as:

$$\frac{\dot{m} \cdot (V_e - V_a)^2}{2}$$

It then stands to reason that this unused exit kinetic energy is a waste energy and, once it goes out of the engine body it is not of any use for thrust production.

Although inlet diffuser provides aerodynamic pre-compression of air, it also produces ram drag.

The propulsive efficiency  $\eta_p$  can be written as

$$\eta_p = \frac{\dot{m} \cdot V_a \cdot (V_e - V_a)}{\dot{m} \cdot \left[ V_a \cdot (V_e - V_a) + \frac{(V_e - V_a)^2}{2} \right]} = \frac{2}{1 + \frac{V_e}{V_a}}$$

$\eta_p$  is also known as *Froude efficiency*.

From the above equations it is evident that :

- $F_n$  is maximum when  $V_a = 0$ , (Take off) but  $\eta_p = 0$
- $\eta_p$  is maximum when  $V_e/V_a = 1$ , when thrust is zero.

- The propulsion efficiency is a measure of how well the propulsive device is being used for propelling the aircraft.
- It is different from the efficiency of energy conversion.
- The efficiency of energy conversion is given by

$$\zeta_{energy} = \frac{\dot{m} \cdot \left[ \frac{V_e^2 - V_a^2}{2} \right]}{\dot{m}_f \cdot \dot{Q}_{fuel}}$$

Where,  
 $\dot{m}$  and  $\dot{Q}_{fuel}$  are the fuel mass flow and its heating value respectively

The denominator refers to the energy released by burning of fuel

The overall engine efficiency is given by

$$\sigma = \frac{\dot{m} \cdot V_a \cdot (V_e - V_a)}{\dot{m}_f \cdot \dot{Q}_{\text{fuel}}} = \sigma_p \cdot \sigma_e$$

- At supersonic aircraft speeds the ram drag is also high.
- Moreover, at supersonic flight speeds it is difficult to design an air intake to efficiently handle the air flows required by the engine, which may have an afterburner for thrust enhancement.
- This requires matching the intake characteristics to the engine over a wide operating range of flow conditions as well as altitudes.
- At hypersonic flight speeds this prompts us to look at *ramjet* for thrust generation. Since there are no rotating components e.g. compressor /turbine, matching the inlet to the engine is simplified.

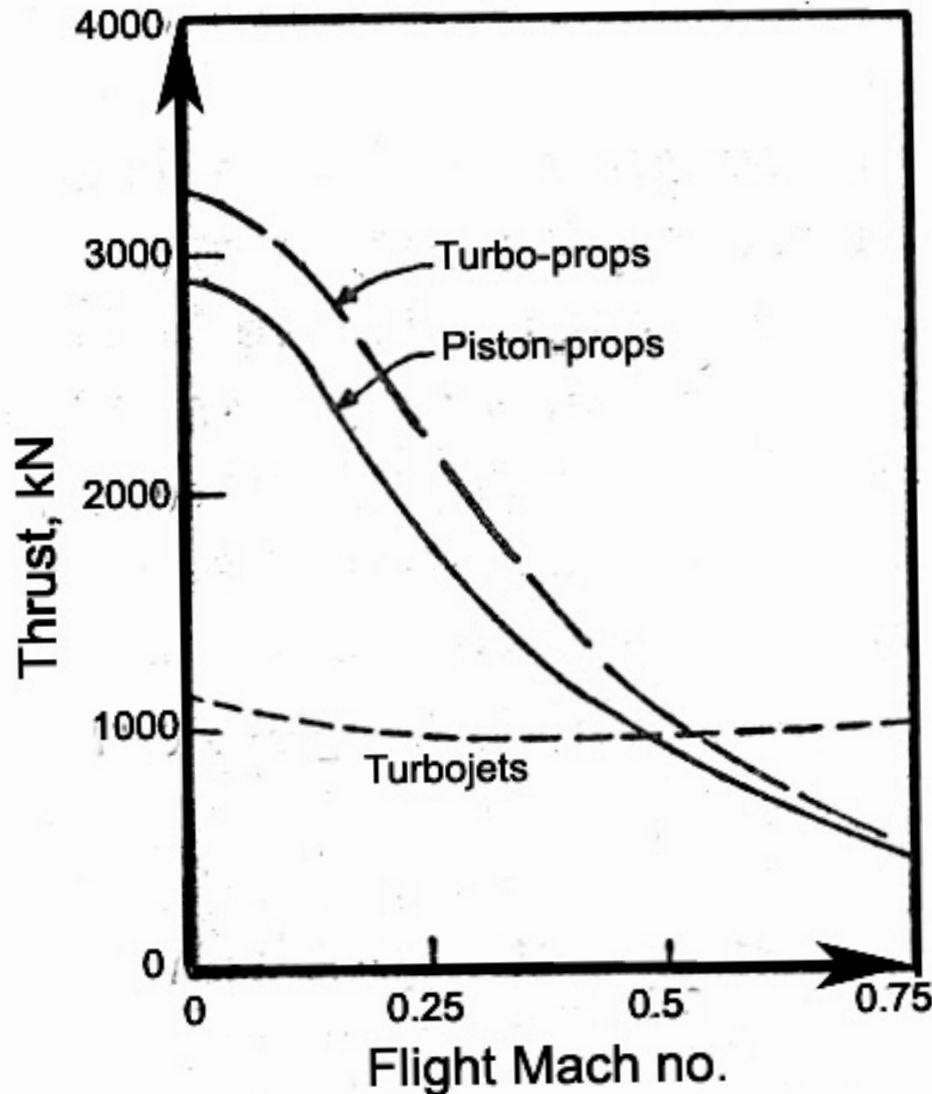
- Fuel consumption for turbojet and other jet engines is normally presented in terms of *thrust specific fuel consumption* (TSFC).
- The thrust specific fuel consumption varies with engine rpm, Mach number and altitude generally a minimum at the tropopause at 80-90 % rated rpm.
- For jet engines with reheat or afterburning, the fuel consumption would be quite high, and SFC would show up as high value. In such operation sheer thrust requirement outweighs the high SFC.
- Turbo-props have lower SFC. This fact has prompted development of Prop-fans .

## Specific fuel consumption

$$\text{s.f.c} = \frac{\dot{m}_f}{F_n}$$

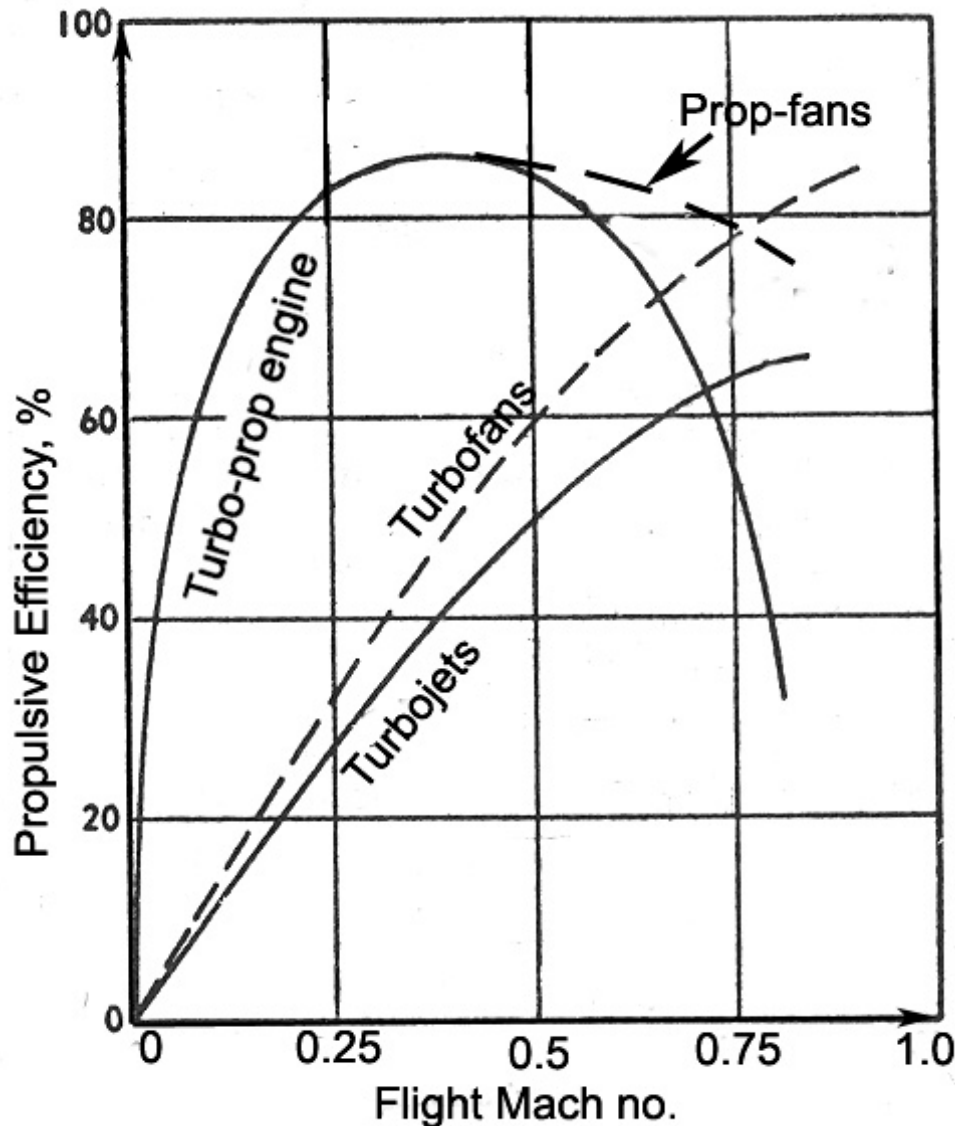
Expressed in kg/N-hr      or  
mg/N-sec

Actual computation of fuel mass flow and net thrust would vary from one kind of jet engine to another



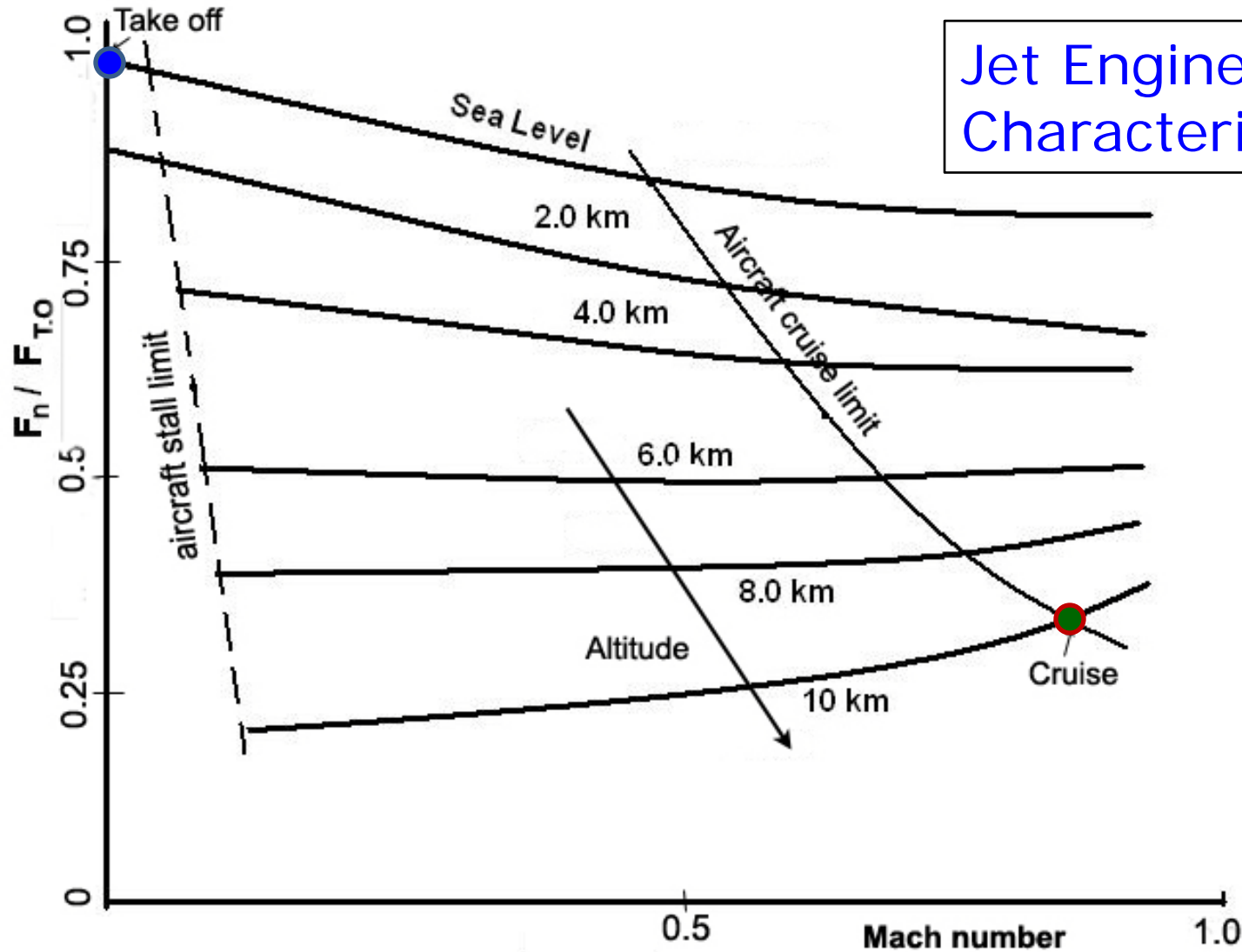
Typical thrust generation capability of small aircraft engines of similar power



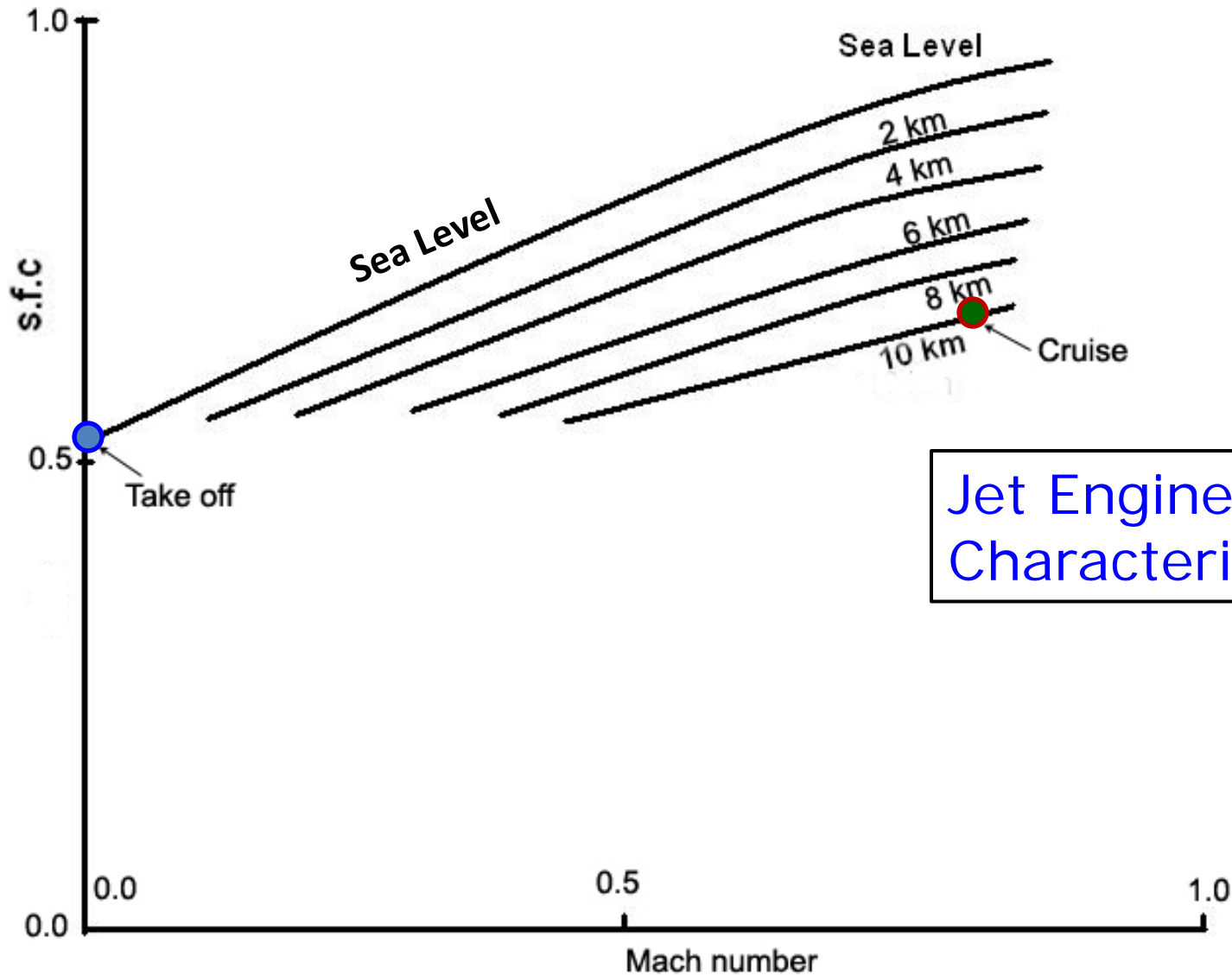


Typical propulsive efficiency of small aircraft engines of similar power

- Because  $V_e$  is considerably greater than  $V_a$ , mainly at low flying speeds, the efficiency is much lower than that attainable with a propeller.
- Since propeller efficiency drops off rapidly at higher Mach numbers ( $>0.7$ ) there is a speed where jet propulsive efficiency exceeds that of a propeller.
- Because the *overall efficiency of a turbojet* is lower, the Mach number at which the *overall efficiency of a turbojet* equals the *overall efficiency of a prop-jet engine* is more than the Mach number at which their *propulsive efficiencies* are equal .



Jet Engine Thrust Characteristics



Jet Engine SFC Characteristics

## Design point of an engine :

- All engine components are designed for a specific engine operating point, which is normally very close to the maximum thrust requirement from the engine.
- That is where the rotating components and non-rotating components are geometrically sized and shaped.
- Most engines meant for transport / passenger aircraft are designed very close to the take off requirement.
- Some military aircraft engines are designed to meet thrust at a supersonic flight condition.

## Off-design points of an engine

All the engine operating points other than the “design point” are known as the off-design operating points. At all these operating points all components of the engine must work together in a matched manner (as an unit) to produce thrust. The aircraft, on which the engine is mounted, must also work within this thrust envelope. Thus, before an engine is mounted on an aircraft a very elaborate aircraft-engine analysis procedure is normally carried out.

## Next class

Turbojet engines with and without reheat

Jet engines with single and multiple spool