AAE 538: Air-Breathing Propulsion

Lecture 8: Performance and Classification of Gas Turbine Engines

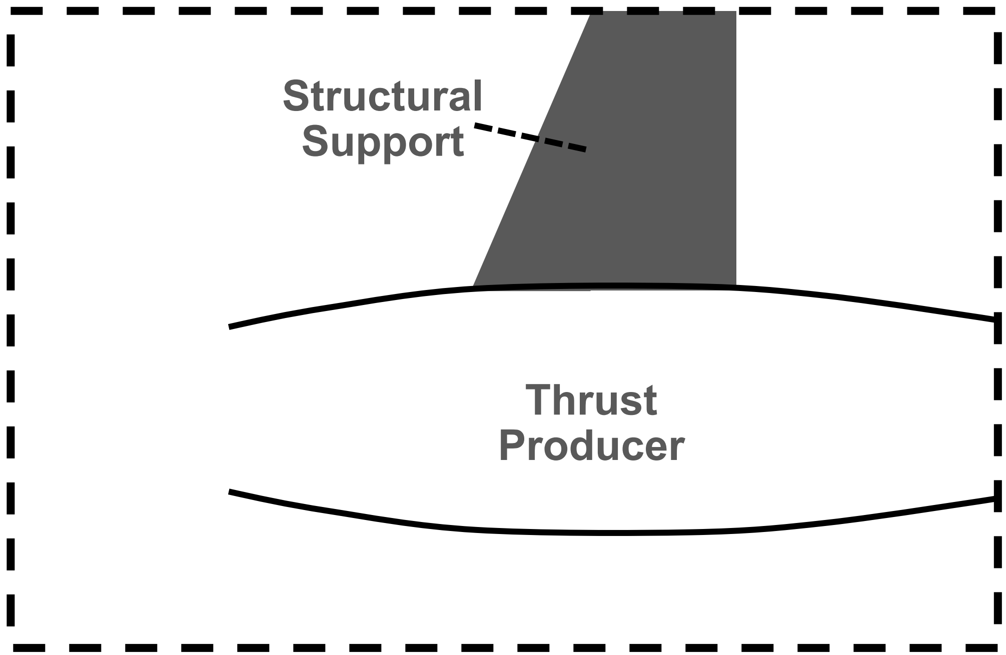
Prof. Carson D. Slabaugh

Purdue University
School of Aeronautics and Astronautics
Maurice J. Zucrow Laboratories

Thrust

Derivation of the Uninstalled Thrust Equation

- Consider and engine mounted on a pylon (structural support) with a control volume slicing through the pylon.
    - Assume steady flow of perfect gases
    - The subscript ‘o’ refers to the free-stream condition and the subscript ‘e’ refers to the nozzle exit condition



Thrust

- In general, the inlet will capture air from an area that is not equal to the physical area of the inlet.
  - Denoted A_0, this area is typically referred to as the ________________________ .
  - Here, ______________________________ and the remainder of the fluid residing in the inlet area streamtube must be diverted around the nacelle of the engine.
  - The excess flow which is 'spilled' around the outside of the engine generates a net mass-flow, $\dot{m}_s$, through the side surface(s) of the control volume.
- We can determine the magnitude of this mass flow by considering the continuity equation over this control volume:
- Which implies:

Thrust

Spillage Flow

- Such that $\dot{m}_s$ becomes
- Noting that the fuel flow rate must equal the change in mass flow rate through the engine, itself
- Substituting

Thrust

Deriving the Thrust Equation

- Now, if we assume that the sides of our control volume lie far away from the engine, then the momentum flux carried out of the control volume by this spilled massflow is simply $\dot{m}_s u_0$. With this in mind, we can apply the conservation of linear momentum.

$$\sum \vec{F} = \frac{\partial}{\partial t} \oiiint_V \rho \vec{u} dV + \oiint_S \rho \, \vec{u}(\vec{u} \cdot \hat{n}) \, dS$$

- Which reduces to

Where $\dot{m}_0$ is the inlet massflow through the capture area A_0 and $\dot{m}_e$ is the mass flow exiting the nozzle. Substituting for $\dot{m}_s$ and simplifying gives the force on the pylon – ___________________________________ .

Engine Characterization

How do we define performance?

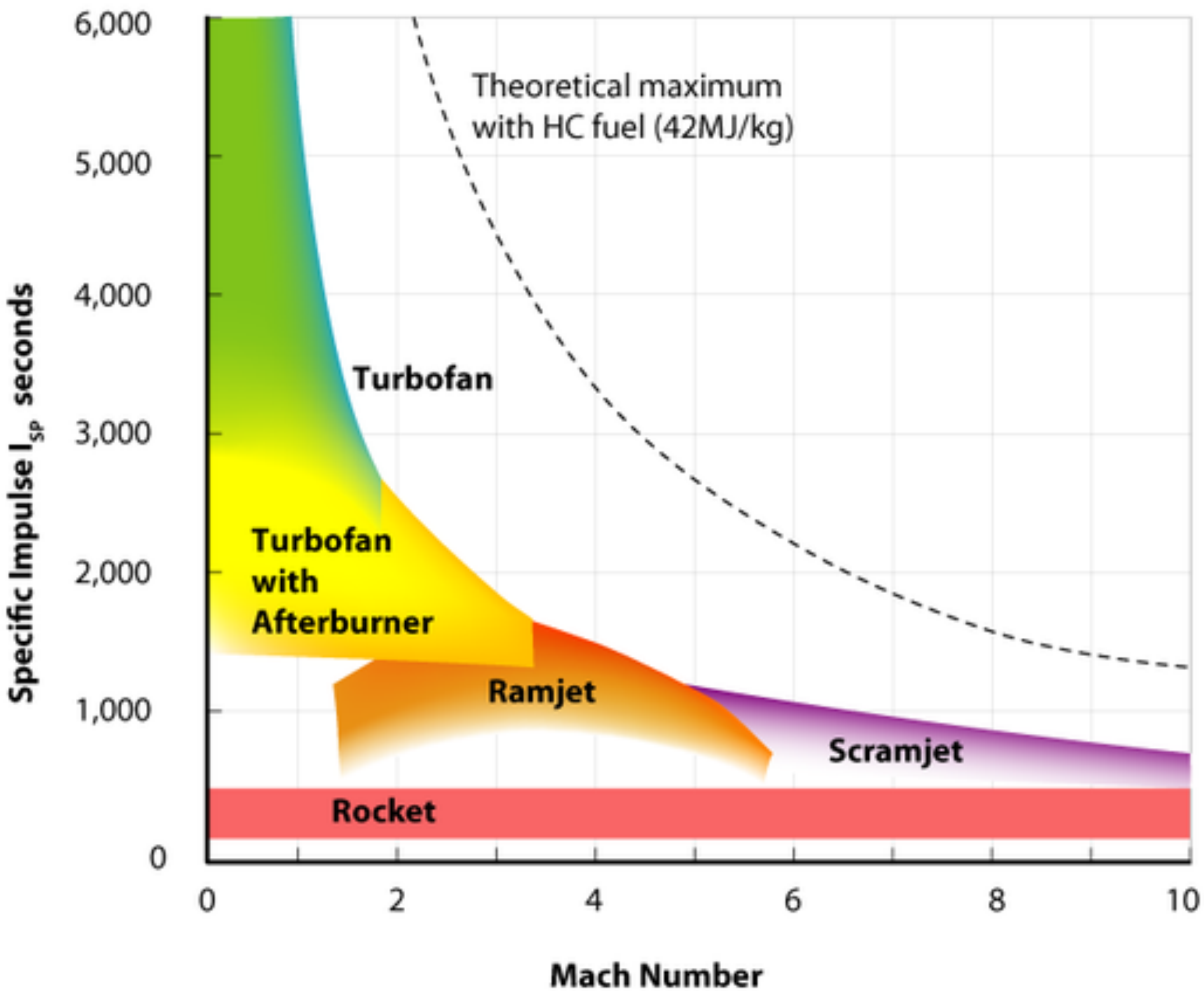
- There are, of course, the obvious matters that an engine designer must take into account when developing a platform, such as:
  - Fuel economy
  - Power generation
  - Weight
  - Durability
  - Reliability
  - Range
  - Flight Speed
  - Size
  - Support for Ancillary Systems
- As engineers, we really prefer to also characterize our machines relative to global scale, so efficiencies are often computed relative to an ______________________ .
- To provide a common basis for comparison, it is necessary to define some standard metrics that indicate the engine's effectiveness in acco.mplishing its design goal
  - The two most commonly-used performance measures for air-breathing applications are:
    -
    -
  - These performance measures are related to more fundamental indicators of engine efficiency
    -
    -

Engine Characterization

- Specific Thrust (**T_{SP}**)
    -
    - ‘Air Specific Impulse’
    - Typical specific thrust values:
        - Propeller-based engines:
        - Turbojets:
        - Chemical Rockets:
- Specific Impulse (**I_{SP}**)
    -
    - A more relevant measure for air-breathing engines than for rockets
        - Air-breathers get their oxidizer for free while rockets have to carry it along.

Engine Characterization

Engine Design Sensitivity to Flight Mach Number



Kahn, Mechanics of Jet Propulsion, 2005

Engine Characterization

- Specific Fuel Consumption (**S** or **SFC**)
    -
    - Fuel economy of the engine
    - Typical SFC values:
        - Propeller-based engines:
        - Turbojets:
        - Turbofans:
        - Chemical Rockets:
- Thrust-to-Weight Ratio (**TWR**)
    -
    - Typical SFC values:
        - Propeller-based engines:
        - Modern Low Bypass Ratio Turbofans:
        - Chemical Rockets:

Engine Characterization

- Thrust Power (**P_T**)
  -
  - Quantifies the impact of packaging. For example:
    - High bypass-ratio turbofans
    - Turbojets
  - u_0 is the free-stream velocity
- Propulsive Power (**P**)
  -
  - The sum of the thrust power and any power due to non-isentropic losses
    - Additive Drag
    - Friction

Engine Characterization

- In propulsion applications, we recognize that the useful mechanical output of our engines appears entirely as the ______________________________ in the exhaust stream(s); from a thermodynamics perspective, kinetic energy is equivalent to _____.
  - This works for us, because the kinetic energy of an exhaust stream is already in an appropriate form to provide thrust.
    - Here, we are considering the shaft-power output to a fan, for example, in the same way as that to a compressor; it is not included as a net work ___________.
- Thermal Efficiency (η_{th})
  - *A simple modification to the classical developments, with substitution of the propulsive power as the work output. Effectively defining as the ratio of the propulsive power to the rate at which thermal energy is delivered to the system*
- Propulsive Efficiency (η_P)
  - *Gives a measure of how well the energy output of the engine is utilized in transmitting useful energy to the flight vehicle. Defined as the ratio of the power transmitted to the vehicle to the rate of kinetic energy generation.*

Propulsive Efficiency

Application and Realization in Engine Design

- Picking up from our definition of the propulsive efficiency and the propulsive power:

$$\eta_P = \frac{P_T}{P}$$

we can write

where P_L represents the power losses from non-isentropic processes, or effectively, the ____ . We can represent those losses as unused kinetic energy in the exhaust, where

Expanding our definition of the Thrust Power with the uninstalled thrust, assuming that the nozzle is perfectly expanded
(no pressure thrust)

$$P_T = u_0 T =$$

Propulsive Efficiency

we can substitute the two expressions for solve for the propulsive efficiency

$\eta_P =$ where we define

where, as a reminder, the subscript ‘o’ refers to the free-stream condition and the subscript ‘e’ refers to the nozzle exit condition.

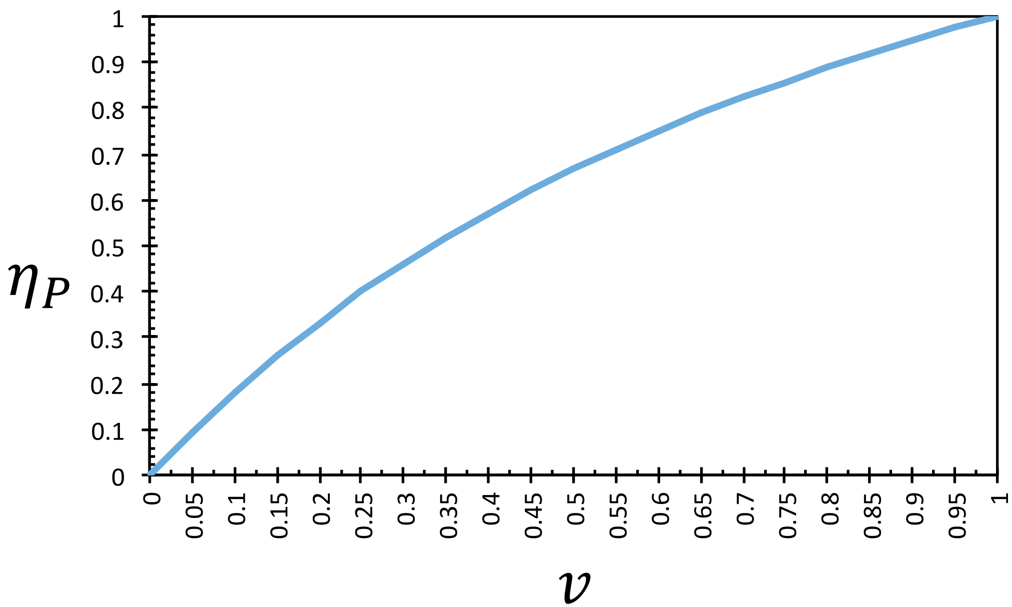
Introducing the Fuel-Air ratio to relate the free-stream (inlet) and exit mass flow rate, we find that

where

Propulsive Efficiency

For a propeller-based engine, _______________ because the jet exhaust makes no appreciable contribution to the thrust generated by the engine (strictly from the standpoint of work-output). In the other extreme of a turbojet, we also know that the fuel mass flow rate is very small compared to the air mass flow rate through the core; hence we can assume _________________ so that:

where



Differentiation shows us that the maximum propulsive efficiency is achieved when

Thermal Efficiency

- So there has to be more to it… Let's pick up with our thermal efficiency:

$$\eta_{th} =$$

where the thermal efficiency represents the ratio of the total propulsive power (P) to the total energy added to the system. We can express the total energy added as the heat of combustion ($\dot{m}_f \Delta H_B$).

Casting into terms of fuel-air ratio (f) and velocity ratio (v), as before,

$$\eta_{th} = \frac{P_T + P_L}{\dot{m}_f \Delta H_B} =$$

Thermal Efficiency

Dividing the numerator and the denominator by $\dot{m}_0 u_e^2$

$$\eta_{th} = \frac{[(1+f) - v]v + \frac{1}{2}(1+f)(1-v)^2}{f\Delta H_B / u_e^2}$$

Rearranging and substituting velocity ratio in the denominator

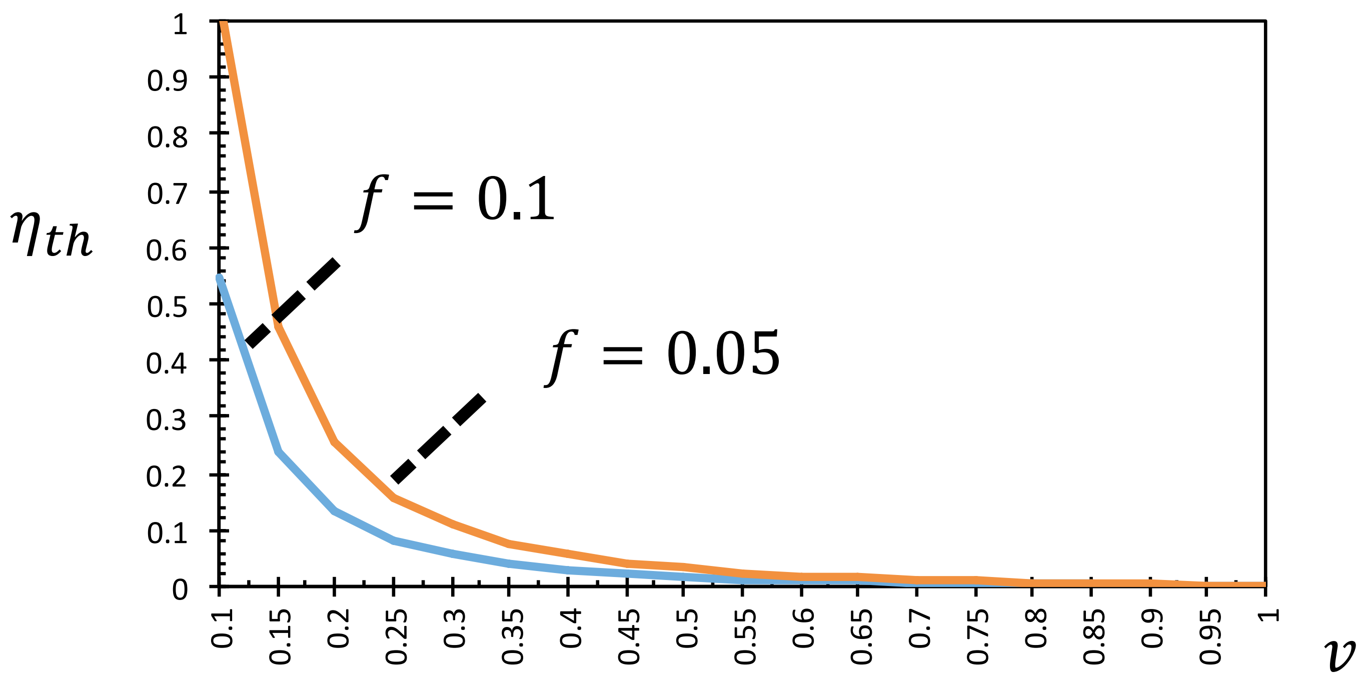
Simplifying, we can cast the thermal efficiency into terms of the velocity ratio, the fuel-air ratio, the free-stream velocity and the heat of combustion for a chosen fuel.

Thermal Efficiency

- We see that as the velocity ratio tends to one, the ______________________________.

$$\eta_{th} = \frac{(1 - v^2) + f(1 + v^2)}{2fv^2 \frac{\Delta H_B}{u_0^2}}$$

- As $v \rightarrow 0$, η_{th} becomes non-physical because the velocity is effectively too high for the heat input to actually achieve.
    -



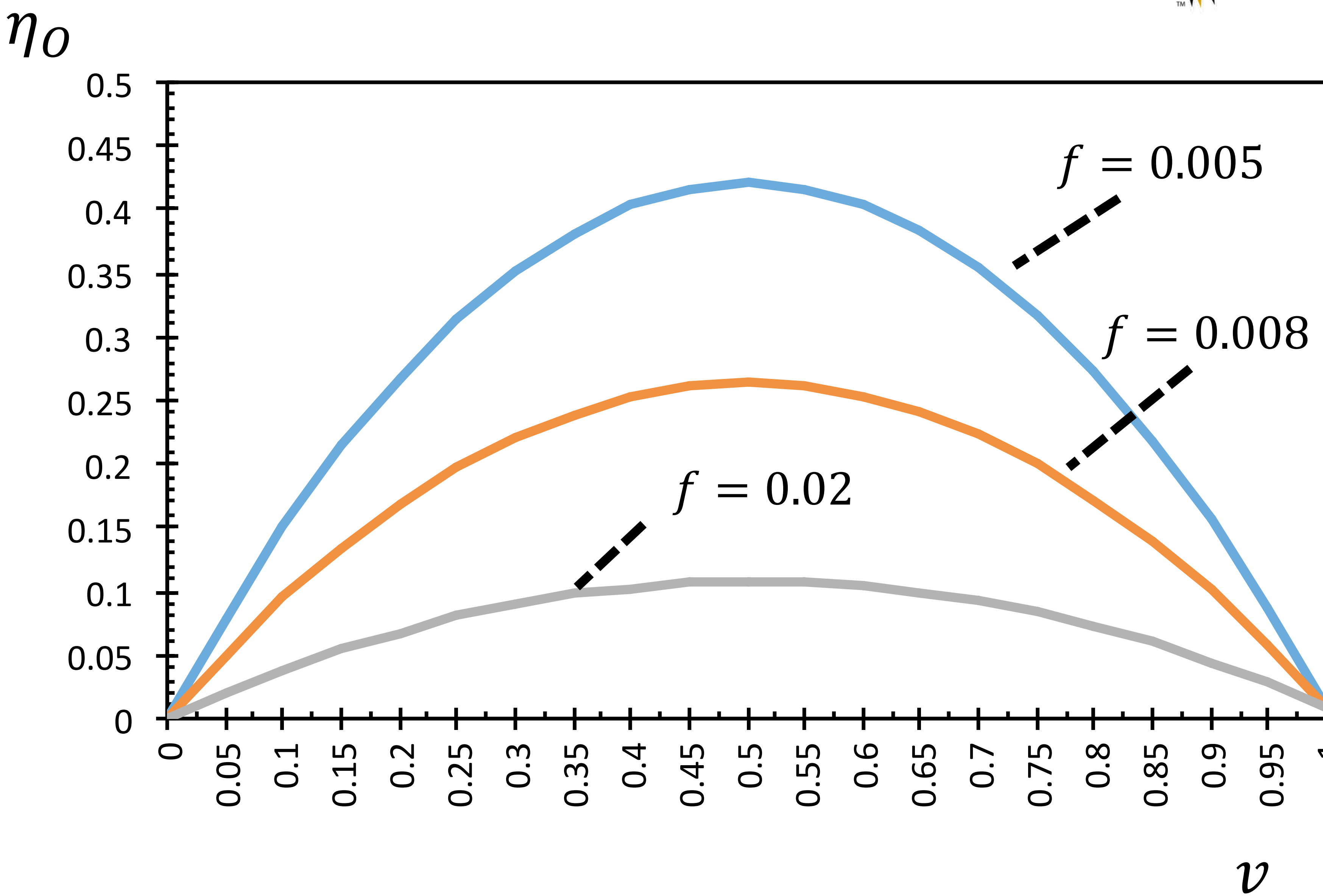
Overall Engine Efficiency

- Now, we can recognize a competing effect between these two efficiency definitions.
  - Which one is more important?
- Combining the relations for the propulsive and thermal efficiencies, we can derive an expression for the overall efficiency, which represents

  Where we have chosen to non-dimensionalize the heat of combustion with u_e instead of u_0 because the $u_0 \to 0$ vanishes when $v \to 0$.

- On the following slide, the overall efficiency is plotted for a number of different fuel-air-ratios.
  -
  -

Overall Engine Efficiency



Aircraft Range

- As you might expect, the optimum balance between the various engine specifications is a strong function of the 'mission'. For example,
  - An engine designed for fighter aircraft will need ___________________________.
  - Engines for long-range transport aircraft will need _________________________.

- Evidently, the overall efficiency is an important factor in determination of the aircraft range.

  In level, constant speed flight, thrust balances drag and lift exactly balances the aircraft weight at that point in time (remember the aircraft gets lighter as it burns fuel). Under these conditions, we can write

  where L/D is the __________________ of the aircraft, which is a function of the aerodynamic shape of the aircraft as well as the Mach number at which the aircraft is operating. For constant speed, level flight, we can assume that the aircraft L/D is fixed.

  Now, let's write the engine thrust in terms of the overall efficiency of the engine.

Aircraft Range

Using the definition of the thermal and propulsive efficiency, we can write:

$$\eta_o = \frac{P_T}{P_T + P_L}\frac{P_T + P_L}{\dot{m}_f \Delta H_B} =$$

Substituting for thrust (T) from the L/D definition and manipulating

$$\dot{m}_f =$$

Hence, the total change in the aircraft mass as a function of time must be related to the mass flow rate of fuel (through the engine)

$$\dot{m}_f = \frac{dm}{dt}$$

Aircraft Range

Flying at a constant speed, we can write the derivative in terms of a distance derivative

Combining with the fuel $\dot{m}_f$ equation in terms of the overall efficiency

Integrating assuming a constant overall efficiency and L/D, we can show that

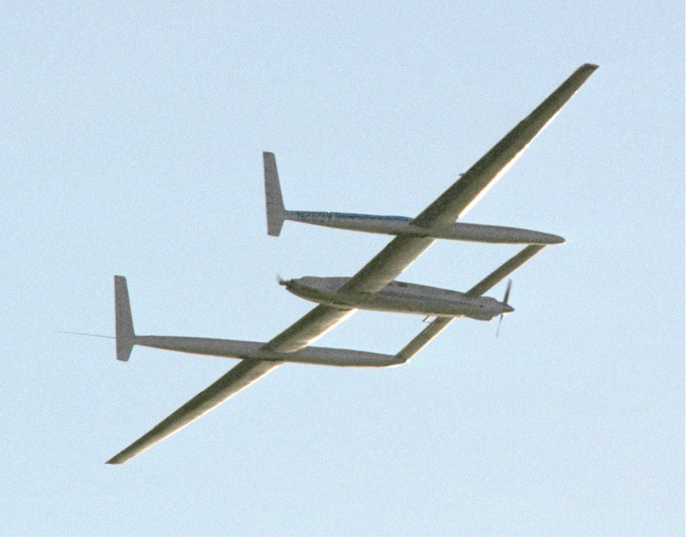
Brequet's Range Formula

- This formula shows that the range of an aircraft is directly proportional to:
  - The overall efficiency of the propulsion system
  - The energy content of the fuel
  - The aerodynamic efficiency of the vehicle

$$x = \eta_0 \Delta H_B \left(\frac{L}{D}\right)\left(\frac{1}{g}\right)\ln\left(\frac{m_1}{m_2}\right)$$

Aircraft desiring long range:

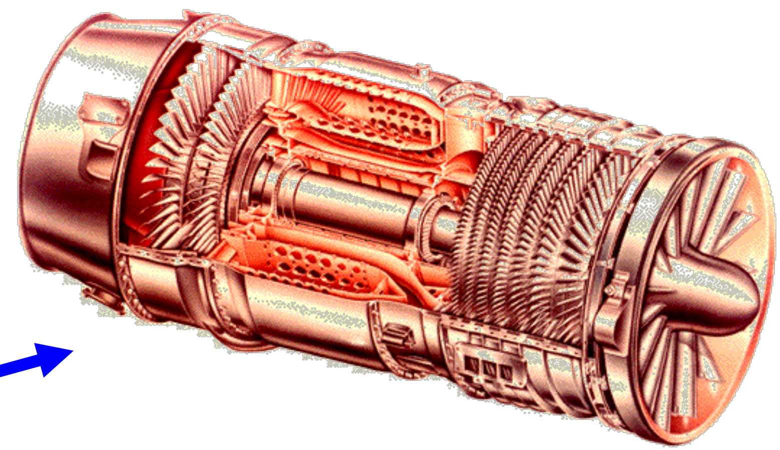
-
-



Rutan Voyager

Aircraft Range

- Aircraft range is only one example of the way these metrics can be related to more tangible aspects of engine performance.
  - We see the evidence of these various factors in the fact that a fighter jet and a commercial airliner do not share the same engines.
  - Let’s look at the values associated with some (admittedly, old) examples.

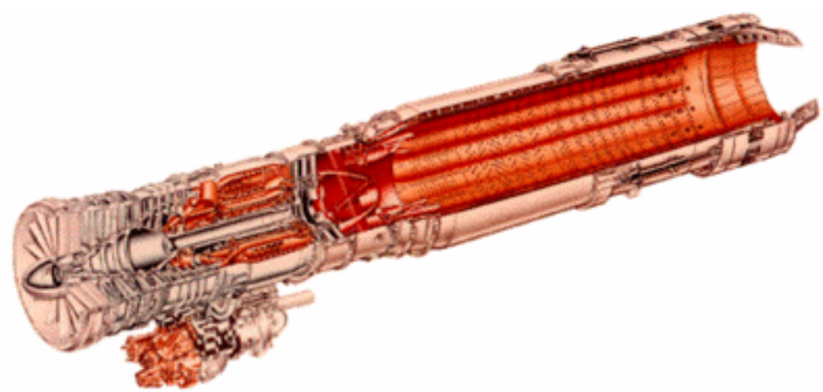


General Electric J85 Turbojet Engine Found in Northrop T-38 Trainer and F-5 Trainer

Engine Classification

Turbojets

- Thrust is generated primarily from the high-velocity exhaust jet
- Operation Specifications
  - 44 lbm/s of air
  - 16,500 rpm
  - 7:1 compression ratio



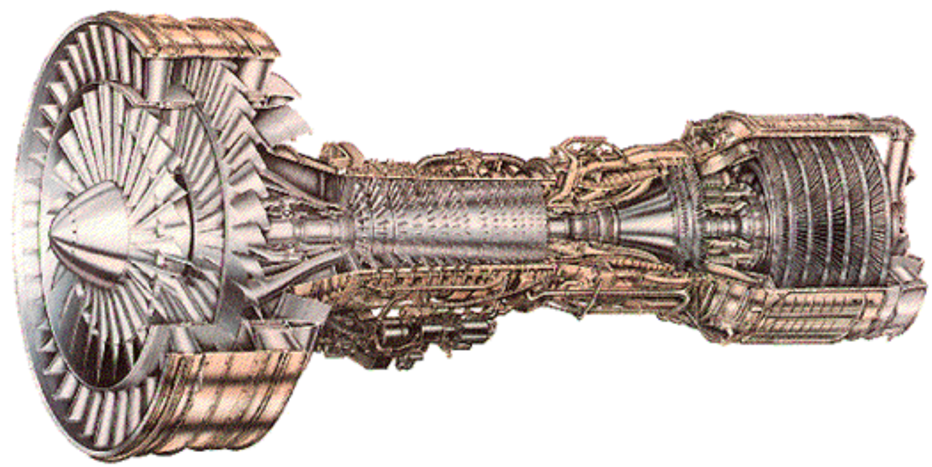
General Electric J85 with Afterburner

- Design Specifications
  - Single shaft
  - Eight stage axial compressor
  - Variable inlet guide vanes and compressor bleed valves
  - Two stage turbine to drive the compressor
  - Annular combustor
- Performance Characterization
  - T = 4000 lb_f (with AB)
  - SFC = 0.95 $lb_m/hr/lb_f$ (2.2 with AB)
  - Weight = 600 lb_f

Engine Classification

Turbofan

- Thrust is generated primarily by the fan, with some portion of jet thrust, as well.
- Design Specifications
  - Two-shaft, high bypass ratio, front-fan
  - The first two turbine stages drive the compressor
  - The last six turbine stages drive the fan
  - Annular Combustion Chamber
  - Cooled Turbine Blades to Achieve T.I.T. = 2300 F (previously limited to 1800 F)
  - 16 stage axial compressor (7 stages with variable guide vanes)



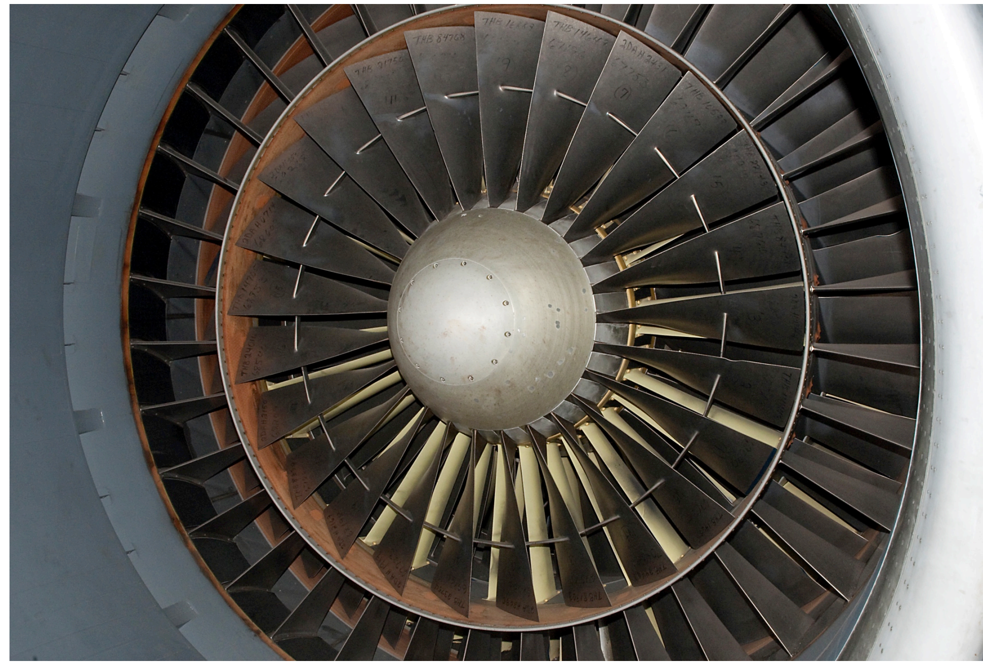
General Electric TF39 used in Lockheed C-5A Galaxy (4 engines)

Engine Classification

Turbofan

- Operation Specifications
  - Fan
    - 1333 lb_m/s
    - 2:1 Compression Ratio
  - Core
    - 167 lb_m/s
    - 25:1 Compression Ratio
  - Bypass Ratio = 6.98

- Performance Characterization
  - $T = 41000\ lb_f$
  - $SFC = 0.6\ lb_m/hr/lb_f$
  - $Weight = 7400\ lb_f$

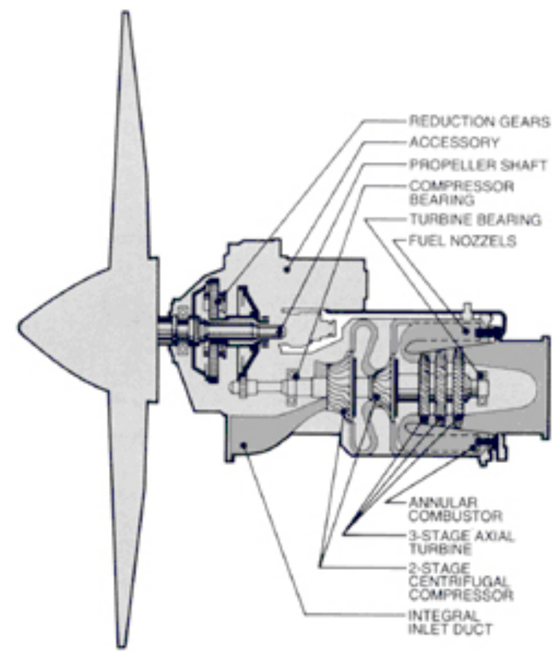


General Electric TF39 Fan

Engine Classification

Turboshaft (Turboprops)

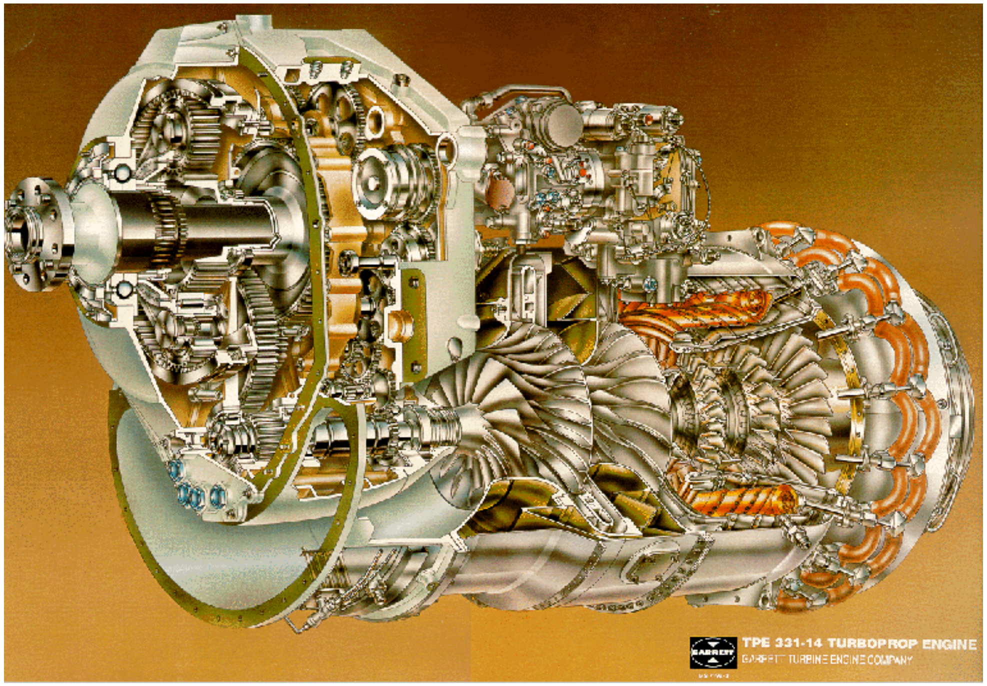
- Propulsion is generated by shaft work, with only a very small amount of thrust from exhaust
- Applications
    - (slower) Aircraft
    - Helicopters
    - Marine and Industrial



Garrett T76 (TPE 331) found in MQ-9 Reaper

Engine Classification

Turboshaft



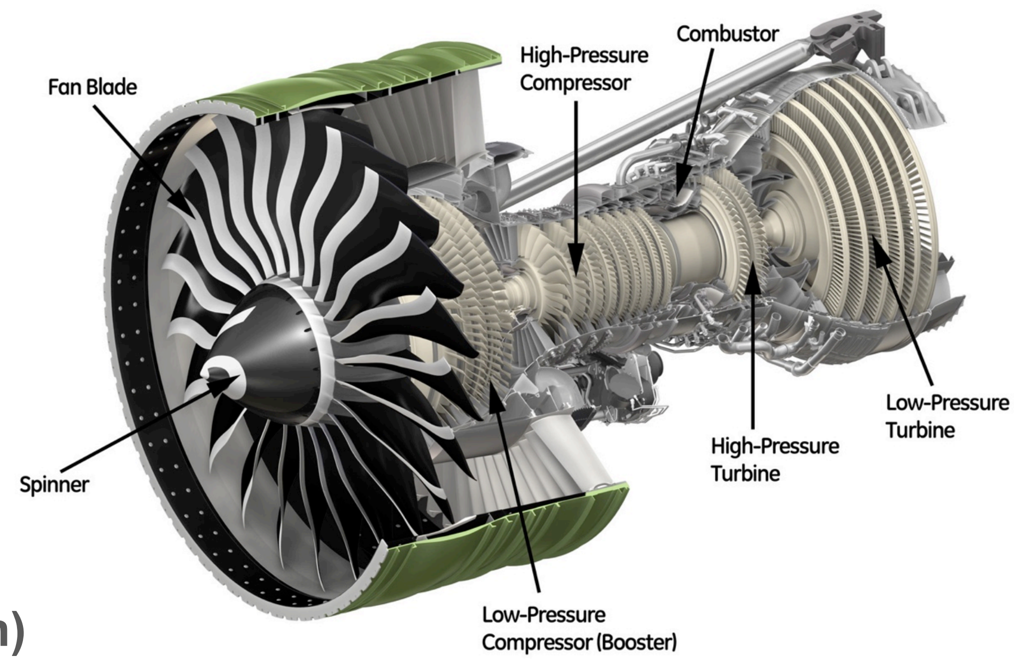
Garrett T76 (TPE 331) used to power the OV-10 military aircraft as well as civilian transport

- Design Specifications
  - Single-shaft design
  - Two-stage centrifugal compressor
  - Three stage turbine
  - Reverse flow combustion chamber
- Performance Characterization
  - P = 575 shp
  - T = 75 lb_f
  - SFC = 0.534 $lb_m/hr/lb_f$
  - Weight = 336 lb_f
- Operation Specifications
  - 7.9:1 compression ratio at 5.8 lb_m/s when operating at 41,730 rpm
  - Propeller rpm is reduced to 2000 with integral gearbox

Engine Classification

Modern Turbofans

- **In between a turbojet and turboprop**
  - 6-8:1 ratio between mass flow rate through the fan and through the engine core.
- **Ducting over the internal propeller (fan) allows control of aerodynamics**
  - Up to Ma = 0.85-0.90
- **Expansion in turbine allows for better utilization of thermal energy than in a turbojet**
- **No gearbox required (but everyone is going that direction)**
- **EU Clean Sky**
  - Unducted fans vs. geared turbofans
  - (battle of the ultra-high bypass ratio engines)



GE Aviation GE90 Turbofan Engine