Caratteristiche propulsive

- Razzi (Rockets)
- Ramjet
- Turbojet
- Turbofan
- Turboprop
- Motoelica

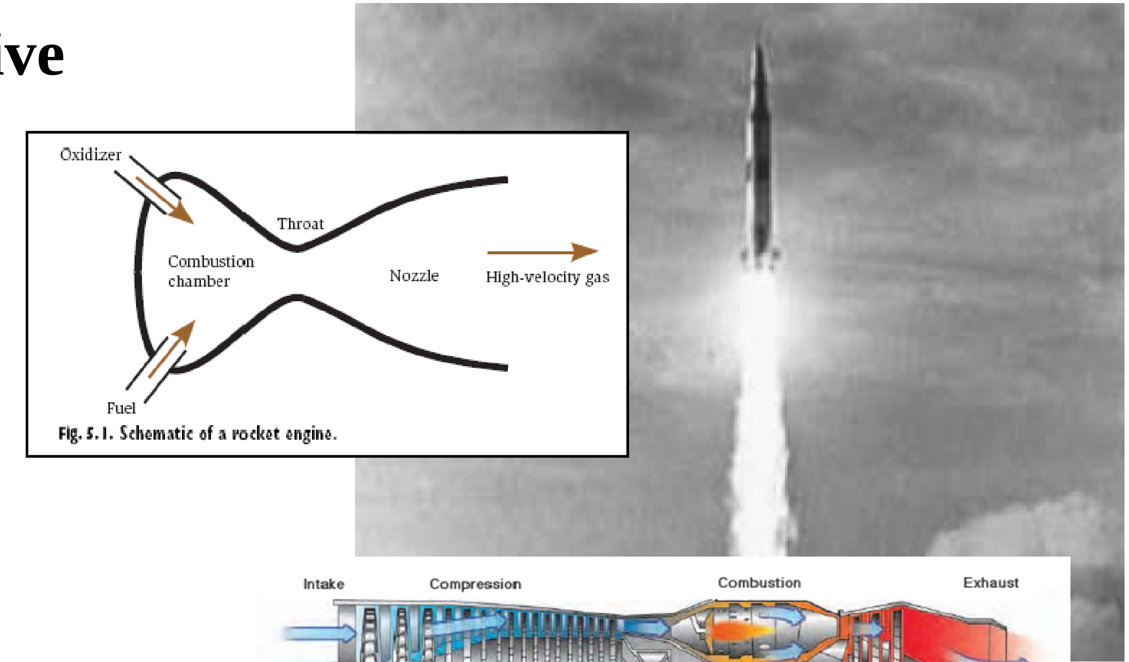
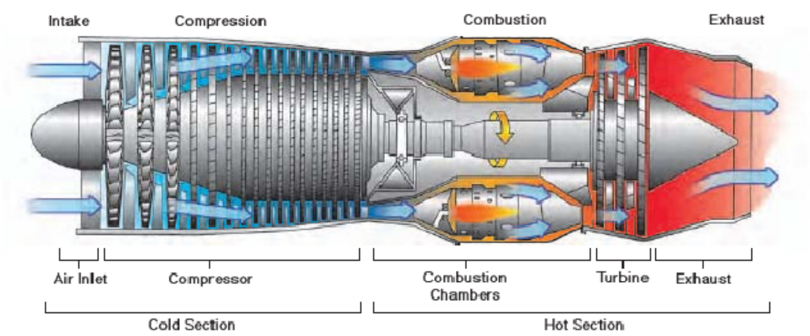
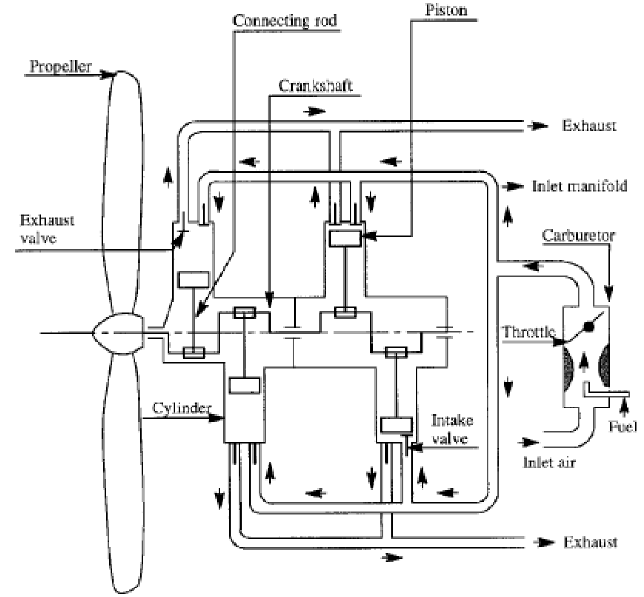


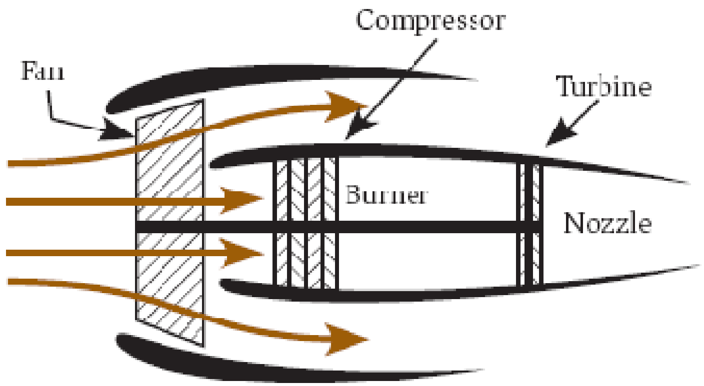
Fig. 5.1. Schematic of a rocket engine.





Note: modern engines tend to use fuel injection rather than carburetors

Figure 6.6 Typical Cross-section of a Four-cylinder Piston Engine



Caratteristiche propulsive

- Razzi (Rockets) (o anche Endoreattori)

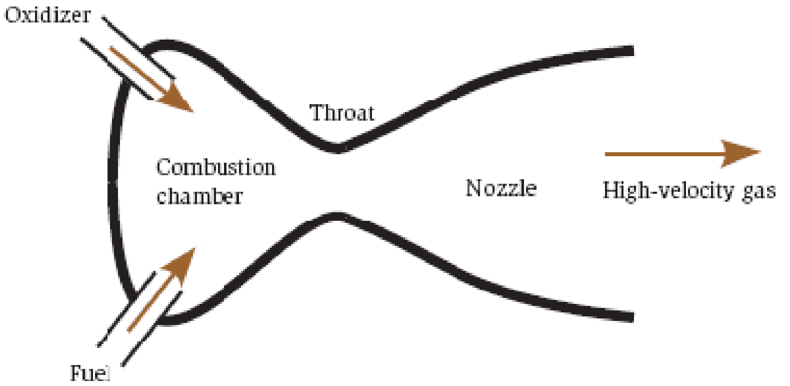
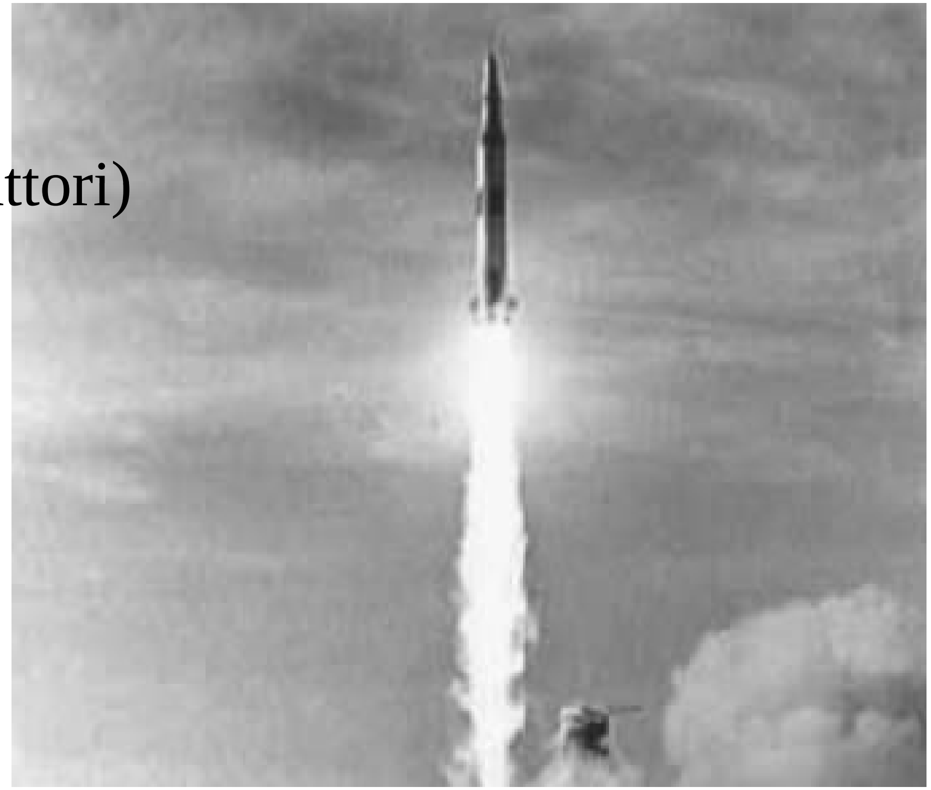
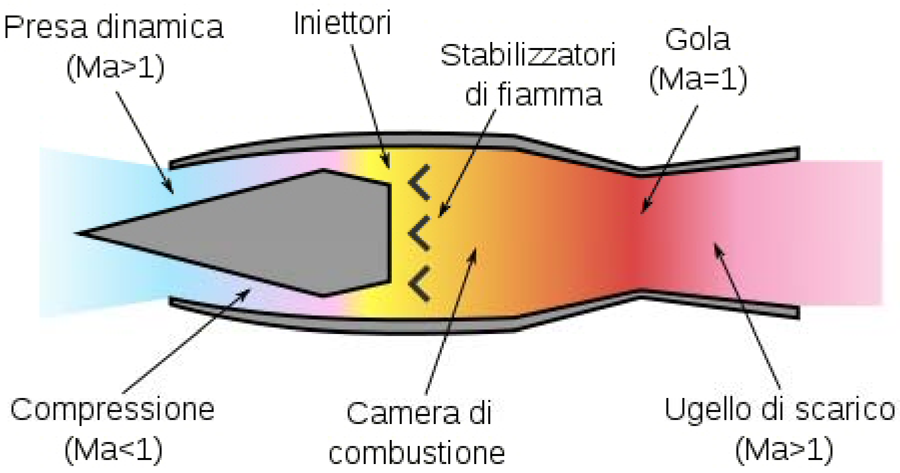


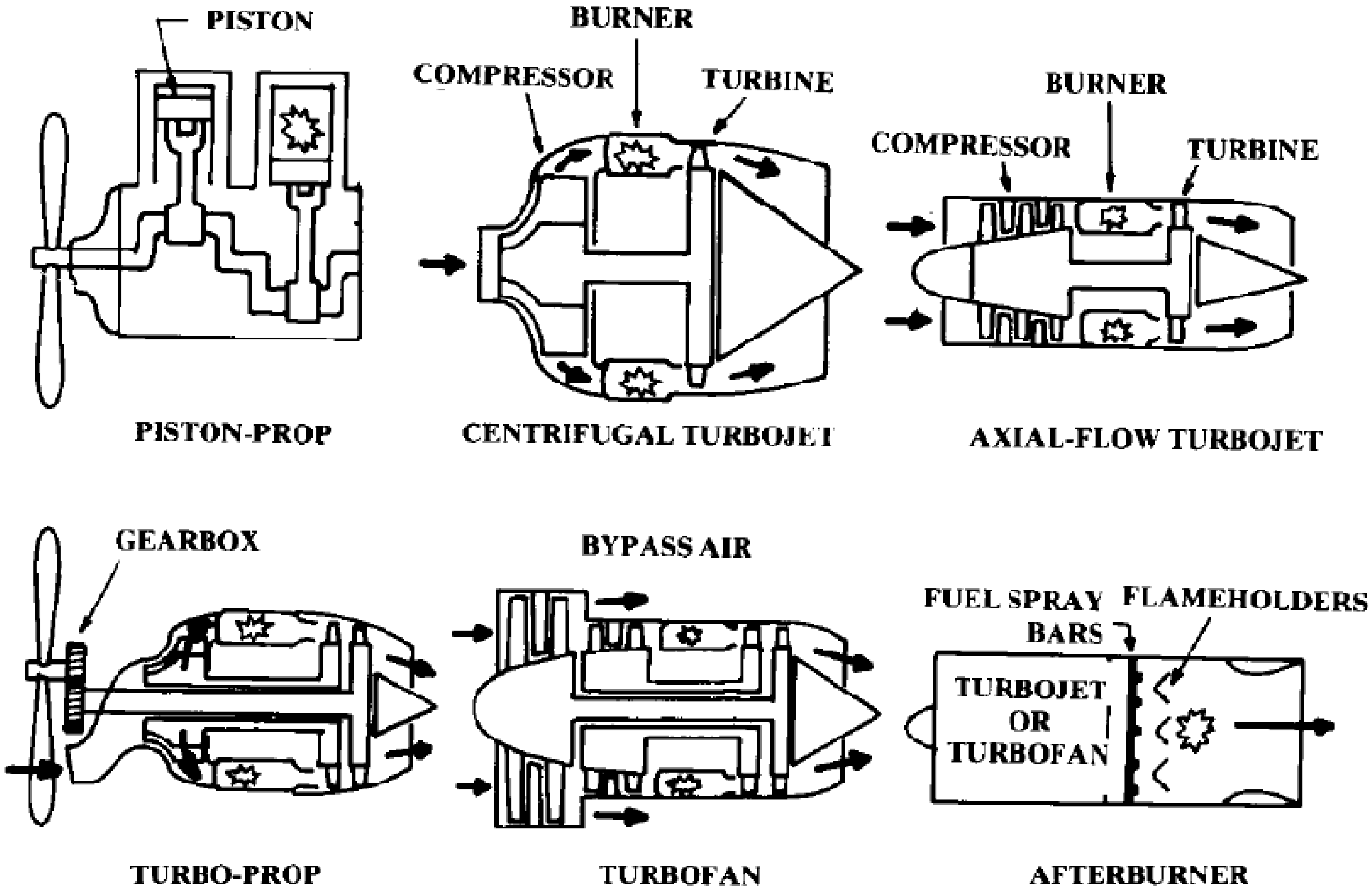
Fig. 5.1. Schematic of a rocket engine.



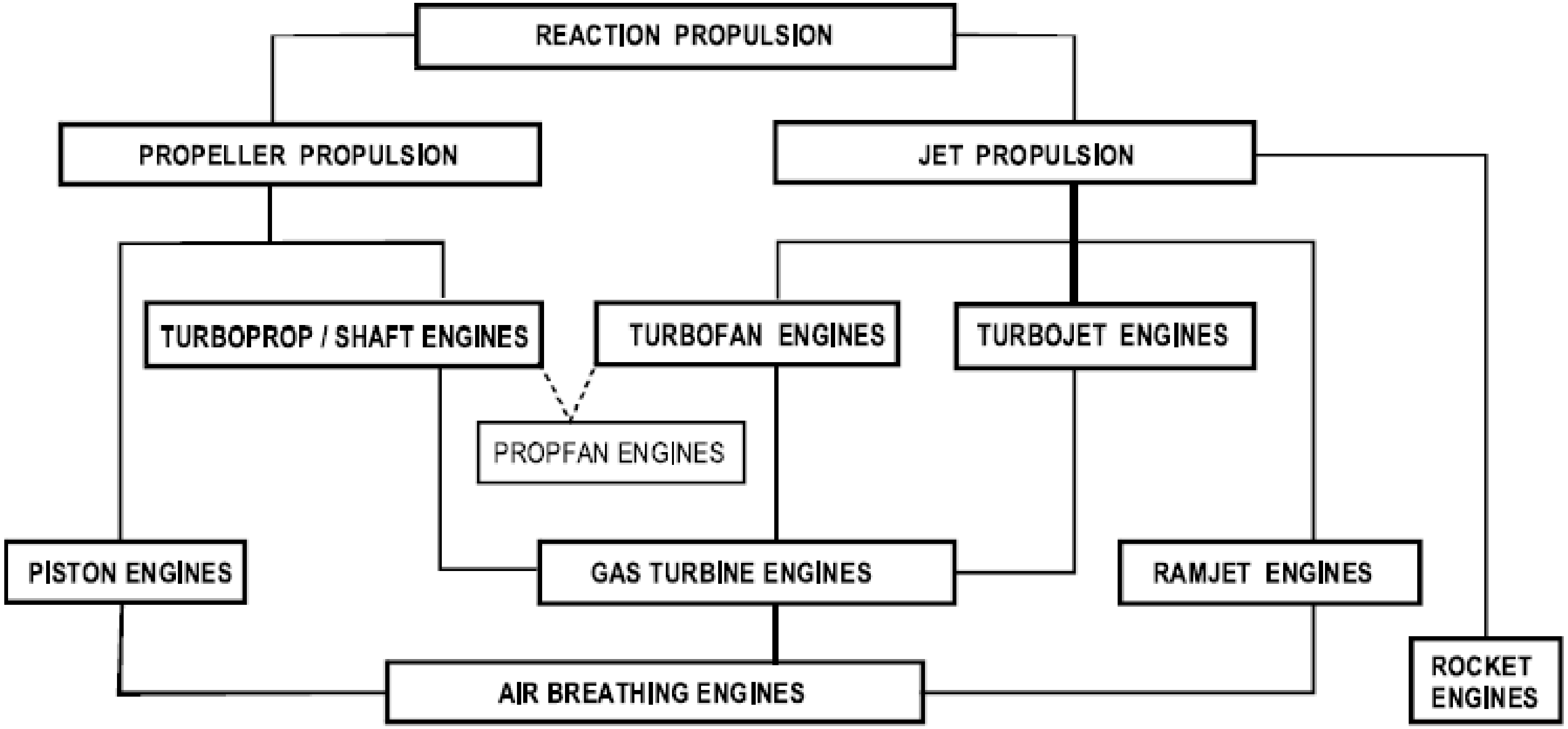
- Ramjet



Caratteristiche propulsive

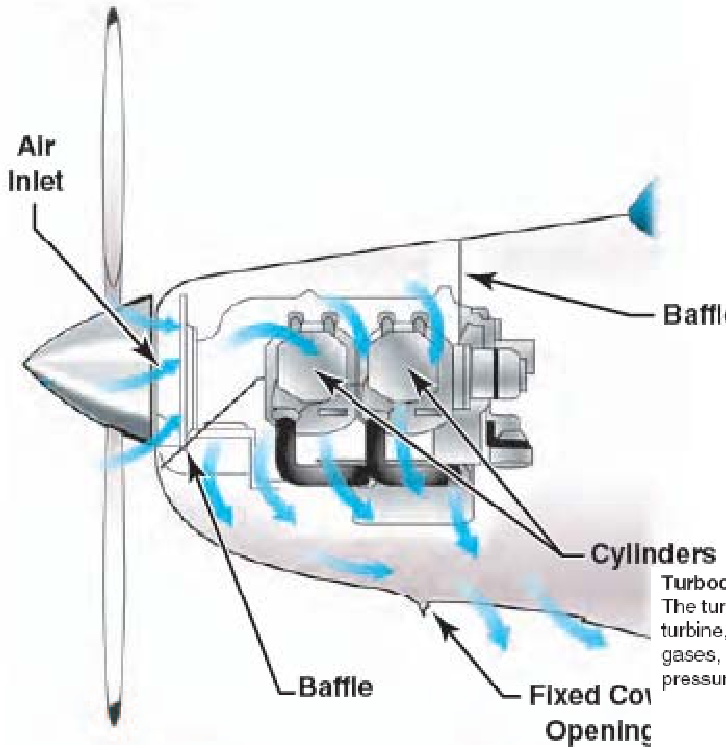


Caratteristiche propulsive



Cap.6 – Caratteristiche propulsive

<u>Motoelica</u>



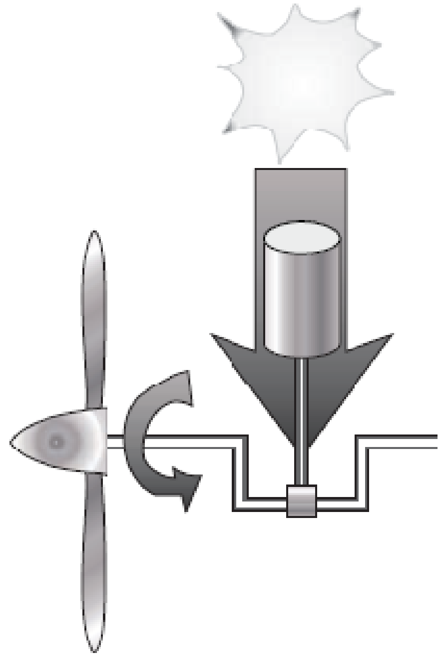
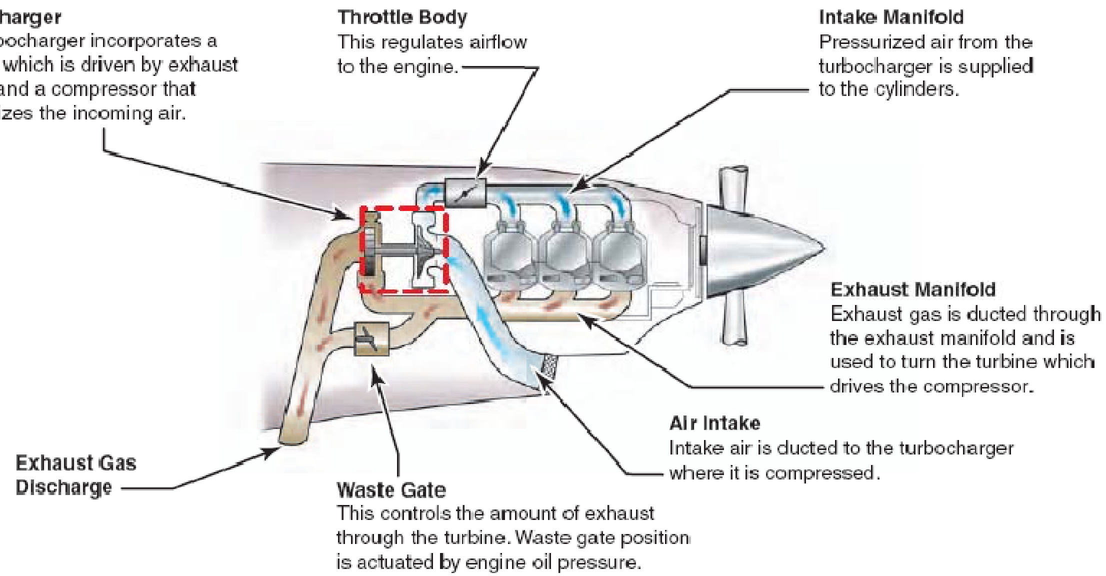
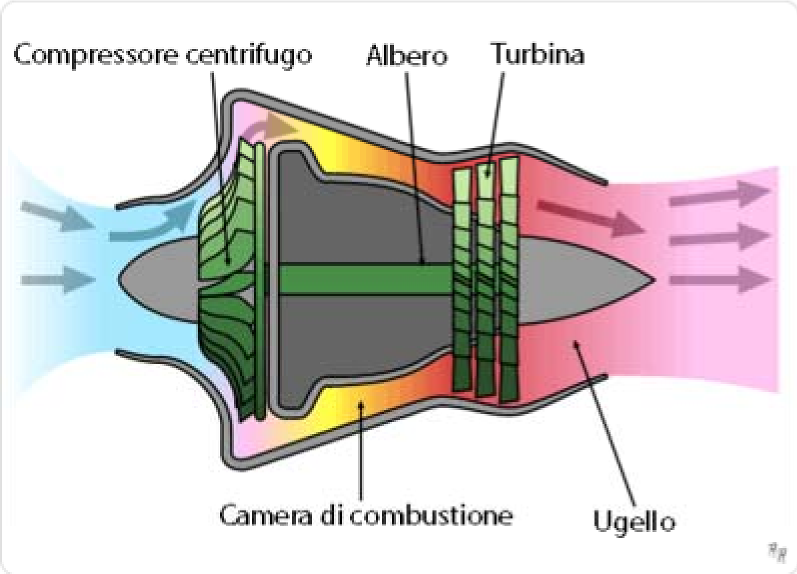


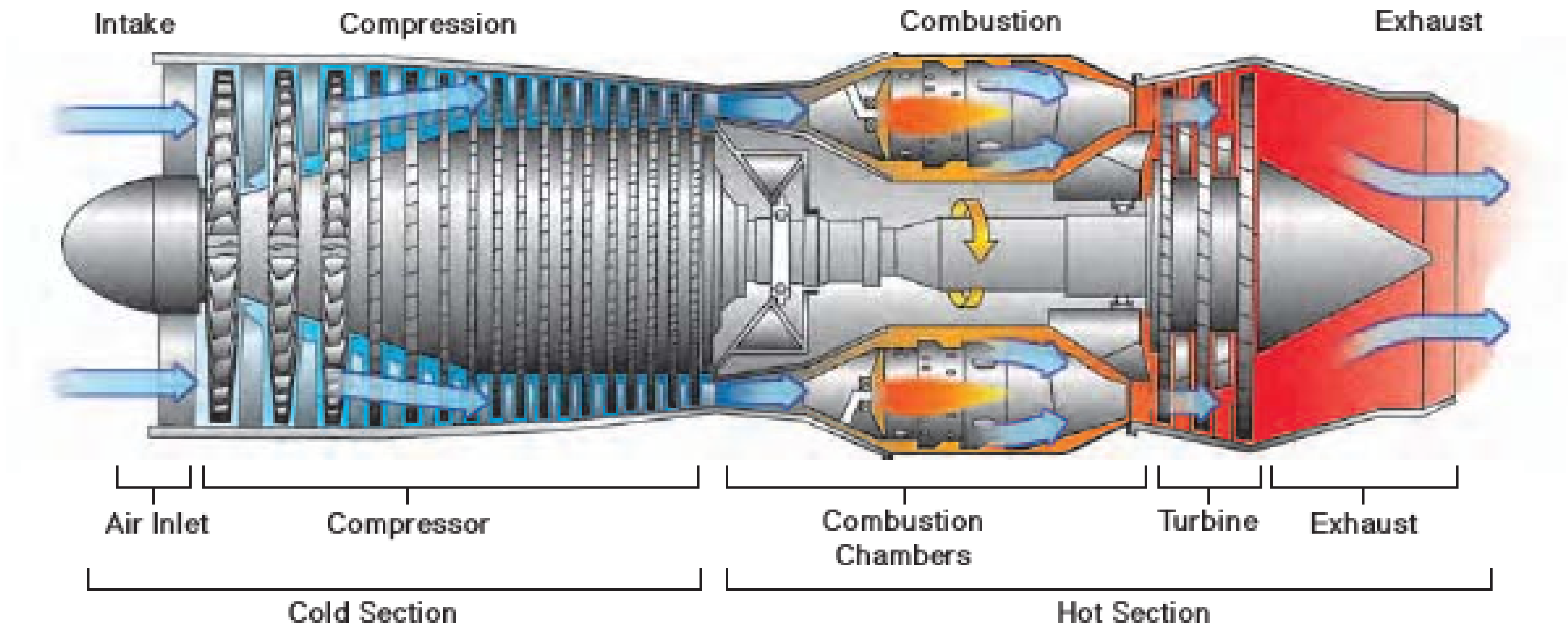
Fig. 5.7. How a piston engine converts chemical energy to propeller rotation.



Caratteristiche propulsive

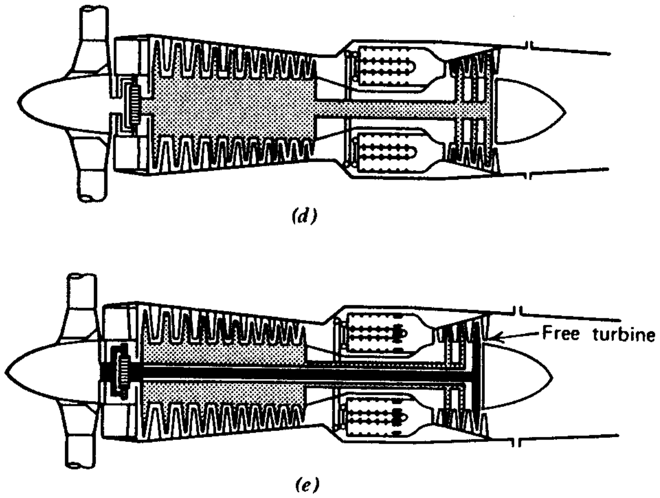
Turbogetto

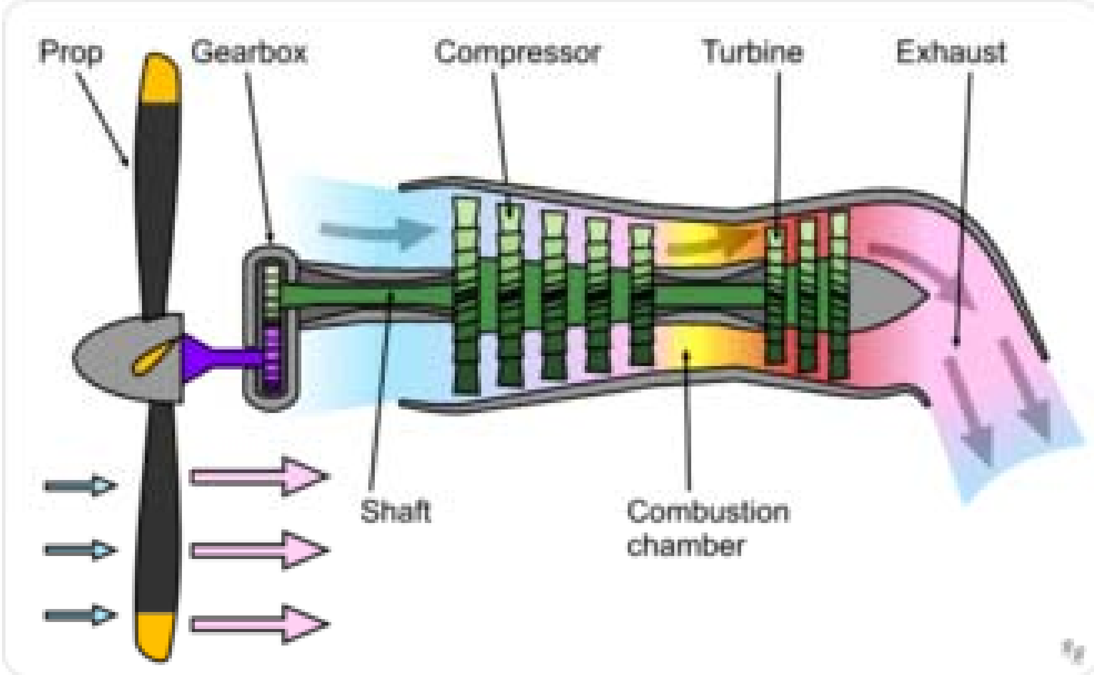




Caratteristiche propulsive

Turboprop (tipo ATR42)

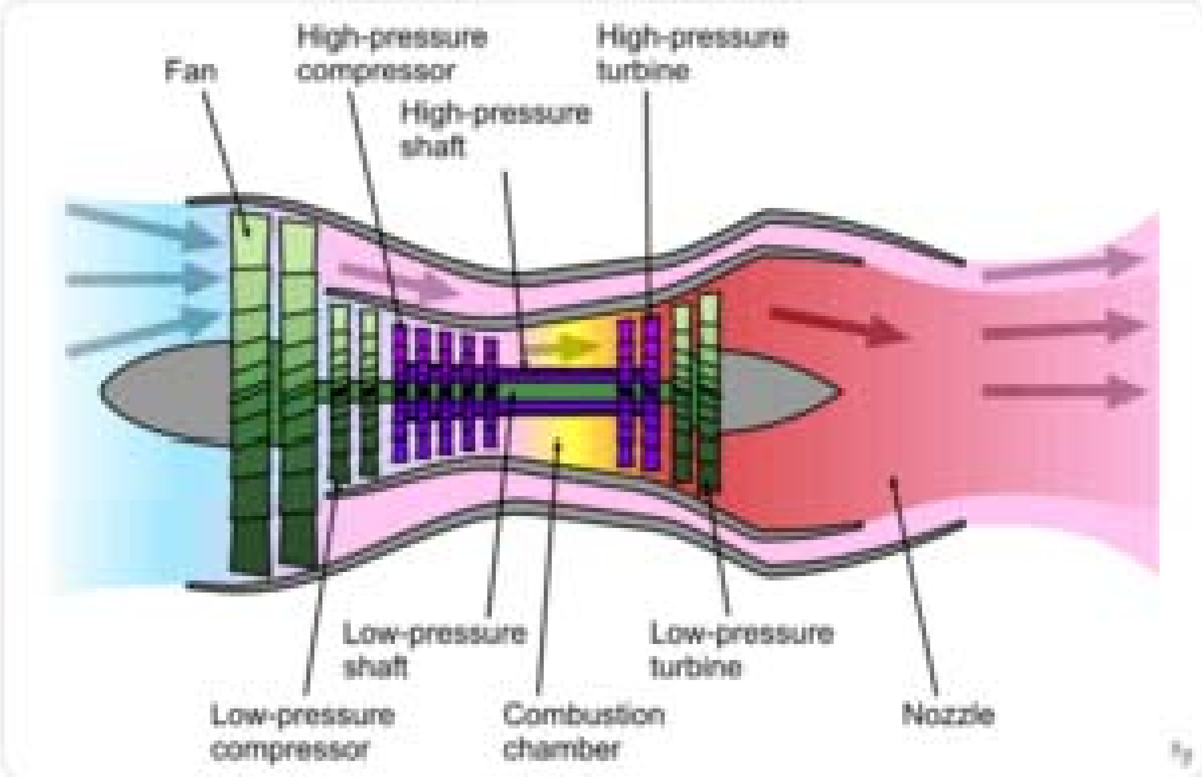


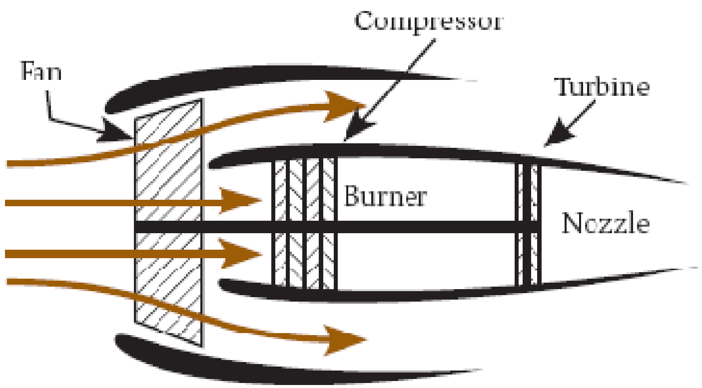


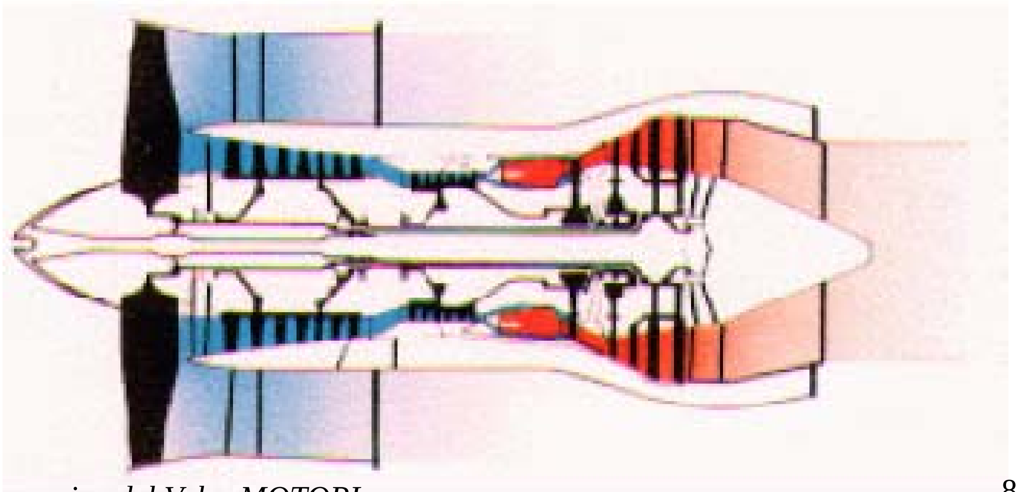
Caratteristiche propulsive

Turbofan

BPR (By-Pass Ratio)







Caratteristiche propulsive

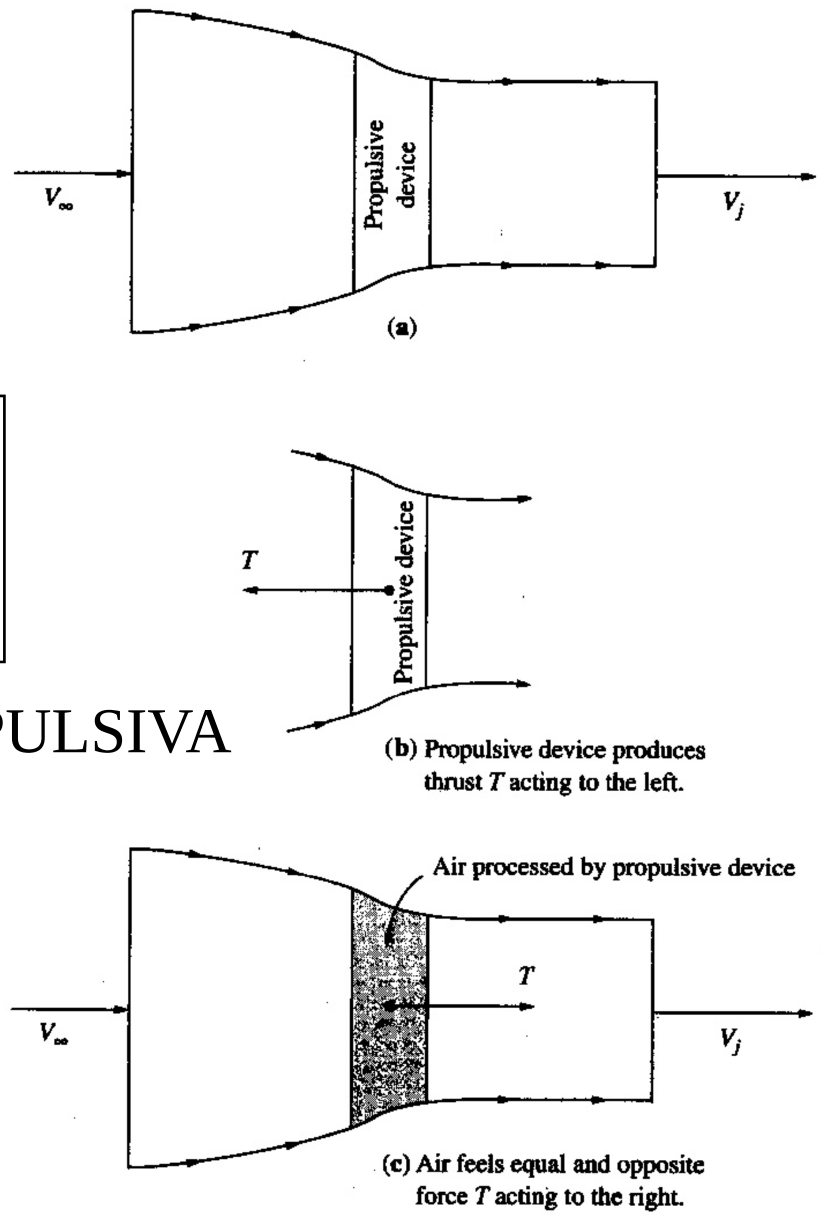
Principio di funzionamento

$$T = \dot{m}(V_j - V_\infty)$$

$$\eta_j = \frac{1}{1 + \frac{1}{2}(V_j - V_\infty)/V_\infty} = \frac{1}{\frac{1}{2}\left(1 + \frac{V_j}{V_\infty}\right)}$$

$$\eta_j = \frac{2}{1 + \frac{V_j}{V_\infty}}$$

EFFICIENZA PROPULSIVA
(Froude Efficiency)



(a)

(b) Propulsive device produces thrust T acting to the left.

(c) Air feels equal and opposite force T acting to the right.

Caratteristiche propulsive

Possiamo definire anche la spinta specifica:

$$\frac{T}{\dot{m}} = \left(V_j - V_\infty\right)$$

Spinta prodotta per unità di portata di massa [N/(kg/sec)] o anche dimensione di una vel. [m/s]

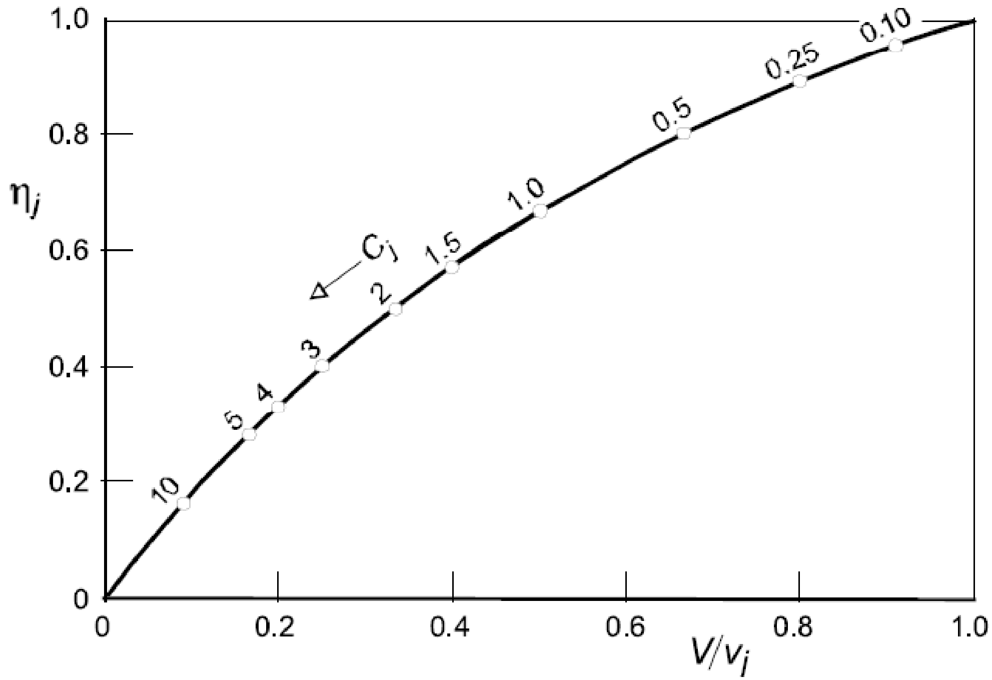
$$\eta_j = \frac{2}{2 + (V_j - V_\infty)/V_\infty} = \frac{2}{2 + \frac{T}{\dot{m}} V_\infty} = \frac{2}{2 + C_j}$$

$$C_j = \frac{T}{\dot{m}} V_\infty = \frac{V_j}{V_\infty} - 1$$

Abbiamo introdotto il "jet vel. coeff."

$$\eta_j = \frac{2}{1 + \frac{V_j}{V_\infty}}$$

$$\eta_j = \frac{2}{2 + C_j}$$



Caratteristiche propulsive

Table 5.1 Example of *propulsive efficiency* data.

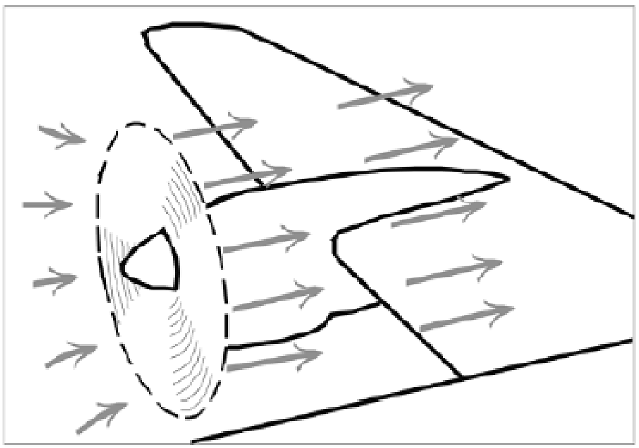
Type of propulsion	*Alti-tude* km	*Flight speed* V, m/s (Mach no.)	*Jet velocity* v_j, m/s	*Speed ratio* v_j/V	*Specific thrust* $T/\dot{m}_a$, m/s	*Jet coefficient* C_j	*Propulsive efficiency* η_j
propeller	6	150	160 (0.47)	1.07	10	0.067	0.97
subsonic jet engine	9	250 (0.82)	750	3.00	500	2.00	0.50
low BPR turbofan	9	250 (0.82)	582*	2.33	332	1.33	0.60
high BPR turbofan	9	250 (0.82)	418*	1.67	168	0.67	0.75
supersonic jet engine	16	600 (2.03)	1,000	1.67	400	0.67	0.75

* weighted average of primary and secondary airflow

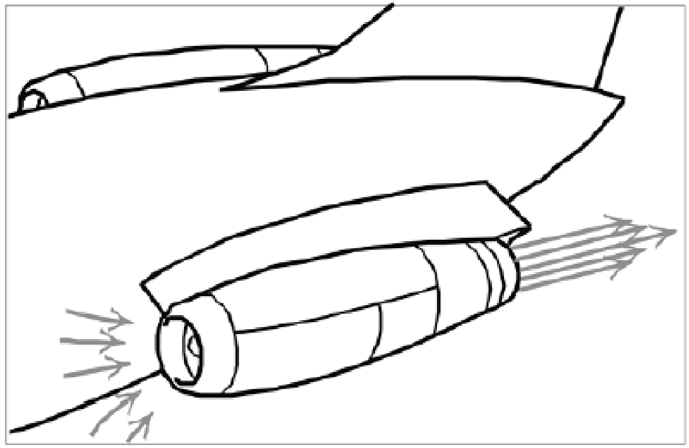
Caratteristiche propulsive

L'efficienza propulsiva dell'elica è maggiore di quella del getto.

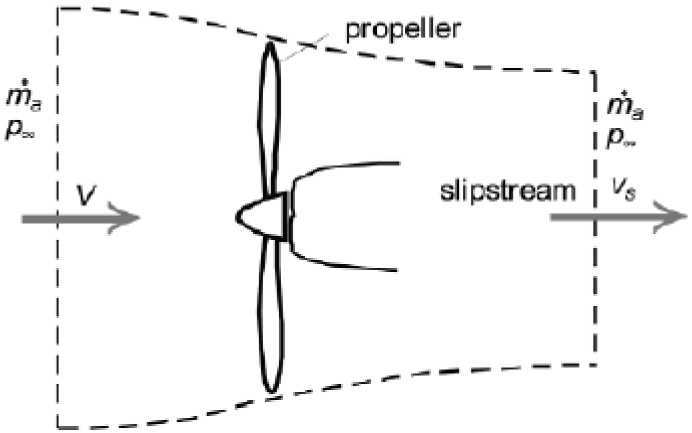
- Elica: piccolo incremento di velocità ad una grossa massa aria
- Jet: grande incremento di velocità ad una piccola quantità di aria

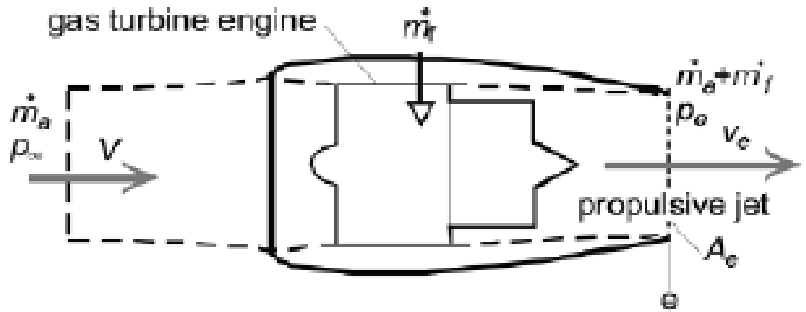


(a) A propeller imparts a small velocity increment to a large mass of air



(b) A turbojet engine imparts a large velocity increment to a (relatively) small amount of air

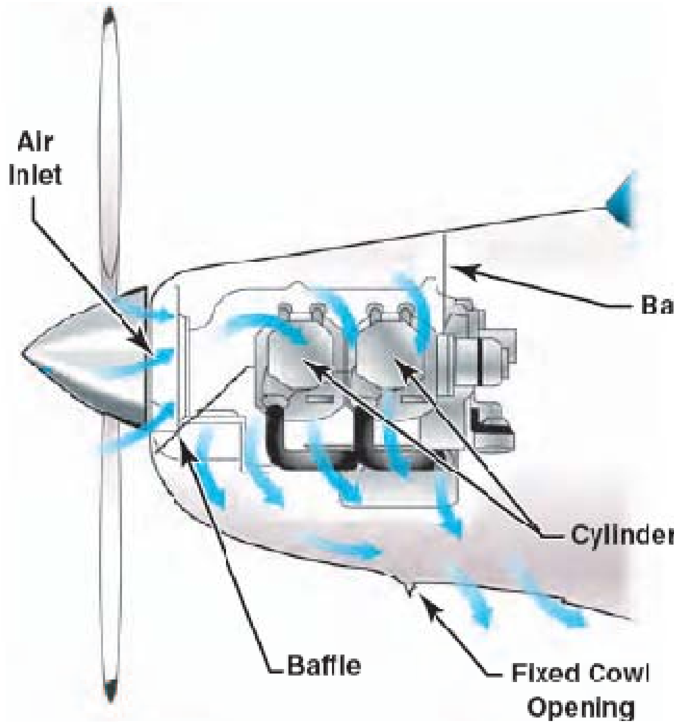


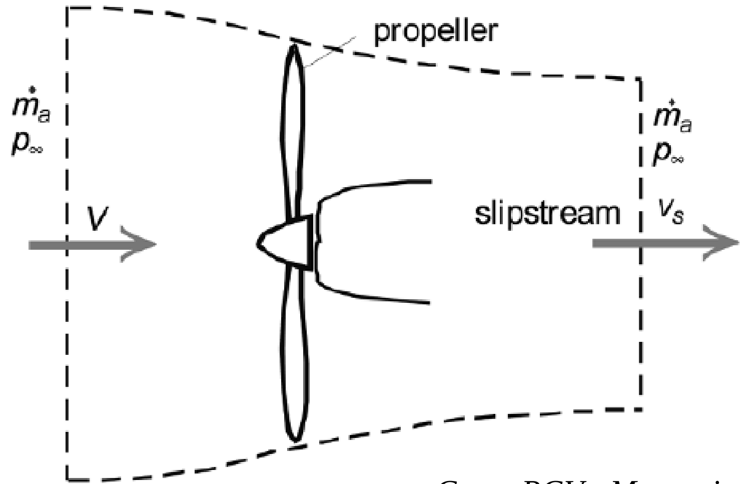


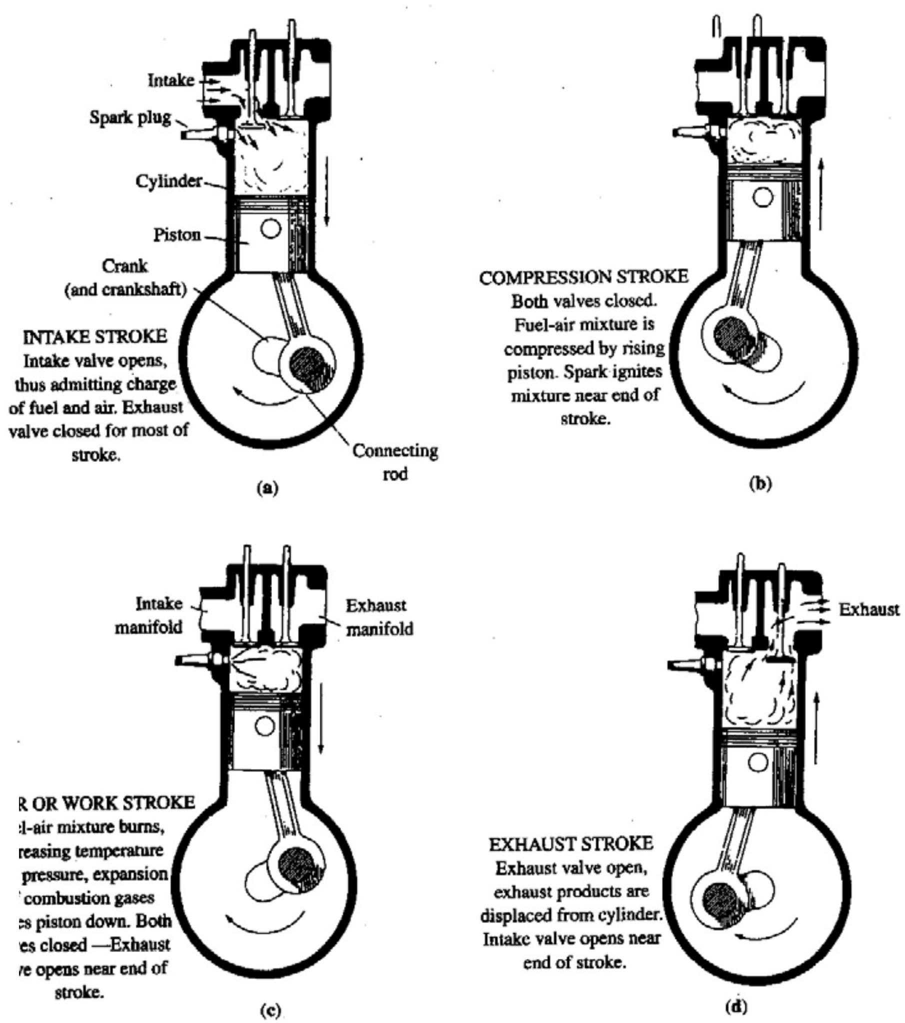
(b) Airflow through a jet engine

Caratteristiche propulsive

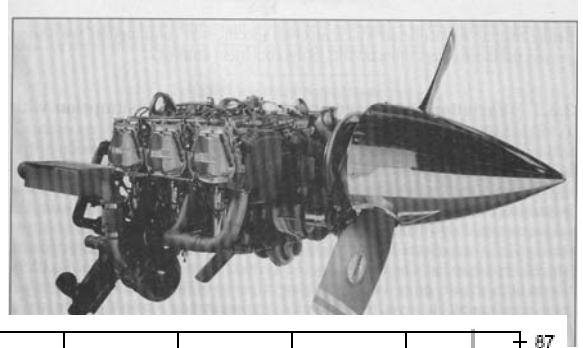
MOTOELICA







Caratteristiche propulsive MOTOELICA



$$\Pi_a \propto d \cdot p_e \cdot RPM$$

- la cilindrata con *d* (dall'inglese *displacement*)
- *pressione media efficace* p_e

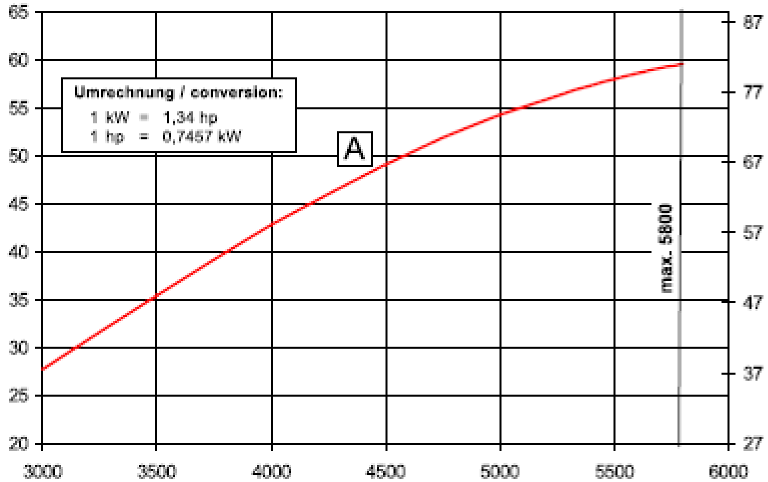
<u>Consumo specifico</u>

$$[c] = \frac{lb}{(ft \cdot lb/s)(s)} \qquad [c] = \frac{N}{W \cdot s}$$

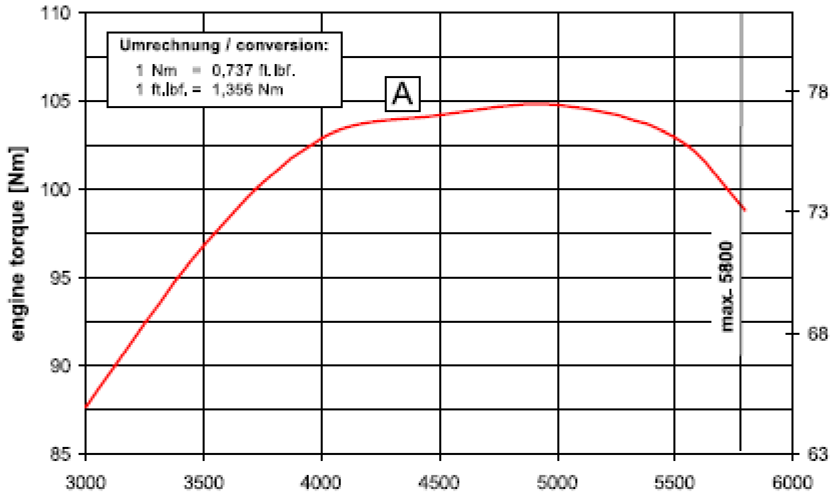
$$SFC = \frac{lb}{hp \cdot h}$$

valore tipico 0.40-0.50 [lb/(hp h)].

Π_a



Q



Caratteristiche propulsive MOTOELICA

Variazione di potenza e SFC con vel e quota

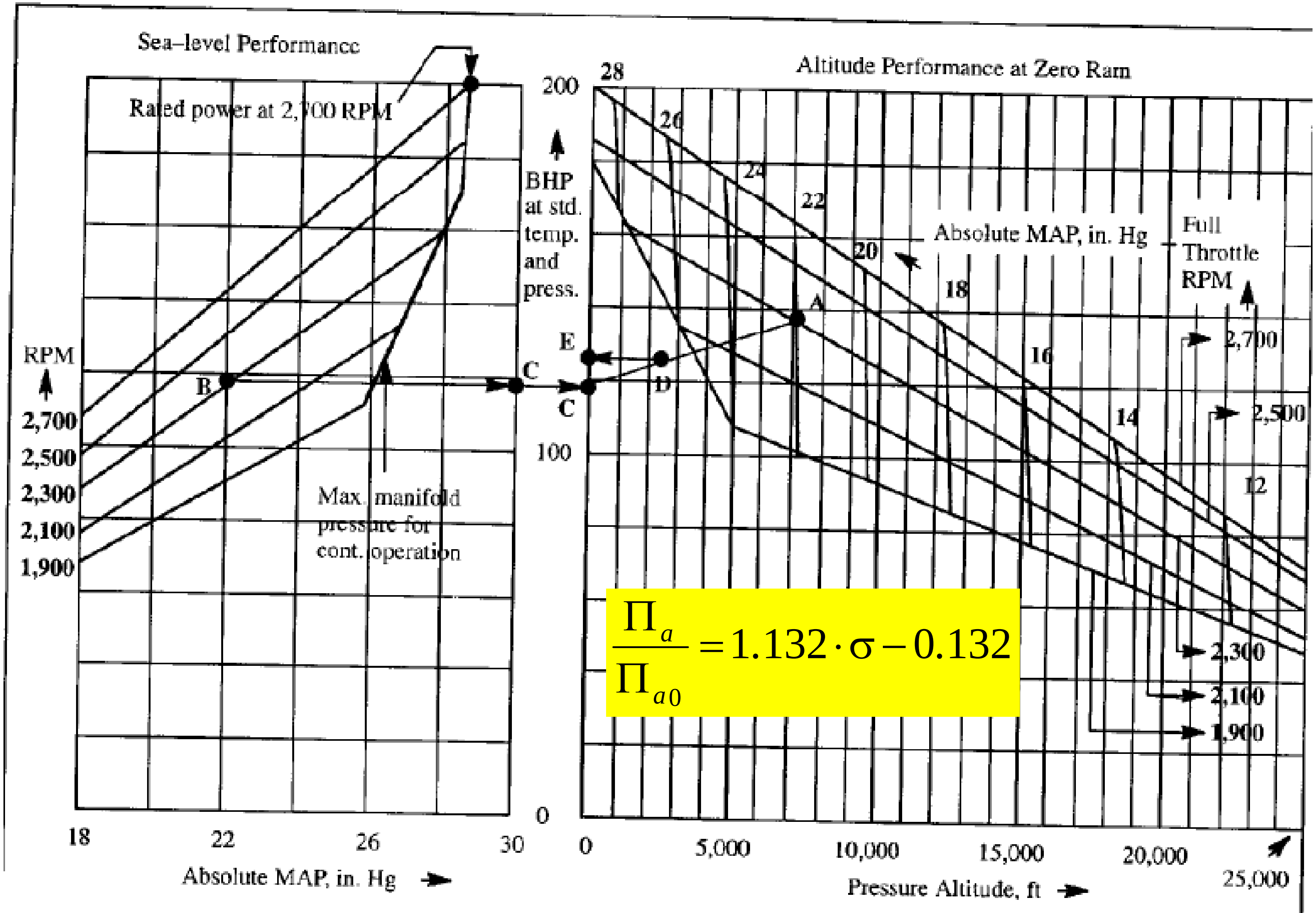
- Π_a è ragionevolmente costante con la velocità
- SFC è ragionevolmente costante con la velocità

Negli Stati Uniti i due principali produttori di motori alternativi aerei sono Teledyne Continental e Textron Lycoming. I cavalli vapore a livello del mare per questi motori generalmente variano da 75 a 300 hp. Per questi motori un tipico valore di SFC è 0.4lb di carburante consumate per cavallo vapore per ora.

Effetto quota

$$\frac{\Pi_a}{\Pi_{a0}} = \frac{\rho}{\rho_0} \qquad \text{oppure} \qquad \frac{\Pi_a}{\Pi_{a0}} = 1.132\frac{\rho}{\rho_0} - 0.132$$

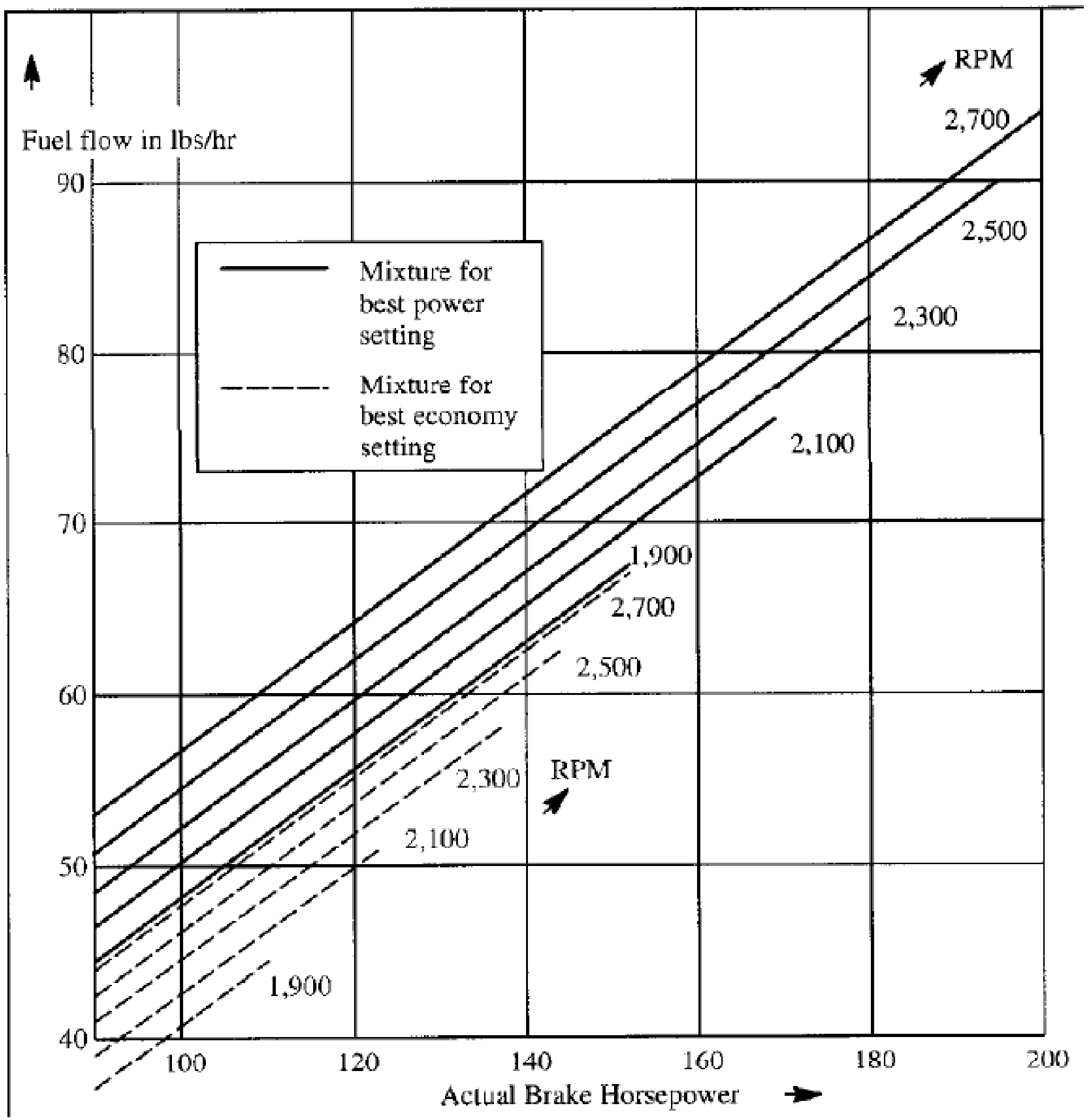
$$\frac{\Pi_a}{\Pi_{a0}} = 1.132 \cdot \sigma - 0.132$$



$$\frac{\Pi_a}{\Pi_{a0}} = 1.132 \cdot \sigma - 0.132$$

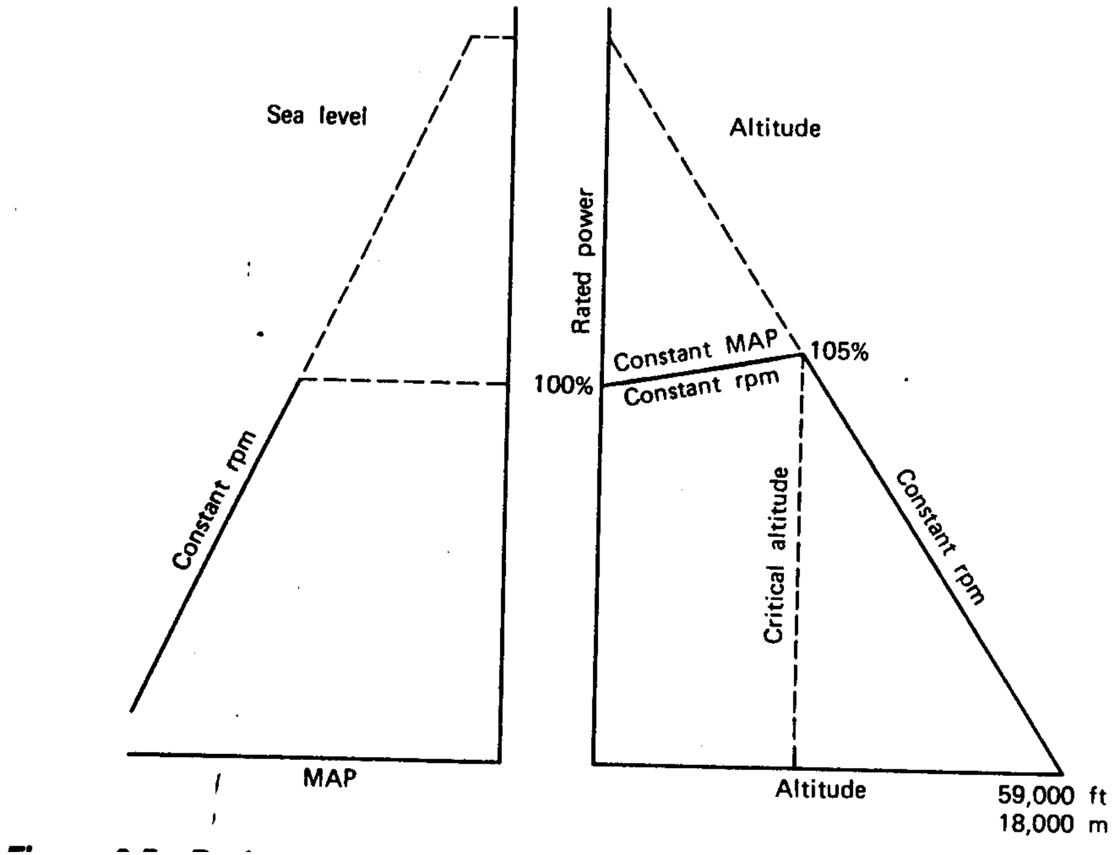
Figure 6.13 Power Diagram for a 200 BHP Piston Engine

Caratteristiche propulsive MOTOELICA

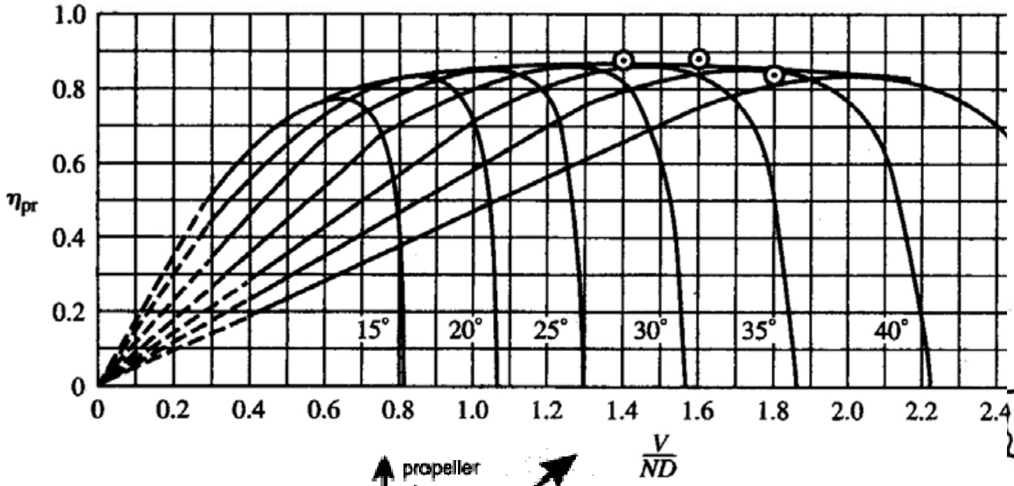


Caratteristiche propulsive MOTOELICA

Motori Supercharged (turbocompressi)



Caratteristiche propulsive ELICHE



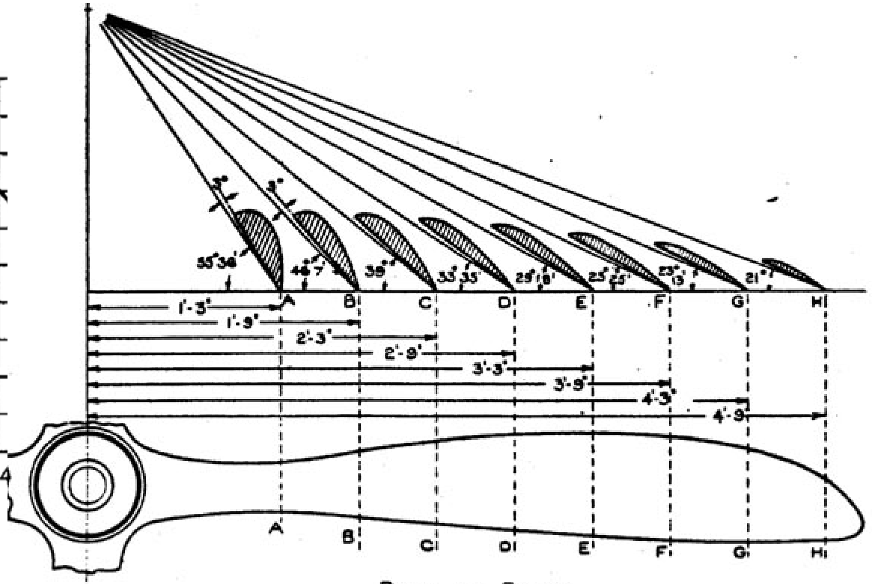
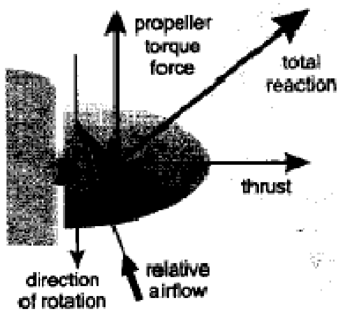


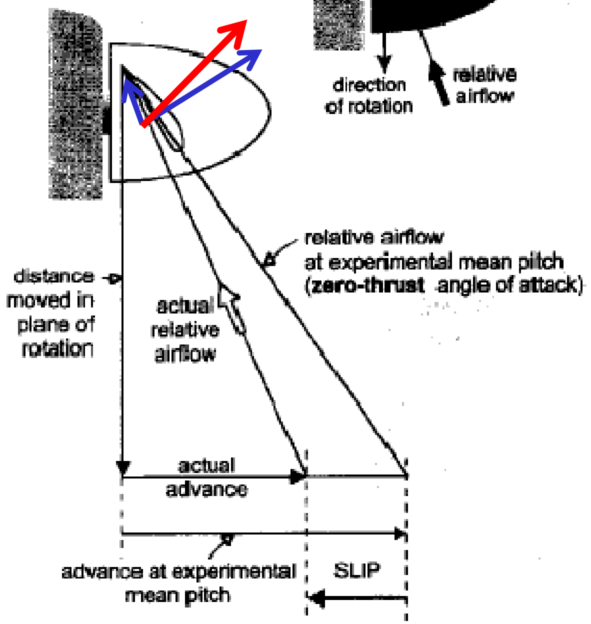
FIG. 219.—Lay-out of an Airscrew.



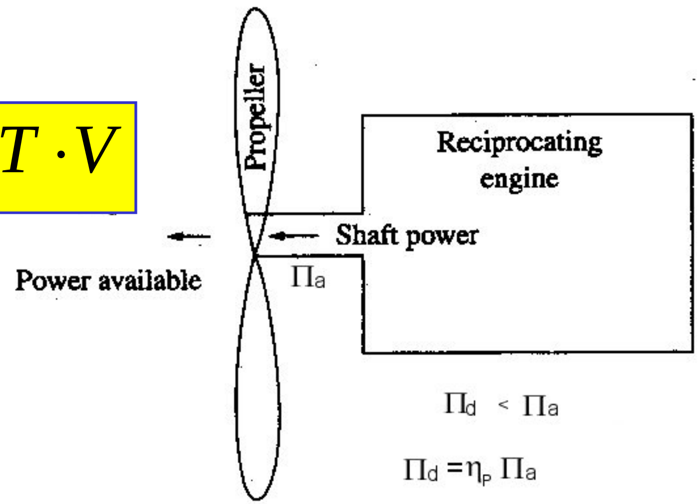
$$J = \frac{V}{n \cdot D}$$

RAPPORTO AVANZAMENTO

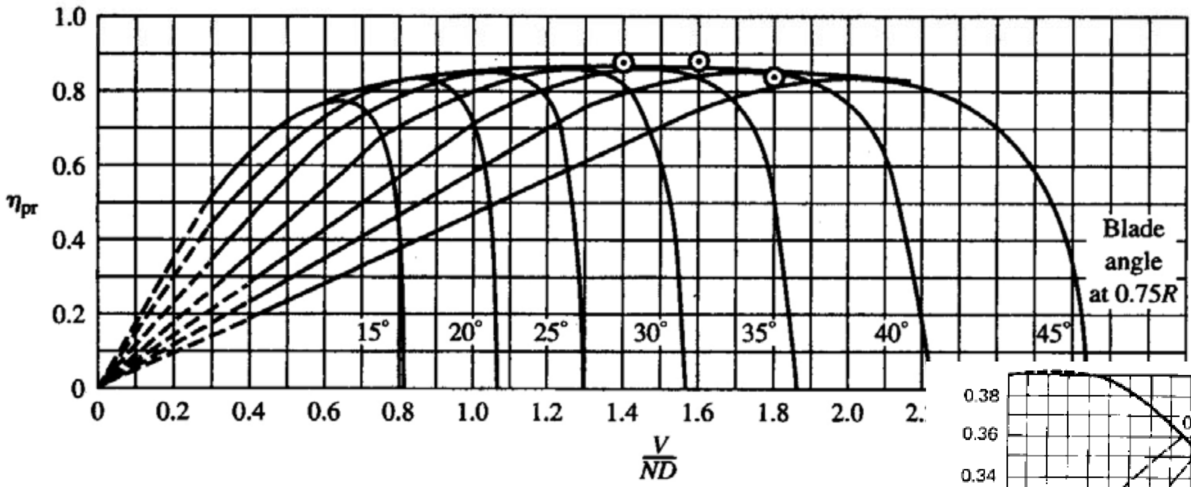
Forza TOT



$$\Pi_d = \eta_{pr} \Pi_a = T \cdot V$$

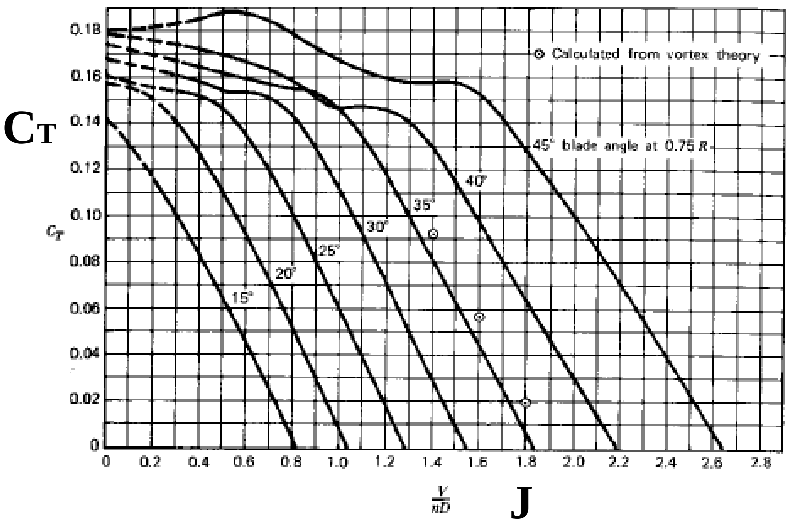


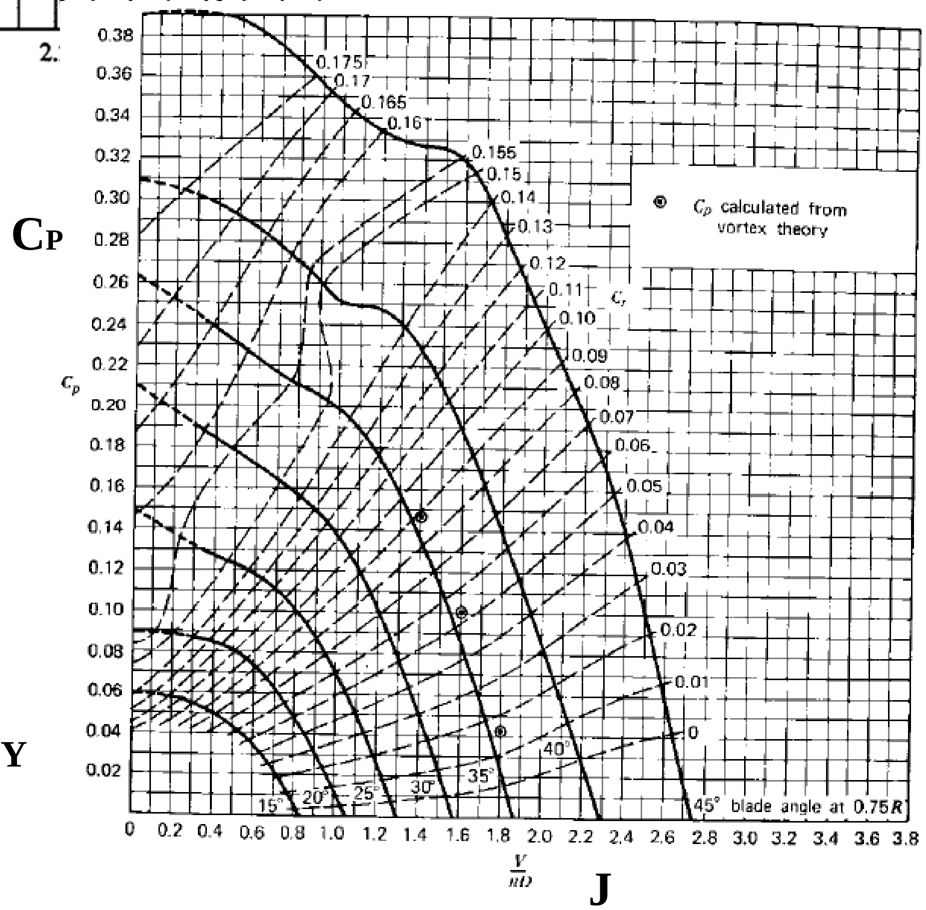
Caratteristiche propulsive ELICHE COEFF. di RENARD



$$C_T = \frac{T}{\rho n^2 D^4} \qquad J = \frac{V}{n \cdot D}$$

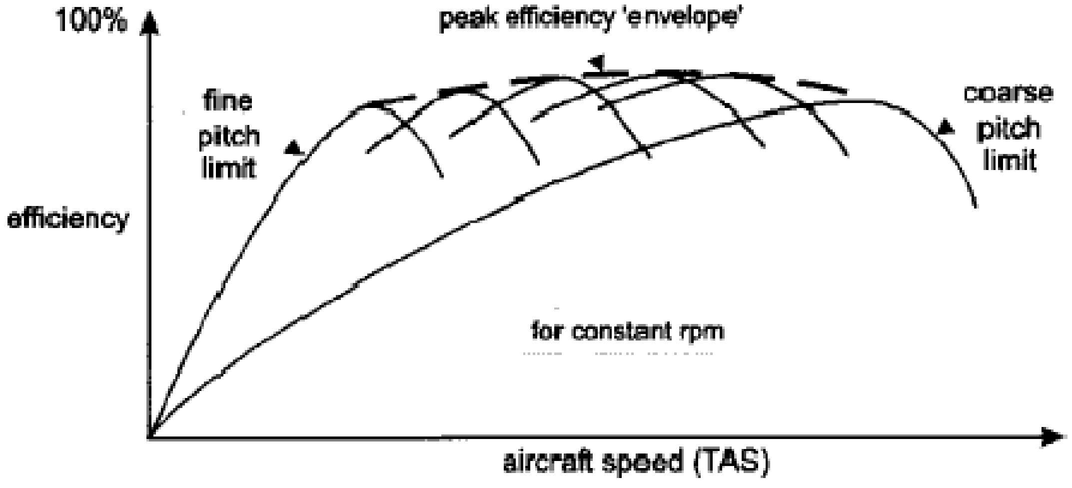
$$C_p = \frac{P}{\rho n^3 D^5} \qquad \eta = \frac{C_T J}{C_p}$$

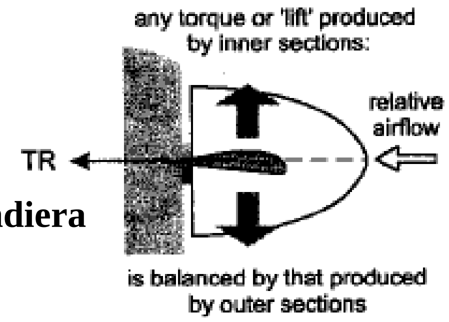




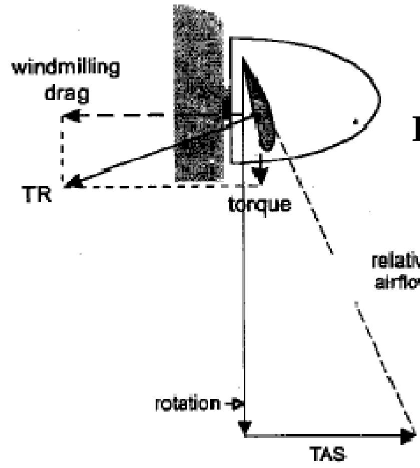
Diagrammi caratteristici
NACA , elica tripala, profilo Clark-Y

Caratteristiche propulsive ELICHE

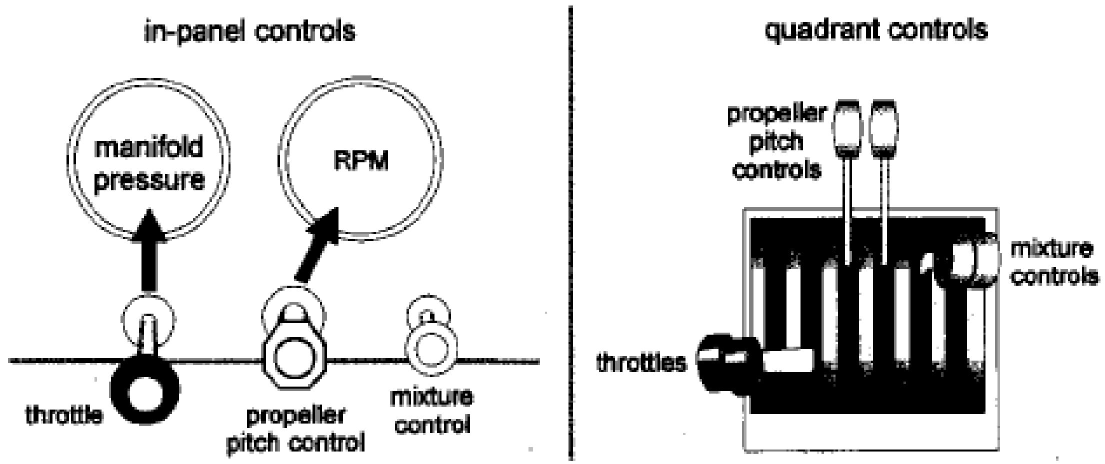


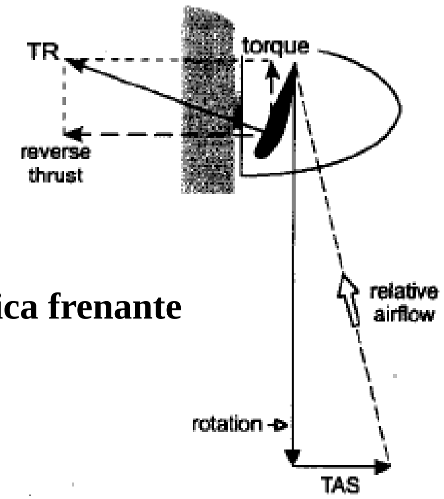


Elica a bandiera



Elica trasparente



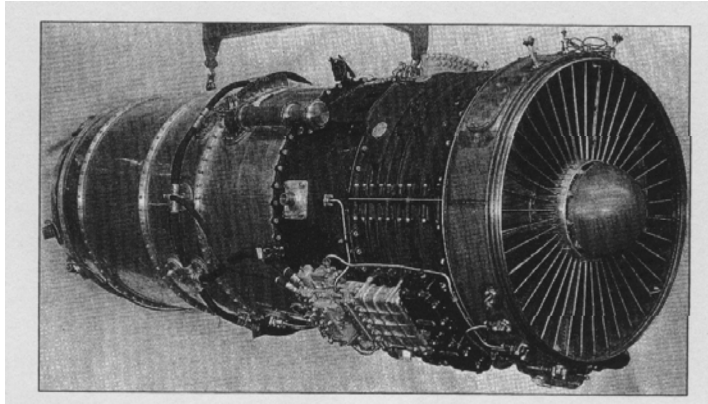


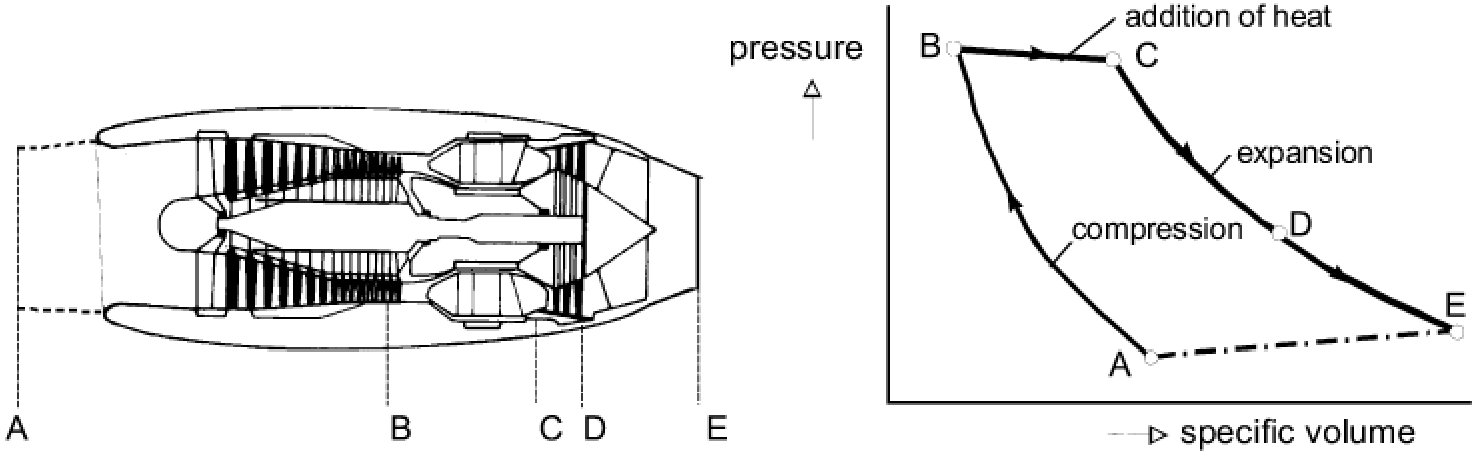
Elica frenante

Caratteristiche propulsive

<u>Turbojet</u>

$$T = \left(\dot{m}_{air} + \dot{m}_{fuel}\right)V_j - \dot{m}_{air}V_\infty + \left(p_e - p_\infty\right)A_e$$





(a) Engine components (b) Brayton cycle

Figure 5.17 Components and cycle of a jet engine.

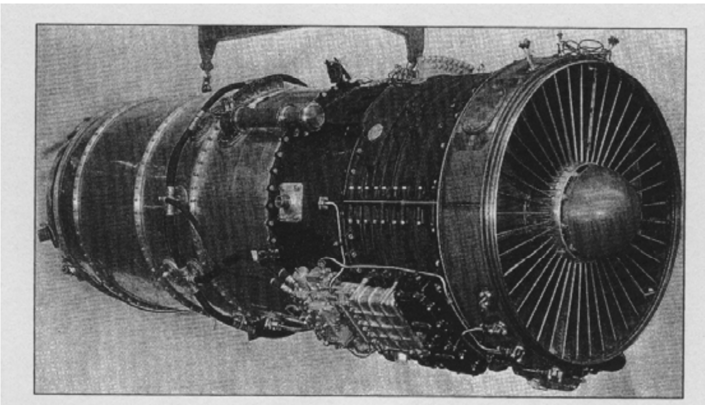
Caratteristiche propulsive

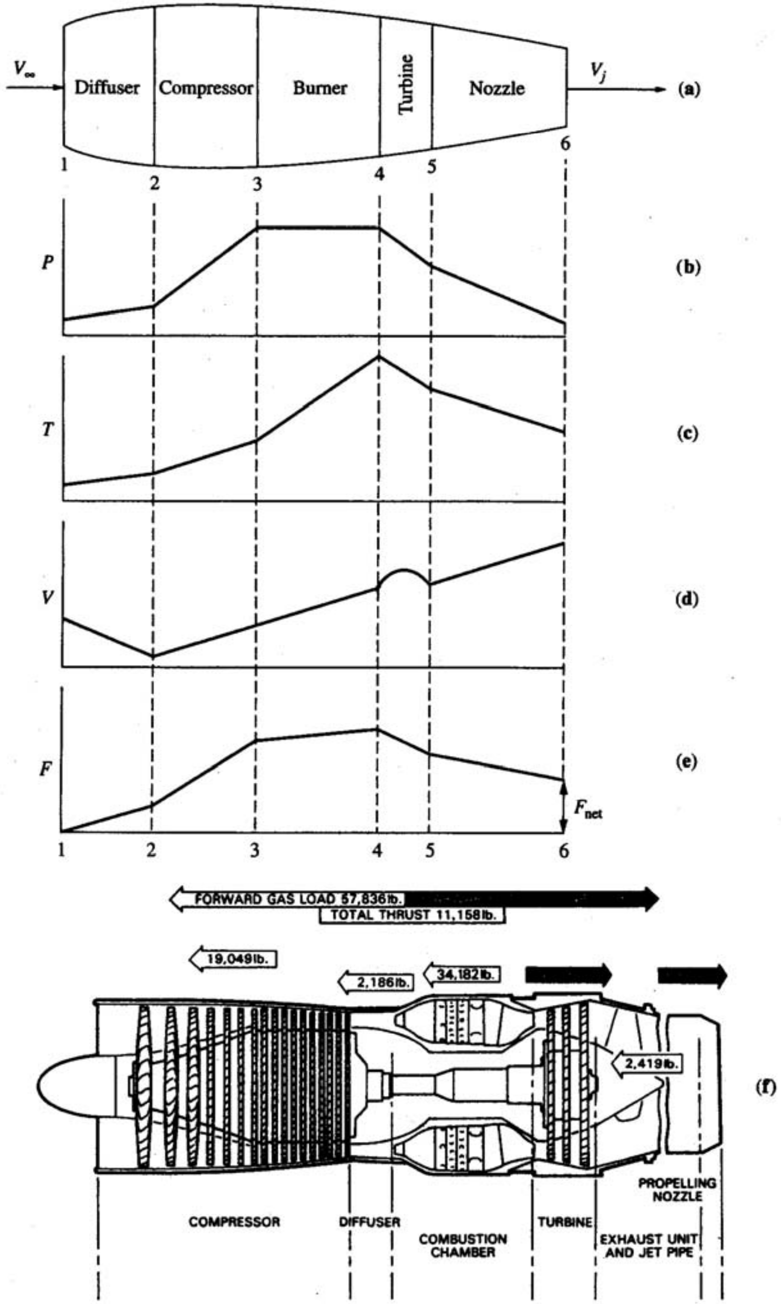
<u>Turbojet</u>

$$T = \left(\dot{m}_{air} + \dot{m}_{fuel}\right)V_j - \dot{m}_{air}V_\infty + \left(p_e - p_\infty\right)A_e$$

$$\left[c_j\right] = \frac{N}{N \cdot s} = \frac{1}{s}$$

$$\left[SFCJ\right] = \frac{lb}{lb \cdot h} = \frac{1}{h}$$





Caratteristiche propulsive

<u>Turbojet</u>

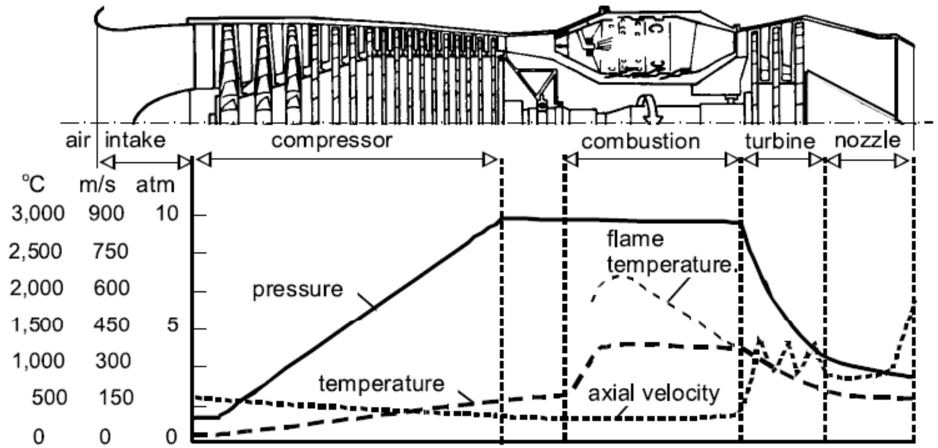
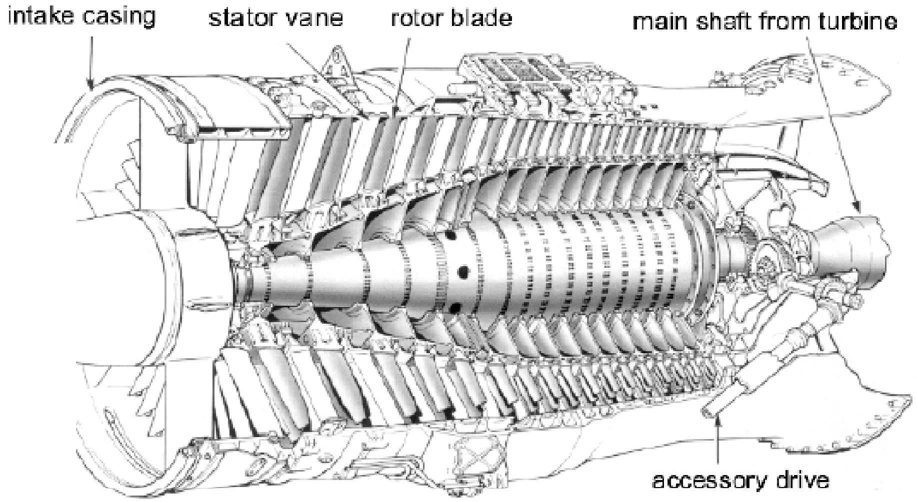


Figure 5.20 Variation of pressure, temperature and flow velocity in a jet engine (courtesy of Rolls-Royce plc).



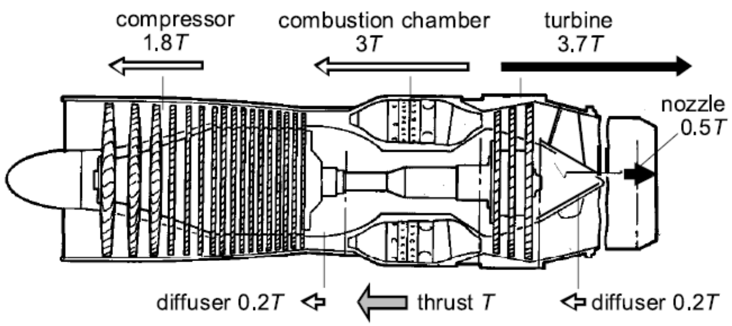
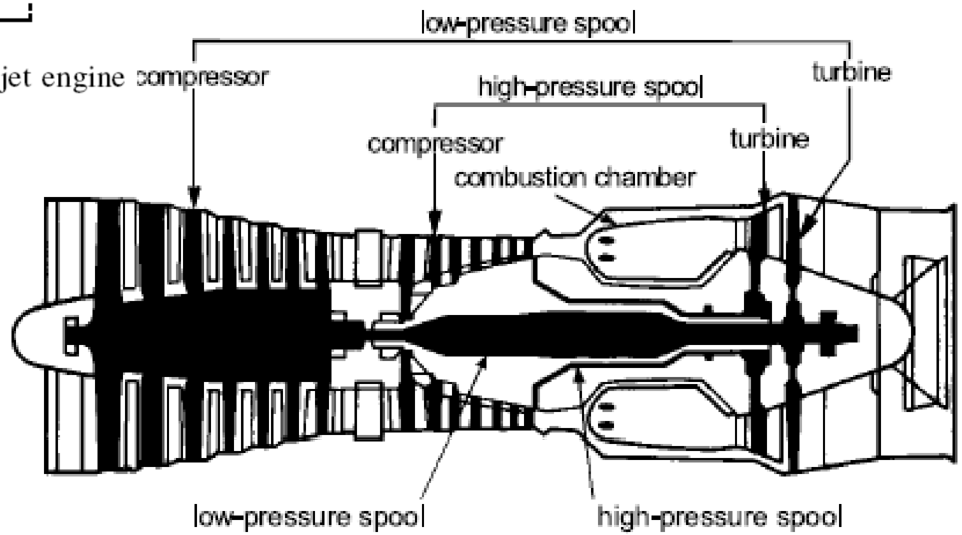


Figure 5.21 Distribution of internal thrust components for a static turbojet.

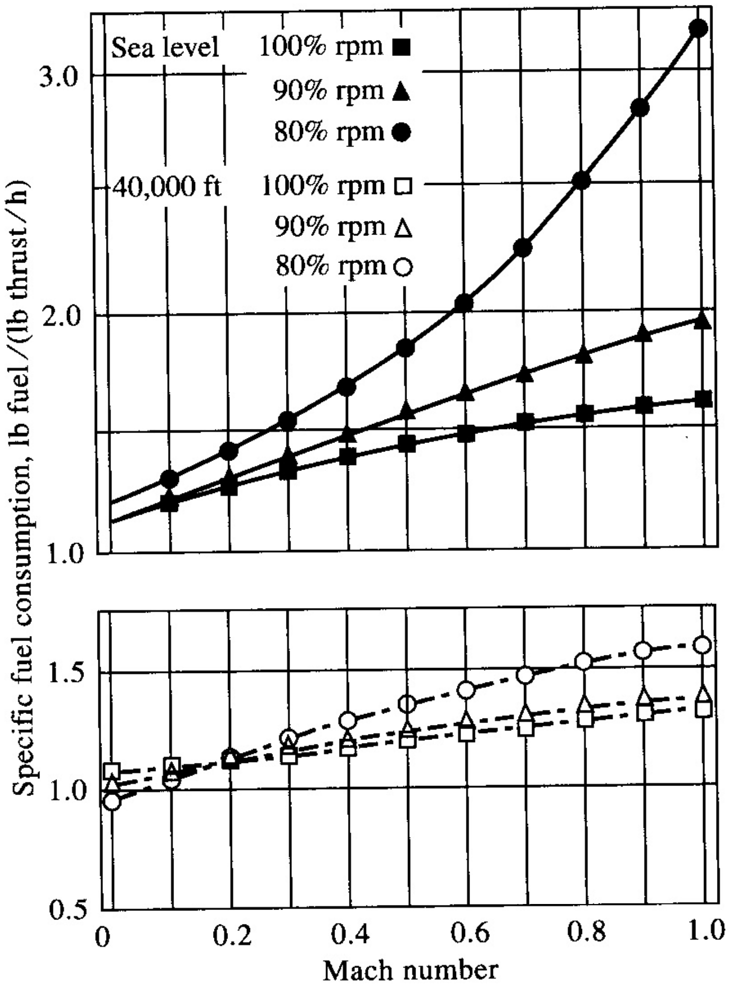


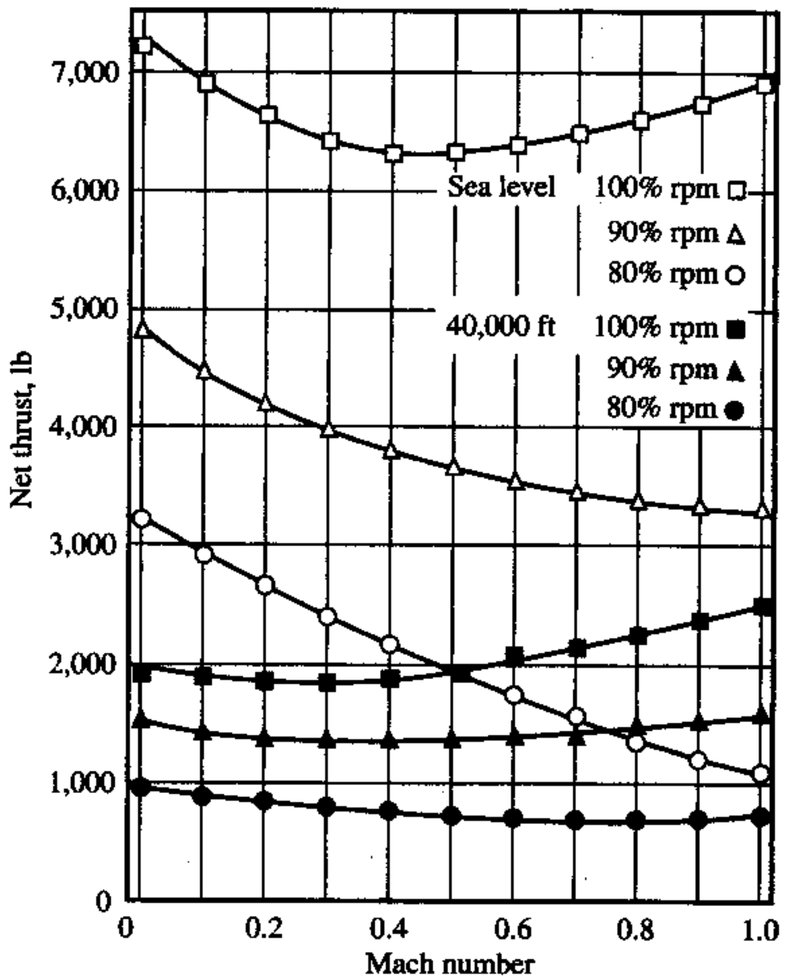
Turbojet bi-albero

Caratteristiche propulsive Turbojet

TSFC = 1.0 + kM_∞

SFCJ è costante con la quota





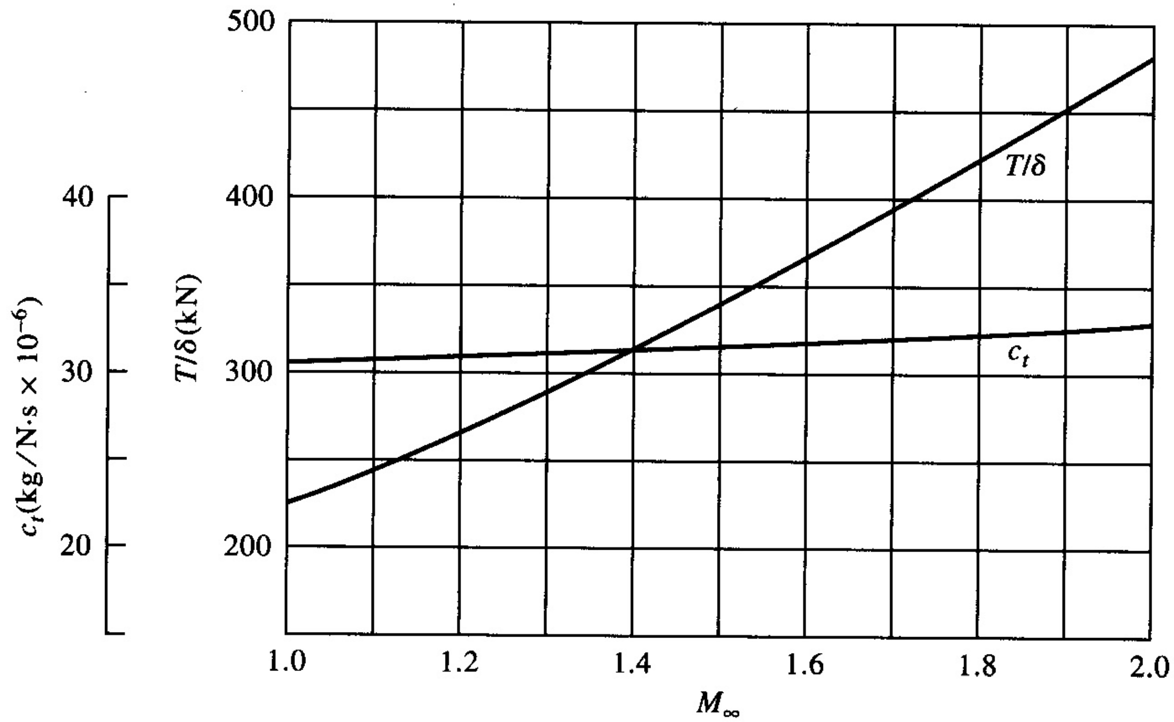
Spinta praticamente cost. con V

Effetto quota $$\frac{T}{T_0} = \frac{\rho}{\rho_0}$$

Caratteristiche propulsive Turbojet

$$\frac{p_{total}}{p_{static}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\gamma/(\gamma-1)}$$

Condizioni supersoniche



$$\frac{T}{T_{Mach1}} = 1 + 1.18(M_\infty - 1)$$

Caratteristiche propulsive Turbojet

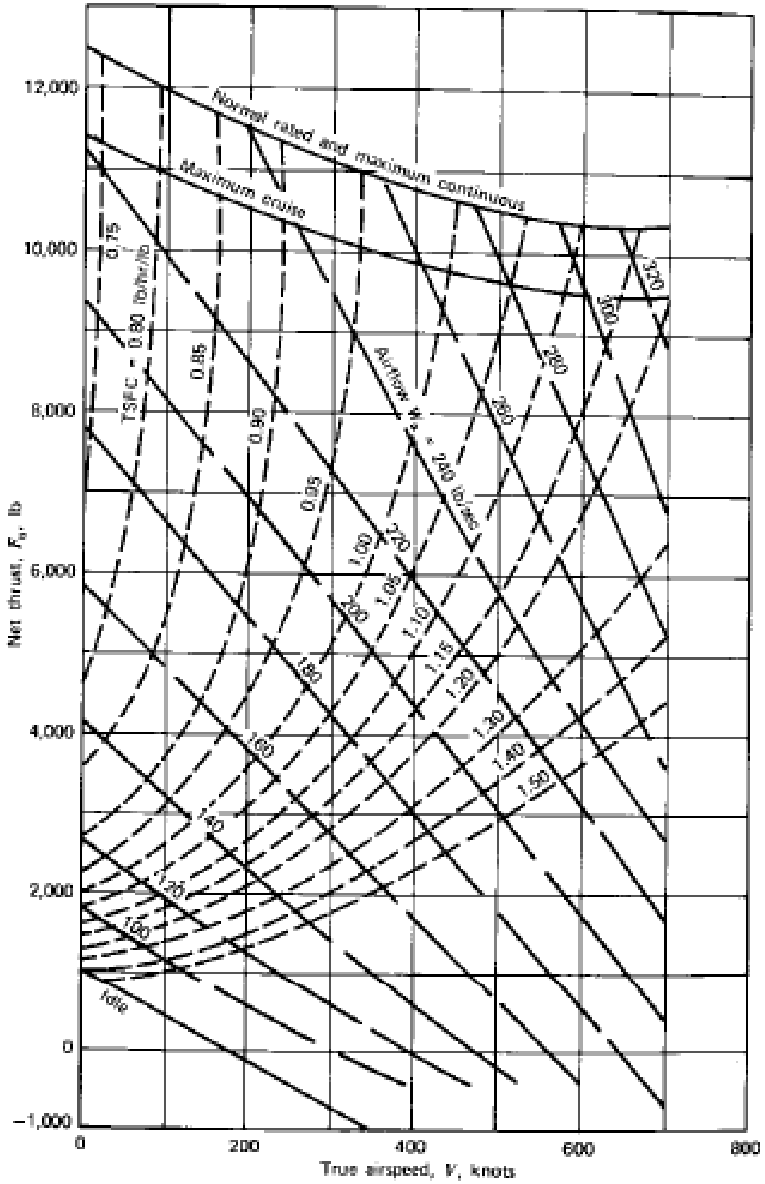


Figure 6.32a Pratt & Whitney Aircraft JT4A-3 turbojet engine. Estimated thrust, TSFC, and airflow at sea level. Standard atmospheric conditions, 100% ram recovery. (Courtesy, Pratt & Whitney.)

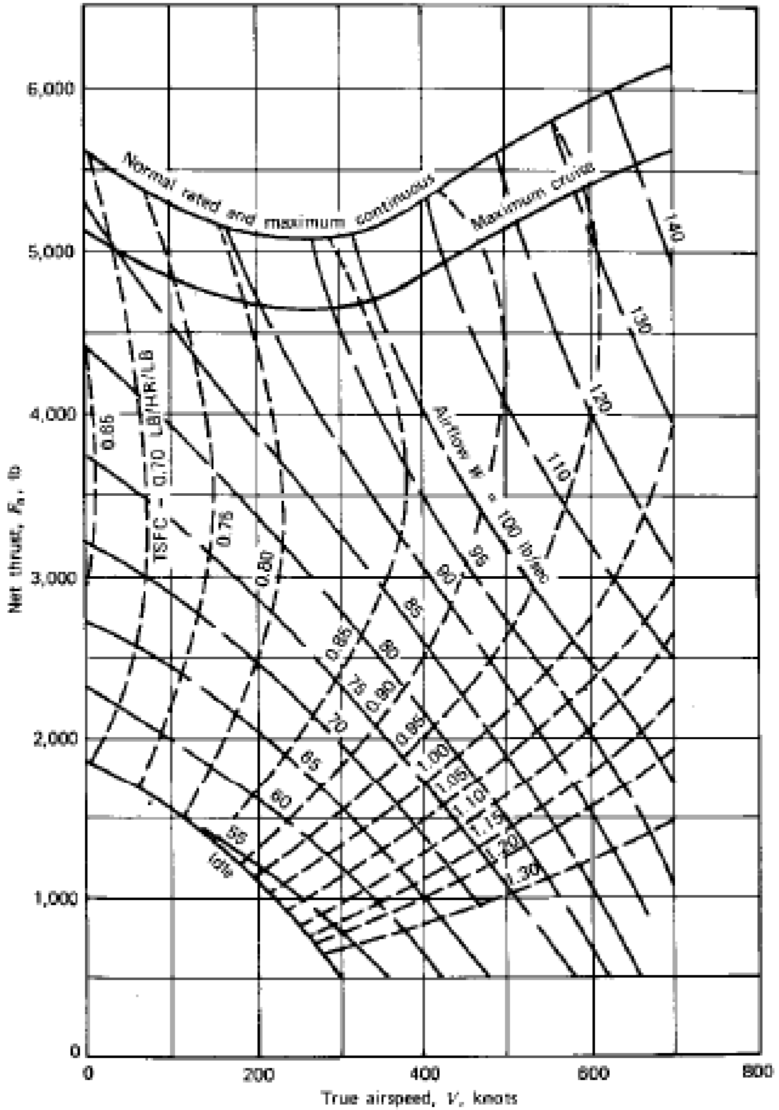


Figure 6.32c Pratt & Whitney Aircraft JT4A-3 turbojet engine. Estimated thrust, TSFC, and airflow at 30,000 ft. Standard atmospheric conditions, 100% ram recovery. (Courtesy, Pratt & Whitney.)

Caratteristiche propulsive

Turbojet

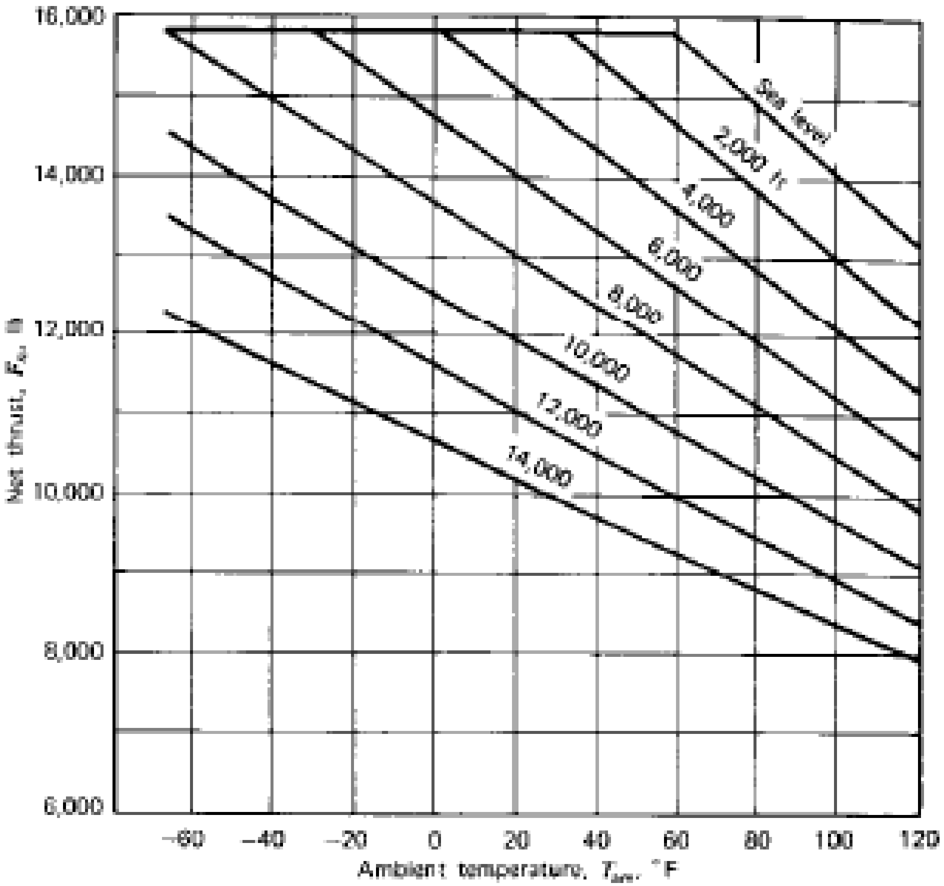
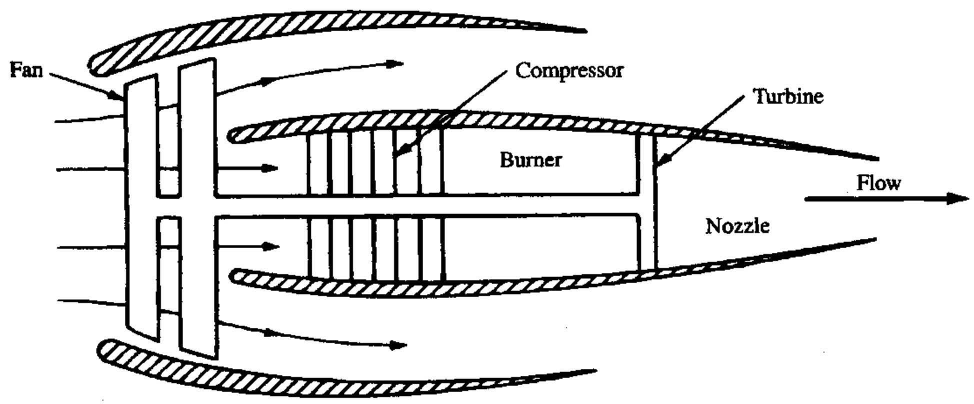


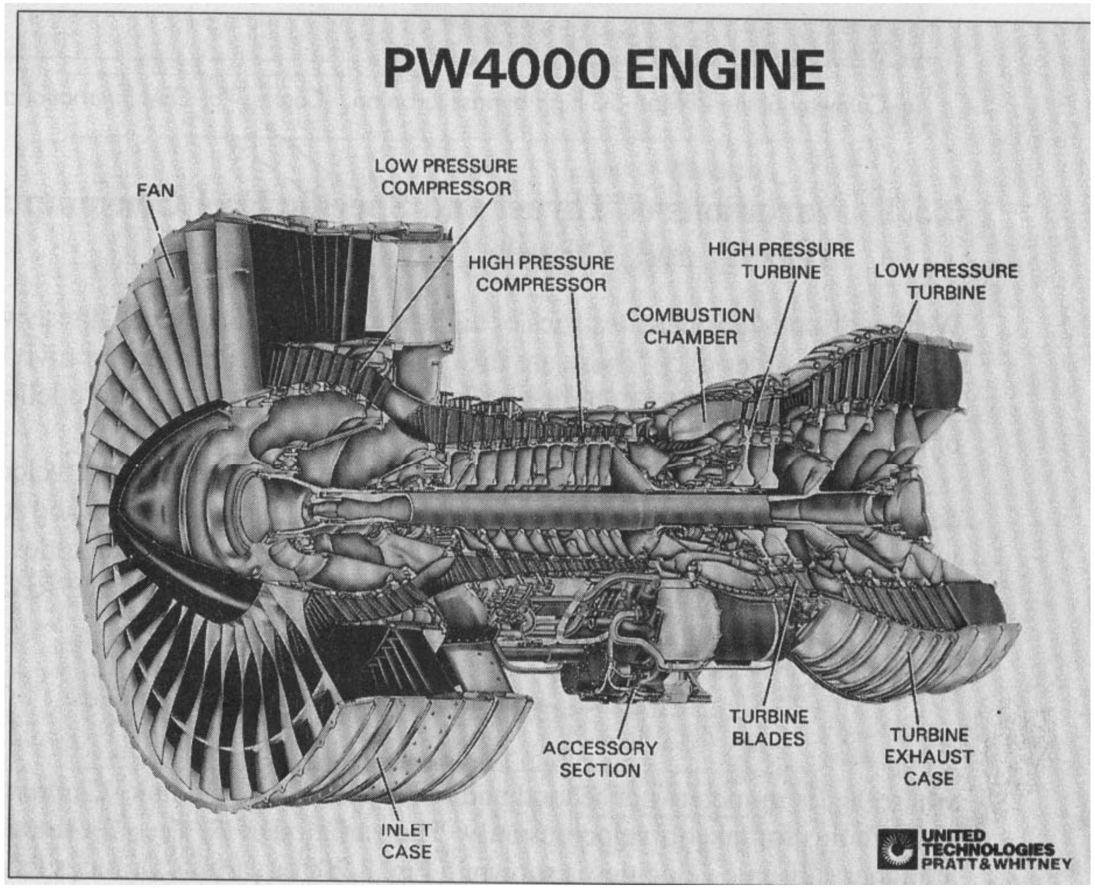
Figure 6.33a Pratt & Whitney Aircraft JY4A-3, -5 turbojet engines. Estimated net thrust on runway during takeoff. Zero knots. (Courtesy, Pratt & Whitney.)

Caratteristiche propulsive

<u>Turbofan</u>

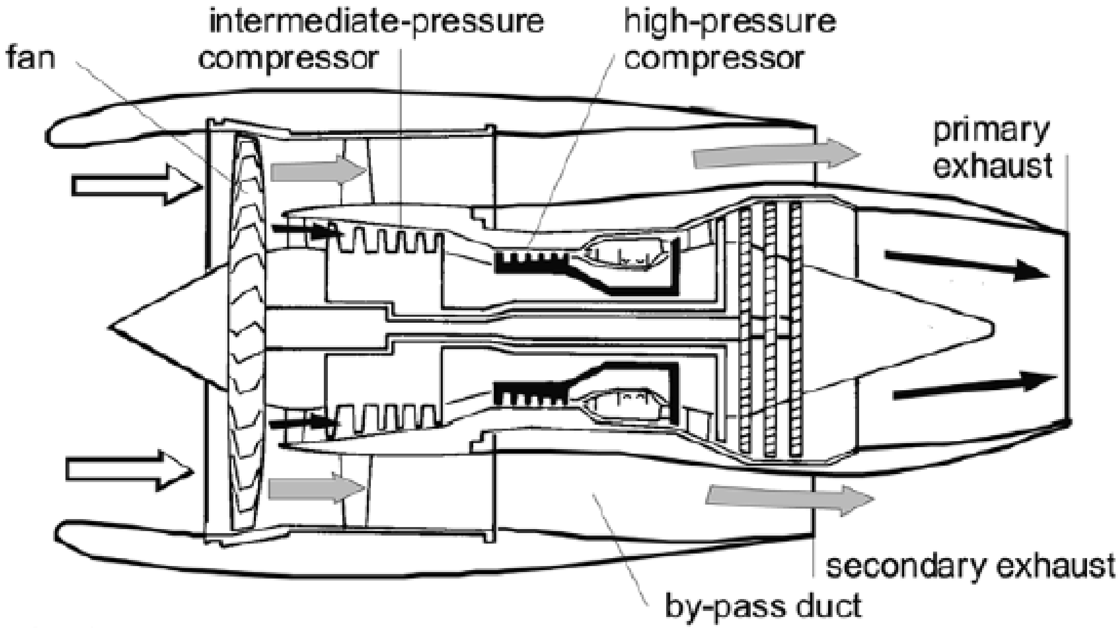
BPR : apporto di By-Pass o anche rapporto di diluizione



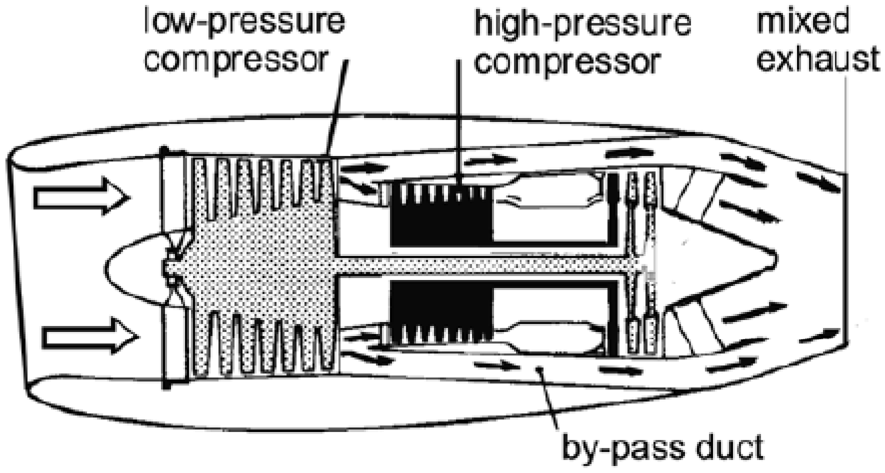


Caratteristiche propulsive

Turbofan



(b) Three-shaft high by-pass ratio turbofan



(a) Low by-pass ratio turbofan

Caratteristiche propulsive

Turbofan

- Low BPR

- HIGH BPR

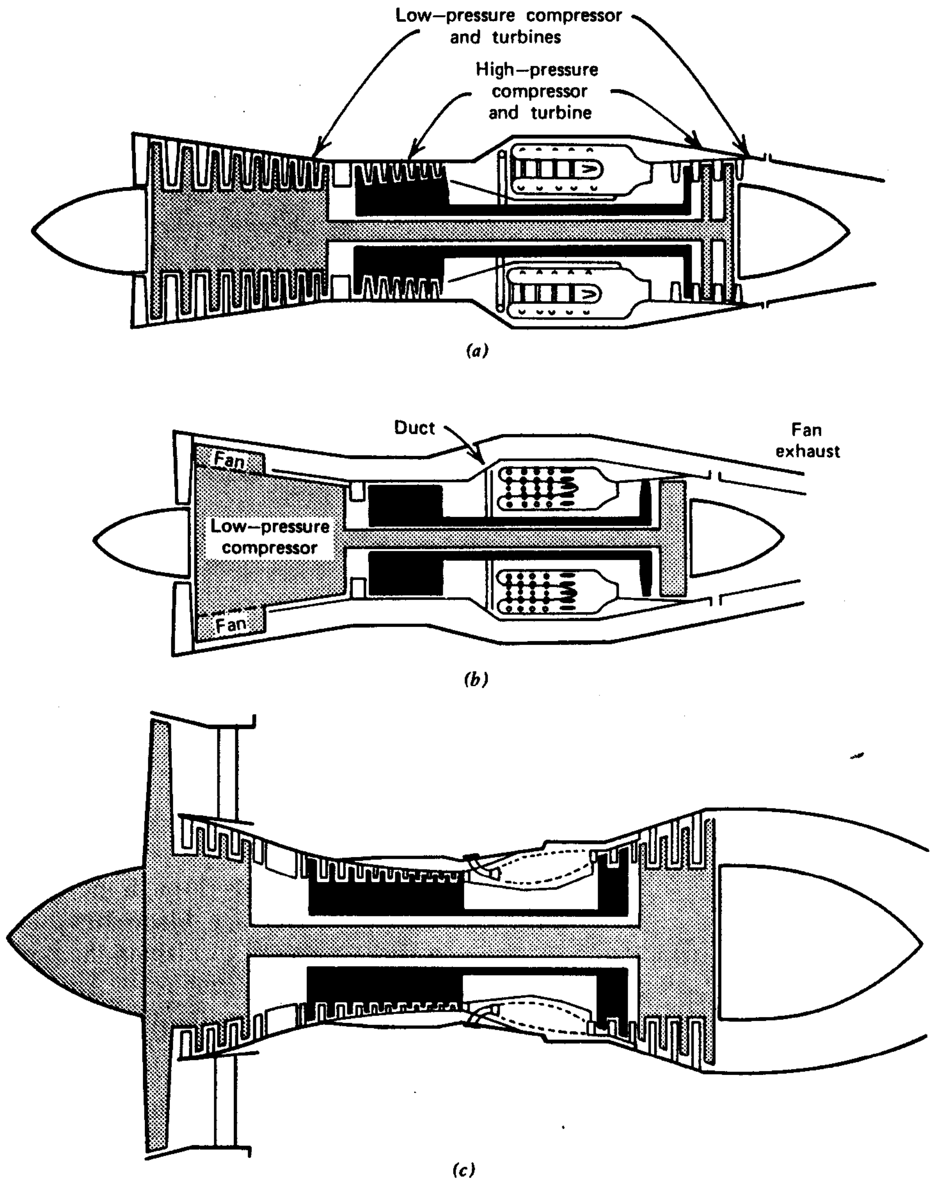


Figure 6.26 Variations on the gas turbine. (*a*) Dual axial-flow compressor turbojet. (*b*) Dual axial-flow compressor, forward fan engine with long ducts. (*c*) High bypass ratio turbofan with short ducts. (*d*) Single axial-flow compressor, direct propeller drive turboprop. (*e*) Single axial-flow compressor, free turbine propeller drive turboprop. (*f*) Dual axial-flow compressor, turbojet with afterburner. (*g*) Dual axial-flow compressor, industrial turboshaft engine.

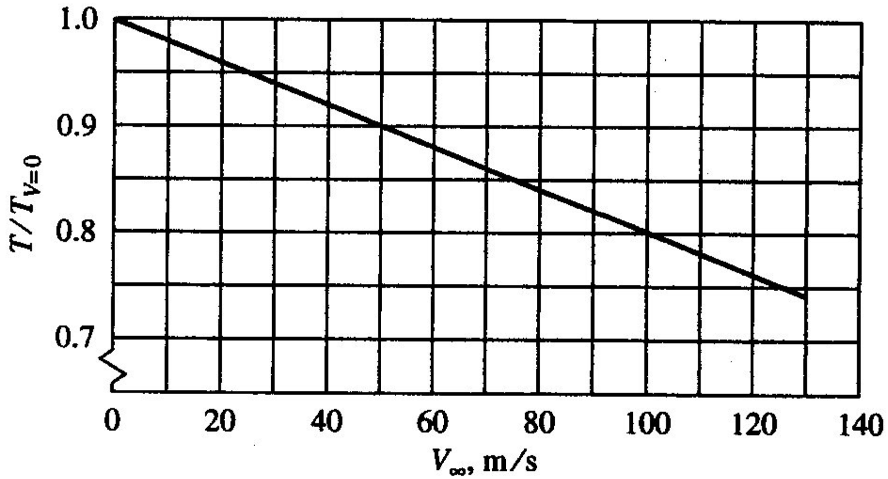
Caratteristiche propulsive

The Pratt & Whitney JT9D-7A is representative of a modern high bypass turbofan engine. This engine has a dry weight of 8850 lb (39,365 N) and delivers a maximum continuous static thrust at SSL of 39,650 lb (176,363 N). The static dry takeoff rating of 45,500 lb (202,384 N) is flat rated up to 27 °C (80 °F). The diameter of the engine is 2.43 m (95.6 in.) with a length of 3.92 m (154.2 in.). The compressor incorporates one fan stage, three low-pressure stages, and eleven high-pressure stages. The turbine has two high-pressure stages and four low-pressure stages. The bypass ratio equals 5.1 at the dry takeoff rating, with a total airflow of 1545 lb/sec (6872 N/s). The dash 7A model

Esempio Turbofan HBPR (BPR=5.1) PW JT9D

To=46000 lb

Spinta al decollo - Effetto velocità



Take-off thrust

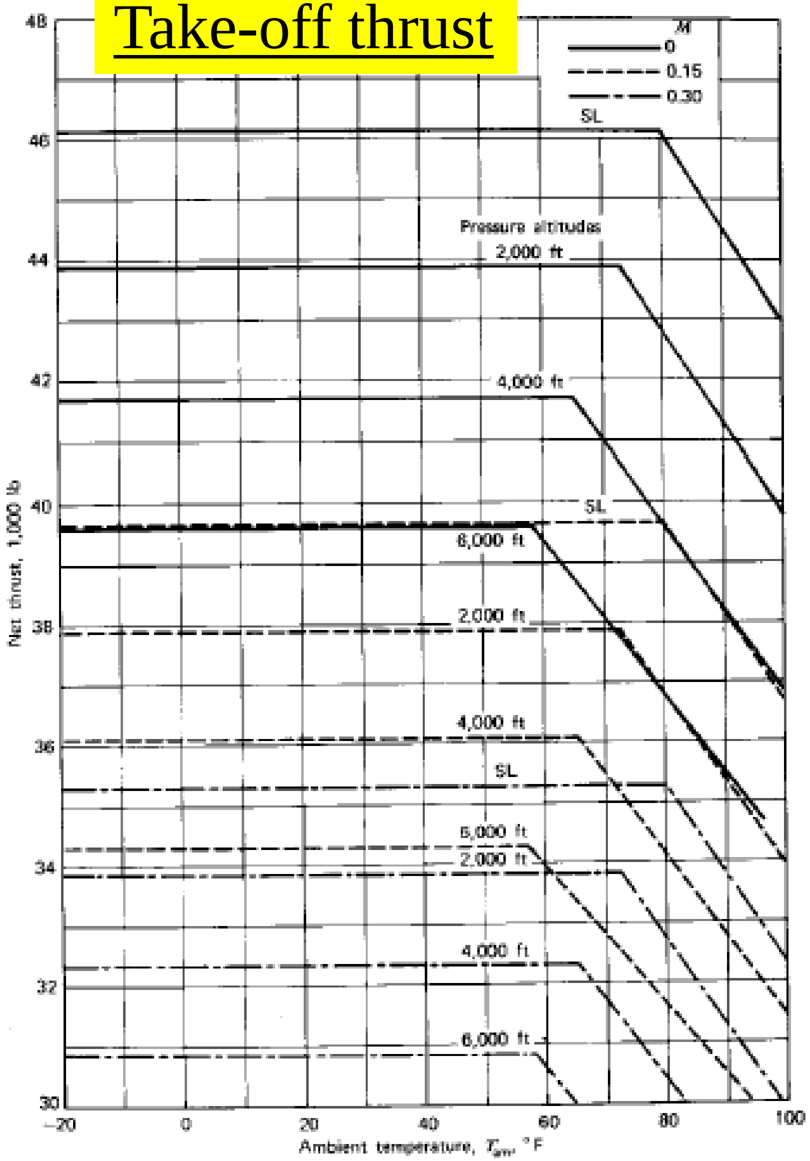


Figure 6.36 JT9D-7A net takeoff thrust. Dry, 100% ram recovery, no airbleed, no power extraction, Pratt & Whitney Aircraft standard exhaust. (Courtesy, Pratt & Whitney.)

Caratteristiche propulsive

PW JT9D

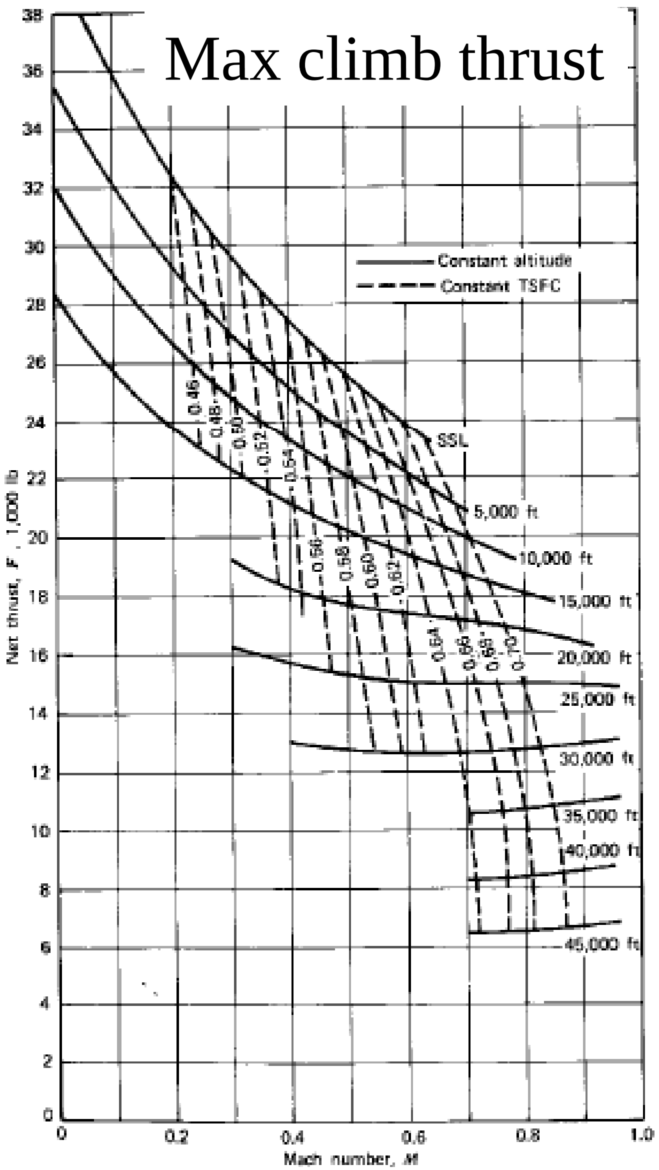


Figure 6.37 JT9D-7A maximum climb thrust. One hundred percent ram recovery, no airbleed, no power extraction, Pratt & Whitney Aircraft reference exhaust system, all curves for ICAO standard day +10°C and below. (Courtesy, Pratt & Whitney.)

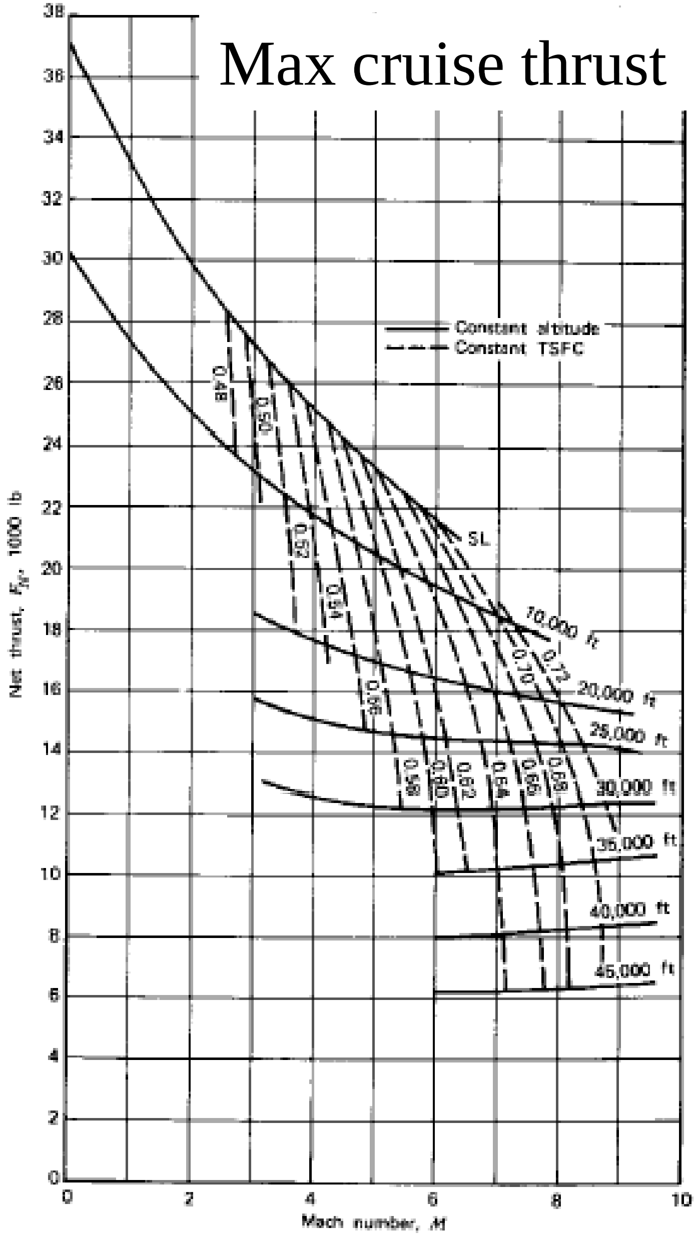
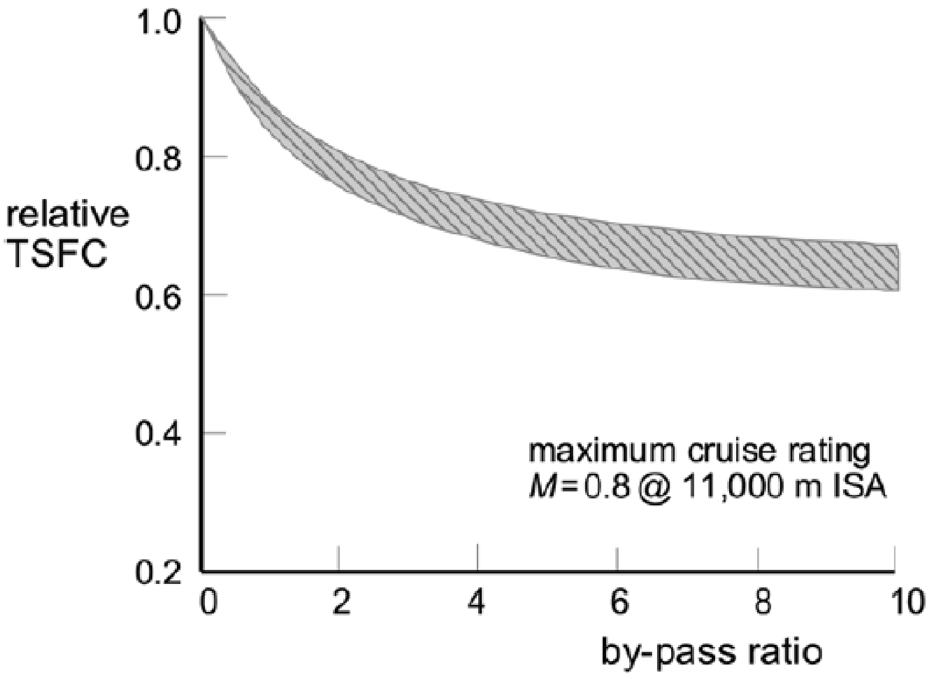
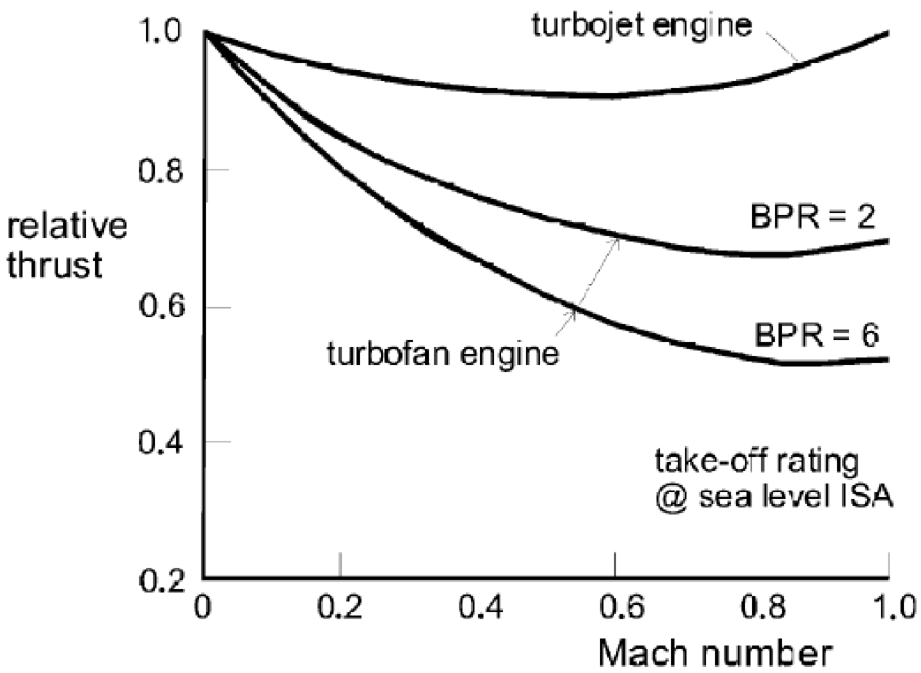


Figure 6.38 JT9D-7A maximum cruise thrust. One hundred percent ram recovery, no airbleed, no power extraction, Pratt & Whitney Aircraft reference exhaust system, all curves for ICAO standard day +10°C and below. (Courtesy, Pratt & Whitney.)

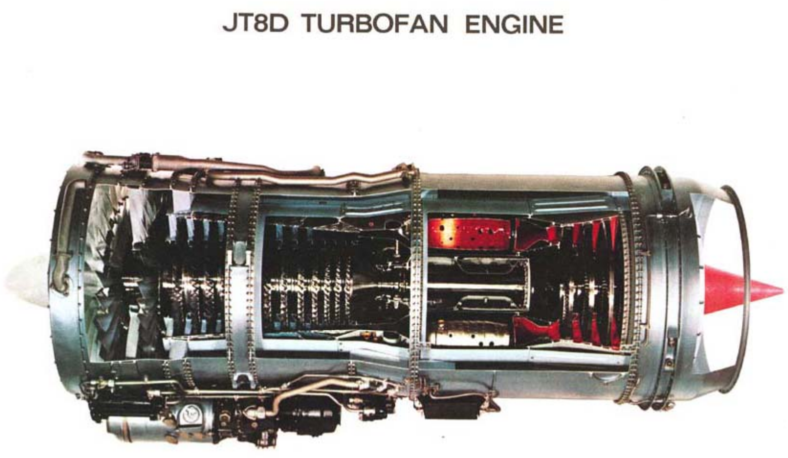
Caratteristiche propulsive



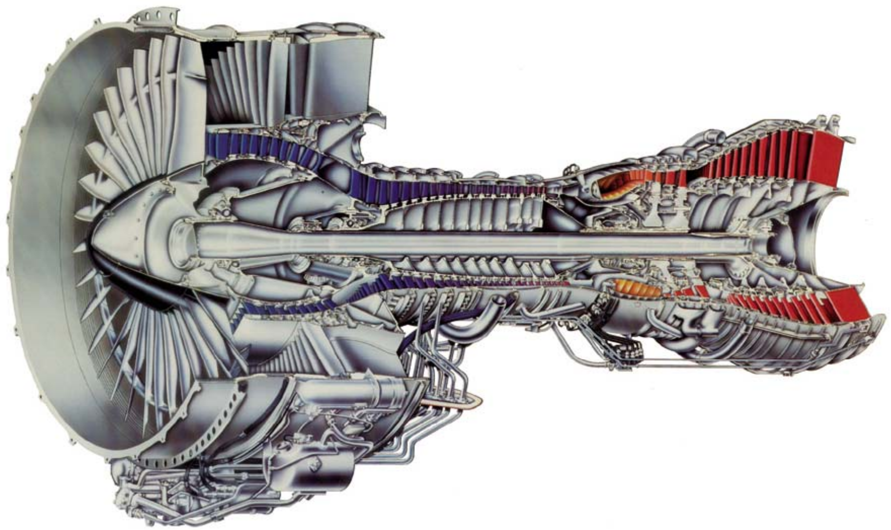
(a) Specific fuel consumption



(b) Thrust lapse with speed



Motore Turbofan basso BPR
Pratt&Whitney JT8-D

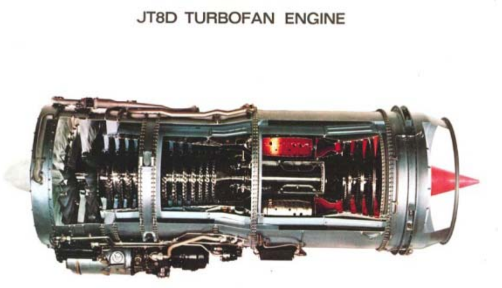


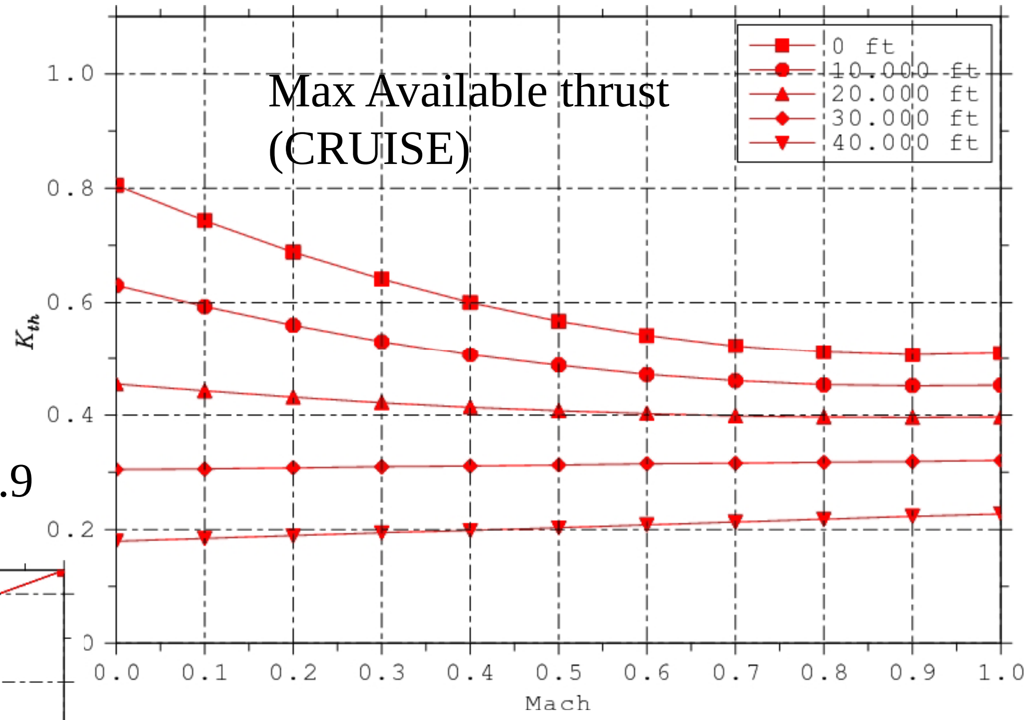
Motore Turbofan alto BPR
Pratt&Whitney PW2037

Modello Motore Turbofan basso BPR

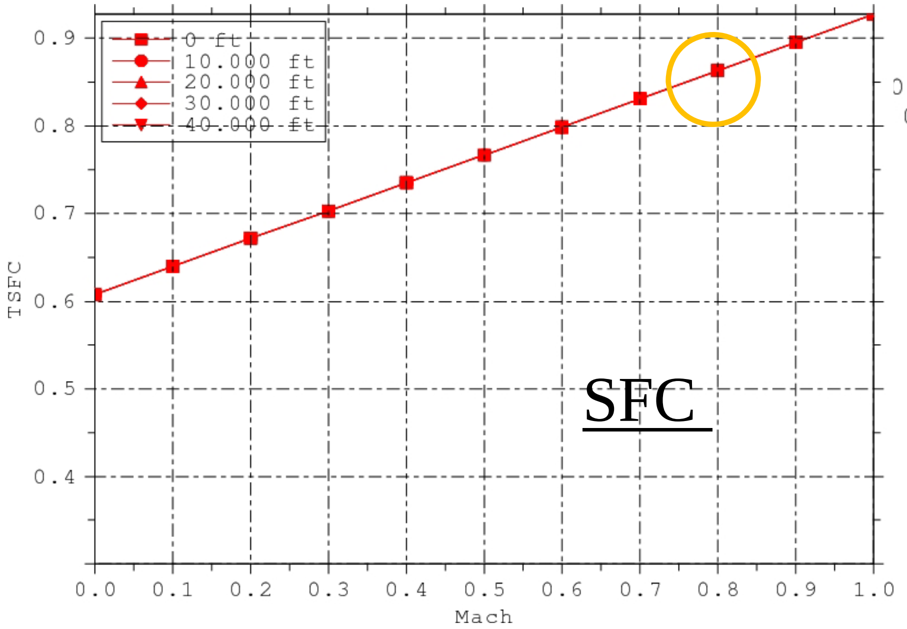
Pratt&Whitney JT8-D

$$T = k_{Th}(h, M) \cdot T_o$$





SFC: valore tipico in crociera , circa 0.8-0.9



<u>Cruise Setting</u>

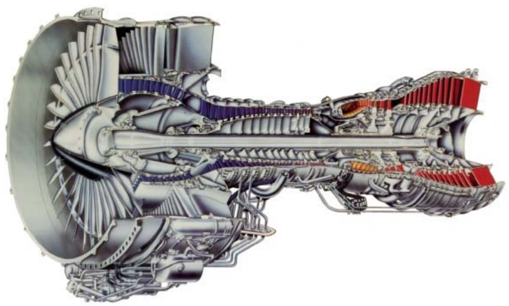
<u>(Per l'assetto di salita moltiplicare per circa 1.10, salita massima continuativa)</u>

Ad alte quote (30-35 kft), si vede che è praticamente costante con la velocità e :

$$T_{cr} \approx 0.85 \cdot \sigma \cdot T_o \qquad T_{climb} \approx 0.93 \cdot \sigma \cdot T_o$$

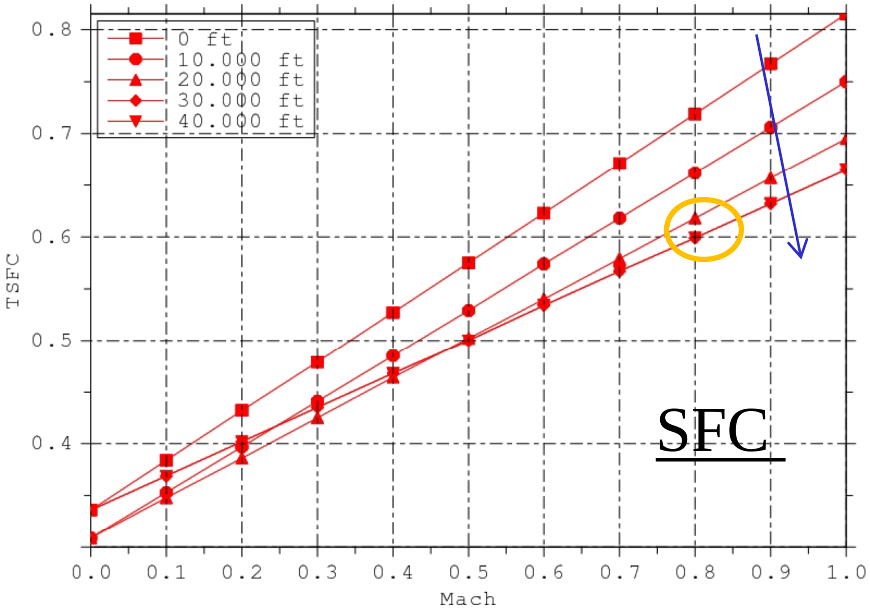
Modello Motore Turbofan alto BPR
Pratt&Whitney PW2037

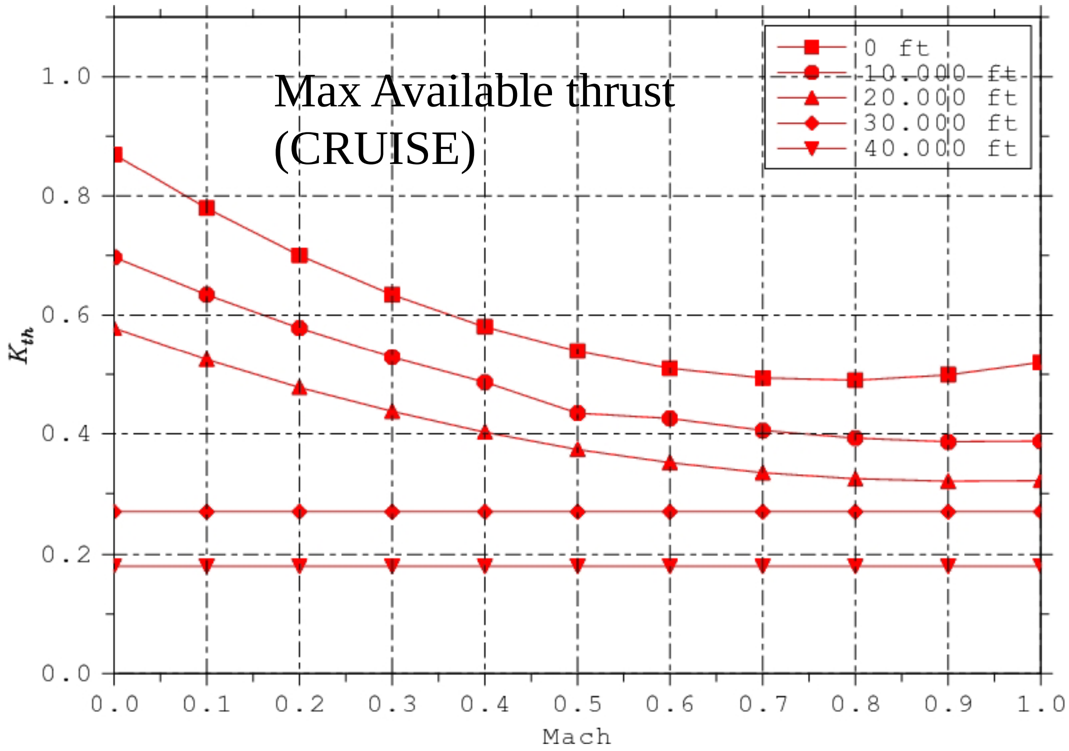
$$T = k_{Th}(h, M)\cdot T_o$$



La quota a M=0.80 ha effetto benefico sul SFC
Il motore è ottimizzato a 30000-33000 ft.

SFC tipico in crociera =0.55-0.65 [lb/(lb hr)]





<u>Cruise Setting</u>

<u>**(Per l'assetto di salita moltiplicare per circa 1.10, salita massima continuativa)**</u>

Ad alte quote (30-35 kft), si vede che è praticamente costante con la velocità e :

$$T_{cr} \approx 0.8 \cdot \sigma^{1.1} \cdot T_o$$

Caratteristiche propulsive Turbofan

Table 6.1 Weight and Performance Data for Turbojet and Turbofan Engines

Manuf./Type/ Config./B.P.R.	Weight (lbs)	Thrust at take–off s.l.s. (lbs)	s.f.c. at take–off s.l.s. (lbs/hr/lbs)	Massflow take–off s.l.s. (lbs/sec)	Alt./ M	Thrust at altitude/M (lbs)	s.f.c. at altitude/M (lbs/hr/lbs)
(1)/CF6–6D/ TBF/5.72	7,896	40,000	0.346	1,303	35K/ 0.8	7,160 (80% max)	0.616
(1)/CF6–32/ TBF/4.90	7,140	36,500	0.357	1,104	35K/ 0.8	6,630 (80% max)	0.609
(1)/CF6–50/ TBF/4.26	8,731	51,000	0.390	1,450	35K/ 0.8	8,720 (80% max)	0.628
(1)/CF6–80/ TBF/4.66	8,435	48,000	0.344	1,433	35K/ 0.8	8,260 (80% max)	0.592
(1)/CF34/ TBF/6.30	1,580	8,650	0.362	332	40K/ 0.8	1,420 (max)	0.728
(1)/CFM56–2/ TBF/6.00	4,610	24,000	???	817	35K/ 0.8	5,188 (max)	0.661
(1)/CJ610–5/ TBJ/1.00	402	2,950	0.980	44	36K/ 0.8	870 (max)	1.150
(1)/CF700/ TBF/1.93	725	4,200	0.660	126	36K/ 0.8	1,060 (max)	0.980
(1)/J79–17/ TBJ/0	3,873	17,820	1.980	170	35K/ 0.9	2,600 (max)	0.980
					35K/ 2.0	18,600 (max)	2.070
(1)/TF34–400/ TBF/6.2	1,478	9,275	0.363	338	36K/ 0.8	1,896 (intermediate)	0.682
(1)/F404–402/ TBF/0.27	2,282	17,700	???	146	???	???	???
(2)/CFE738/ TBF/5.3	1,325	5,725	0.372	210	40K/ 0.8	1,464 (max)	0.640
(3)/535E4/ TBF/4.3	7,264	42,000	???	1,150	35K/ 0.8	8,700 (max)	0.598
(3)/RB211/ TBF/4.3	9,814	60,600	???	1,604	35K/ 0.85	11,813 (max)	0.570
(3)/Trent800/ TBF/???	13,133	90,000	???	???	35K/ 0.83	13,000 (max)	0.557

Type: (1) = G.E.
(2) = G.E./Allied Signal
(3) = Rolls Royce

Manuf./Type/ Config./B.P.R. = Manufacturer/Type/ Configuration/By–pass Ratio

Table 6.2 Weight and Performance Data for Turbojet and Turbofan Engines

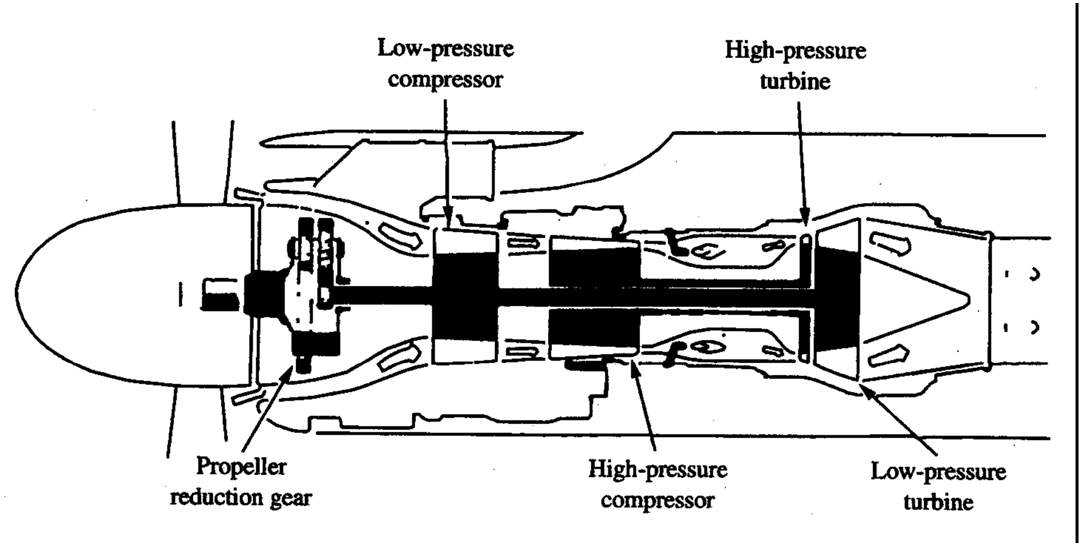
Manuf./Type/ Config./B.P.R.	Weight (lbs)	Thrust at take–off s.l.s. (lbs)	s.f.c. at take–off s.l.s. (lbs/hr/lbs)	Massflow take–off s.l.s. (lbs/sec)	Alt./ M	Thrust at altitude/M (lbs)	s.f.c. at altitude/M (lbs/hr/lbs)
(4)/TFE731–2/ TBF/2.66	743	3,500	???	113	40K/ 0.8	755 (max)	0.815
(4)/TFE731–5/ TBF/3.48	890	4,600	???	143	40K/ 0.8	1,000 (max)	0.760
(4)/ALF502L/ TBF/5.0	1,311	7,500	0.428	???	???	???	???
(5)/JT8D–219/ TBF/1.77	4,612	21,000	???	488	35K/ 0.8	5,250 (max)	0.737
(5)/PW4000/ TBF/4.85	9,400	56,000	???	1,705	35K/ 0.8	???	0.537
(5)/PW2000/ TBF/6.00	7,300	38,250	???	1,340	35K/ 0.8	???	0.563
(5)/PW300/ TBF/4.3	993	4,679	0.388	???	40K/ 0.8	1,155 (max)	0.681
(6)/CFM56–2A2/ TBF/6.0	4,820	24,000	???	817	35K/ 0.8	5,188 (max)	0.661
(7)/IAEV2500/ TBF/4.6	5,224	30,000	???	848	35K/ 0.8	5,752 (max)	0.575
(8)/Larzac 04/ TBF/1.13	639	2,966	0.710	63	35K/ 0.8	772 (max)	???
(9)/FJ44/ TBF/3.28	447	1,900	0.475	???	36K/ 0.7	506 (max. cont.)	0.758
(10)/Adour 871/ TBF/0.80	1,330	5,900	0.740	???	39K/ 0.8	???	0.955

Type: (4) = Allied Signal
(5) = Pratt & Whitney
(6) = CFM International (G.E./SNECMA)
(7) = International Aero Engines
(8) = Turbomeca
(9) = Williams/Rolls Royce
(10) = Rolls Royce/Turbomeca

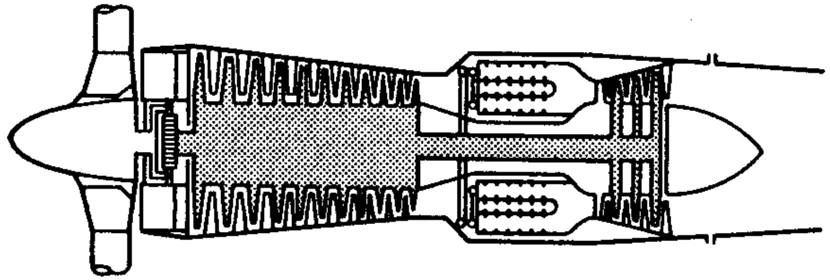
Manuf./Type/ Config./B.P.R. = Manufacturer/Type/ Configuration/By–pass Ratio

Caratteristiche propulsive

Turboelica



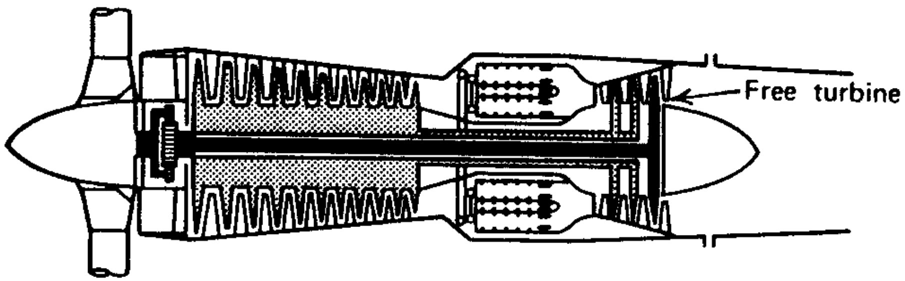
$$\Pi_d = \eta_p \Pi_a + T_j V_\infty$$



(d)

Equivalent Shaft Horsepower
(Pot all'albero equivalente)

$$\Pi_d = \eta_p \Pi_{ea} \qquad \eta_p \Pi_{ea} = \eta_p \Pi_a + T_j V_\infty$$



(e)

$$\Pi_{ea} = \Pi_a + \frac{T_j V_\infty}{\eta_p}$$

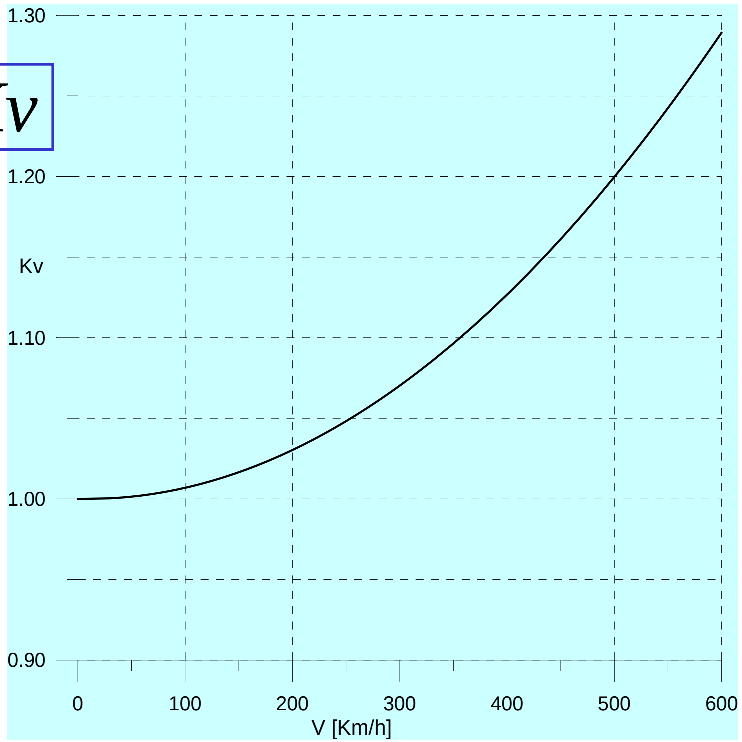
Caracteristiche propulsive <u>Turboelica</u>

EFFETTO RAM

Modello

$$\Pi_a = \Pi_{ao} \cdot \varphi \cdot \sigma \cdot Kv$$

Kv



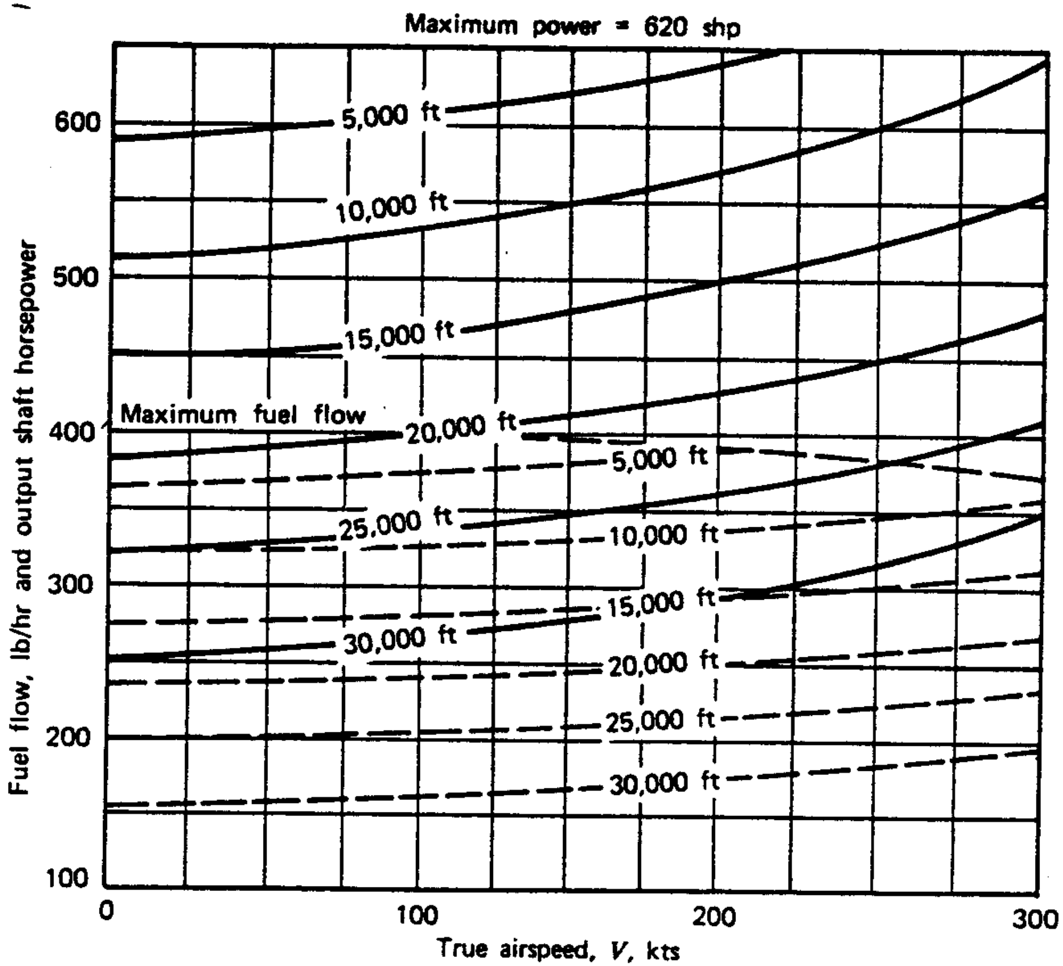
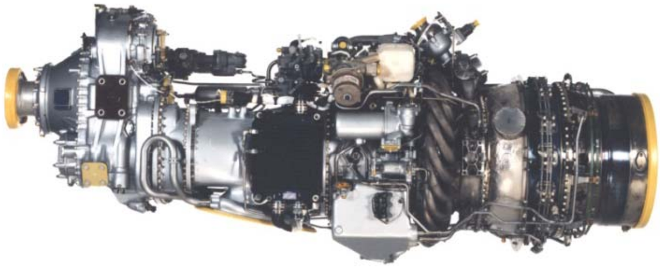


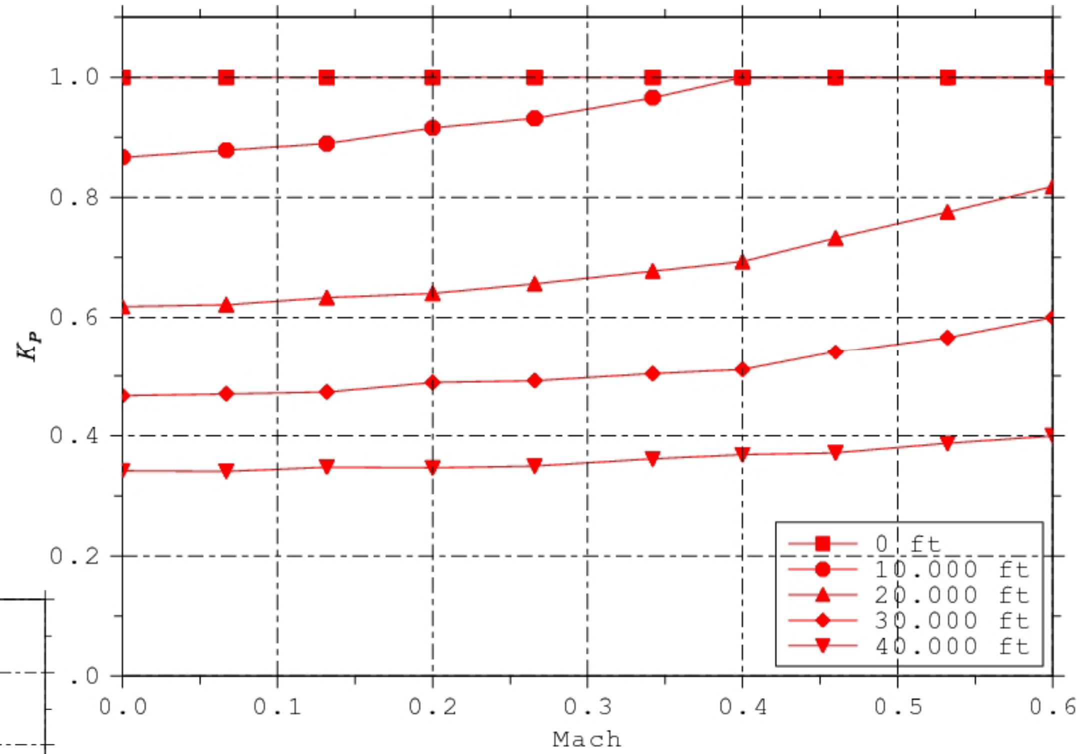
Figure 6.46a PT6A-27 maximum cruise performance. Prop speed—2200 rpm. (Courtesy, Pratt & Whitney of Canada.)

MODELLO Turboelica (più accurato)

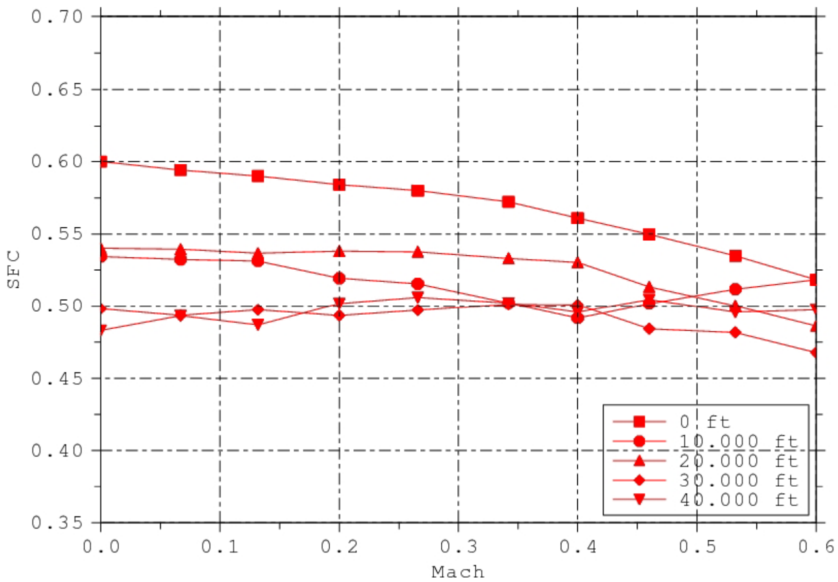
$$P = k_P(h, M) \cdot P_0$$



PW 123



Si nota l'effetto Mach (effetto RAM)
e l'effetto della quota.



SFCp (lb/(hp h))

SFC poco variabile con Mach

Caratteristiche propulsive

Turboelica

Consumo specifico

SFC=0.5-0.6 $\dfrac{\text{lb}}{\text{hp} \cdot \text{h}}$

Per i motori dell'ATR SFC=0.45

Nuovi motori => 0.35-0.40

Table 6.3 Weight and Performance Data for Turboprop Engines

Manufacturer/ Type	Weight (lbs)	ESHP/SHP/Prop RPM at maximum take–off setting, s.l.s.* (hp)	s.f.c. at take–off s.l.s. (lbs/hr/eshp)	ESHP/SHP/Prop RPM at maximum cruise setting, s.l.s.* (hp)	Massflow take–off s.l.s. (lbs/sec)
(1)/PT6A–11	328	528/500/2,200	0.647	528/500/2,200	???
(1)/PT6A–27	328	715/680/2,200	0.602	715/680/2,200	6.8
(1)/PT6A–34	331	783/750/2,200	0.595	783/750/2,200	???
(1)/PT6A–65B	481	1,174/1,100/1,700	0.536	1,174/1,100/1,700	9.5
(1)/PW118	861	1,892/1,800/1,300	0.498	1,593/1,513/1,300	???
(1)/PW123B	992	2,626/2,500/1,200	0.463	2,136/2,030/1,200	???
(1)/PW115	841	1,580/1,500/1,300	0.544	1,580/1,500/1,300	???
(2)/TPE331–1	336	705/665/???	0.605	690/650/???	6.2
(2)/TPE331–10	380	???/1,000/???	0.560	???	???
(3)/CT7–5	676	1,685/1,630/???	0.466	1,465/1,417/???	???
(3)/CT64–820–4	1,145	3,133/3,133/1,160	0.486	2,745/2,745/1,015	???
(4)/Dart RDa7 Mk535–2/TS1637	1,369	????/2,080/????	0.760	????/1,835/????	23.5
(5)/250–B17C	195	420/420/????	0.657	369/369/????	3.45
(5)/250–C30	240	650/650/????	0.592	557/557/????	5.6
(5)/T56–A–15	1,825	4,910/4,591/1,106	0.501	4,365/4,061/1,106	32.4

Type: (1) = Pratt & Whitney, Canada; (2) = Allied Signal; (3) = General Electric; (4) = Rolls Royce; (5) = Allison

* In calculating ESHP from SHP it is usually assumed, that 2.5 lbs of axial jet thrust is equivalent to 1 hp.

Caratteristiche propulsive