AEROSPACE ENGINE DATA

In this Appendix common to Aircraft propulsion and Space propulsion, data for thrust, weight, and specific fuel consumption, are presented for some different types of engines (Table 1), with some values of specific impulse and exit speed (Table 2), a plot of Mach number and specific impulse characteristic of different engine types (Fig. 1), and detailed characteristics of some modern turbofan engines, used in large airplanes (Table 3).

DATA FOR SOME CONCRETE AEROSPACE ENGINES AND THEIR CRAFT

Table 1. Thrust to weight ratio (F/W), for engines and their crafts, at take-off*, specific fuel consumption (TSFC), and initial and final mass of craft (intermediate values appear in [kN] when forces, and in tonnes [t] when masses).

Engine type	Engine thrust/weight	TSFC (g/s)/kN	Whole craft type	Whole craft thrust/weight	Whole craft mass, m_{ini}/m_{fin}
Trent 900	350/63=5.5	15.5	A380	4×350/5600=0.25	560/330=1.8
	cruise 90/63=1.4			cruise 4×90/5000=0.1	
CFM56-5A	110/23=4.8	16	A320	2×110/770=0.29	77/50=1.5
	cruise 25/23=1.1			cruise 2×25/700=0.1	
Flyer-I engine	0.6/0.8=0.8	2	Wright Flyer	0.6/3.5=0.17	0.35/0.35=1
Olympus 593	169/31=5.4	33.8	Concorde	4×169/1830=0.37	180/90=2
EJ200	90/10=9.0	23**	Eurofighter	2×90/220=0.8	22/11=2
Ariane 5 (1st)	6500/2800=2.3	240	Ariane V	2×6500/7700=1.7	750/(16+3)=40
SME (cryogen)	2300/32=72	230			
SRB (solid)	12500/5700=2.2	380	Space Shuttle	29 000 / 20 000=1.5	2000/(104+29)=15
Saturn V (1st)	34000/23000=1.5	390	Saturn V	34 000/30 000=1.1	3000/(118+13)=23

*Notice that at lift-off, neither Lift=Weight (really $L<W$ in aircraft because thrust contributes, and $L>W$ in rockets), nor drag equals thrust, but at cruise (on level flight) $L=W$ and $D=F$.
**TSFC is c_{sp}=49 (g/s)/kN with post-combustion.

DATA ON ROCKET-ENGINE TYPES AND COMPARISON WITH LARGE TURBOFANS

Table 2. Exhaust speed ($v_e = F/\dot{m}_p$)*, specific impulse ($I_{sp}=v_s/g$), typical thrust F range, delta-v, and thrust-to-weight ratio (F/W), for different rocket engines, and comparison with turbofans (Wiki).

Type of rocket engine	Exit speed v_e [m/s]	Specific impulse I_{sp} [s]	Typical thrust F [N]	Delta-v Δv [m/s]	Thrust / Weight
Large turbofan -cruise -take-off	 65 000** 65 000**	 6500 6500	 $(30..100)\cdot10^3$ $(100..400)\cdot10^3$	 - -	 1.4 5.5
Solid fuel	2500..3000	250..300	$10^3..10^7$	7000	2..100

Liquid monopropellant	2000..3000	200..300	$10^{-1}..10^{2}$	3000	2..100
Liquid bipropellant	3000..5000	300..450	$10^{-1}..10^{7}$	9000	2..100
Electrothermal (electric arc)	5000..15 000	1000..1500	$10^{-2}..10^{1}$	?	$<10^{-3}$
Electrodynamic		500..5000			$<10^{-4}$
Electrostatic ionic thruster	20 000..200 000	2000..50 000	$10^{-3}..10^{1}$	>100 000	$<10^{-4}$
Hall effect ionic thruster	10 000..50 000	2000..5000	$10^{-3}..10^{1}$	>100 000	
Electrospray ionic thruster	~10 000	~1000	$10^{-9}..10^{-3}$	?	

*Only exact for adapted nozzle, i.e. when $p_e=p_0$ in $F=\dot{m}_p v_e + A_e\left(p_e - p_0\right)$, but approximate in any case.

**For turbofan engines this is not the real exit speed, which is <300 m/s, but the equivalent or effective exit speed, $v_e = F/\dot{m}_p$, corresponding to the specific thrust per unit of propellant flow-rate, which with the approximation of neglecting the small pressure term explained above, coincides with the real exhaust speed in rocket engines.

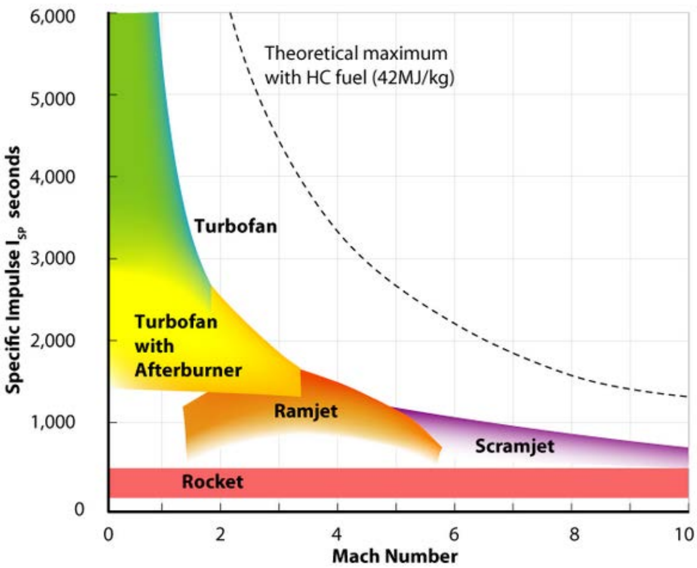

Fig. 1. Specific impulse, $I_{sp}\equiv F/\left(\dot{m}_f g\right)=1/(g c_{sp})$, of different engines types (c_{sp} is TSFC). (Wiki).

DATA ON SOME LARGE AIRLINER ENGINES

Table 1 presents characteristics of some modern turbofan engines, used in large airplanes. Airliners are commercial aircraft with more than 10 passengers, usually grouped by capacity as:

- <100 pax, low-haul or regional airliners, with cabin diameter *D*<3 m.
- 100..250 pax, medium-haul or narrow-body or single-aisle airliners, with cabin *D*=4..5 m. Typical models and motorization are: B727 (3×70 kN engines), B737 (2×90 kN engines), A320 (2×100 kN engines), MD80 (2×100 kN engines)...
- >250 pax, long-haul or wide-body or double aisle airliners (or jumbos), with cabin *D*=5..6 m. Typical models and motorization are: B747 (4×250 kN engines), DC10 (3×200 kN engines), A340 (4×150 kN engines), A330 (2×300 kN engines), B787 (2×150 kN engines), A380 (4×350 kN engines), A350 (2×200 kN engines).

Table 3. Characteristics of some modern airliner engines.

Engine→ Parameter↓	CFM56-5A1 A320 2x	PW4056 A330 2x	CFM56-5C A340 4x	Trent 900 A380 4x	GP7200 A380 4x
Thrust F_{max} [kN] ($F_{cruise} \approx F_{max}/4$) ρ/ρ	110 30	250	150 40	350 80	350 75
Bypass ratio, β	6.0	5.0	6.4	8.4	8.7
Pressure ratio, π	31.3	32	37	39	41
Fan pressure ratio, π	1.55	1.7			
Dry weight, W_e [kg]	2270	4300	3990	6300	6700
Length [m]	2.4	3.9	2.6	4.5	4.7
Fan diameter [m]	1.7	2.5	1.8	3	3.2
Fan-compressor stg.	1+3+9				
Turbine (HP-LP) stg.	1+4				
F_{max}/W_{eng}	4.8		3.8	5.5	5.2
$m_{f,\ takeoff}$ [kg/s]	1.7	2.85	2.3 (100 MW_{LHV})	5.5 (240 MW_{LHV})	
$m_{f,\ cruise}$ [kg/s]	0.4		0.5 (20 MW_{LHV})	1.1 (50 MW_{LHV})	
$P_{prop,\ takeoff}$ [W]=Fv	110·70=8 MW		150·70=10 MW	350·70=24 MW	
$P_{prop,\ cruise}$ [W]=Fv	25·250=6 MW		35·250=9 MW	80·250=20 MW	
$m_{air,\ takeoff}$ [kg/s]	426	775	500	1200	1350
$m_{air\ cruise}$ [kg/s]					
T_{max} [K]	1540	1510		1800	
EGT_{max} [K]	1150				1250
Spool speeds [rpm]	N_1=5 100 N_2=15 200	N_1=4 000 N_2=10 500		N_1=2 700 N_2=8 000 N_3=12 500	N_1=3 000 N_2=13 000
$Mach_{cruise}$	0.80	0.83	0.80	0.83	
TSFC [(g/s)/kN]*	16		15.4	15.5	15.6
Unit price		5.5 M€			10 M€

*TSFC at cruise; take-off values are some 10 % lower.

Data on other aircraft engines and manufacturers

The turbofan engine market is dominated by General Electric (GE), Rolls-Royce (RR), CFM (a joint venture of Snecma and GE), and Pratt & Whitney (PW), in order of market share. There are other joint ventures, like International Aero Engines (IAE) by RR, PW, and MTU, specializing in engines for the A320 family, or Engine Alliance (EA) by PW and GE, specializing in engines for the A380. Williams International is the world leader in smaller business jet turbofans.

Rolls Royce

Trent XWB, with up to F=400 kN thrust, powers (2×) the new A350 XWB (extra wide body). This is a three-shaft architecture, with a 3 m in diameter 22-blade fan (LP), the 8-stage intermediate pressure compressor (IP), and the 6-stage high pressure compressor (HP), driven by separate turbines through coaxial shafts. It has an annular combustor with 20-off fuel spray nozzles, and single stage HP turbine, 2-stage IP turbine, and 6-stage LP turbine. The LP and IP assemblies rotate in a counter-clockwise direction; the HP assembly rotates clockwise, when viewed from the rear of the engine; speeds are N_1=2700 rpm, N_2=8200 rmp, and N_3=12600 rpm. Total length is 5.8 m, and dry mass m=7500 kg (thrust to weight ratio F/W=5.3). Maximum temperature TET=1800 K (1100 K at LP-turbine entry), overall pressure ratio OPR=50, bypass ratio Λ=9.6, and global air flow rate $\dot{m}_a$ =1500 kg/s. Price: 30 M€.

Trent 900, four units used in A380 (the largest airliner, with >500 pax). Rolls Royce is leader, with ITP (Industria de Turbo Propulsores) contributing the low pressure turbine driving the fan, Hamilton Sundstrand (electronic engine controls), Avio S.p.A. (gearbox module), Marubeni Corporation (engine components), Volvo Aero (intermediate compressor case), Goodrich Corporation (fan casings and sensors), and Honeywell (pneumatic systems). Trent 900 has three spools, being based on RR-RB211 (the first 3-spool engine), a 24 hollow-titanium swept-blade fan, an eight-stage IP compressor, a six-stage HP compressor, single-stage HP turbine, single-stage IP turbine, and five-stage LP turbine (the HPC-HPT-shaft is contra-rotating). The burner is annular with 20 injectors. The Trent 900 engines used on the Airbus A380 are designed to fit into a Boeing 747-400F freighter for transport. The Trent 1000 engine is being developed for the Boeing 787 Dreamliner.

RR Olympus 593 powered Concorde (two engines),which was the only commercial supersonic airliner (M=2). It was a pure turbojet with afterburner, with a take-off thrust of F_{TO}=180 kN, and air flow rate of $\dot{m}_{air}$ =190 kg/s; at cruise, F_{cruise}=50 kN, pressure ratio of π_{23}=11, and TSFC=34 (g/s)/kN.

Pratt & Whitney

GP7200, four units used in A380, from Engine Alliance (PW & GE), based on PW4000 and GE90. Two spools. Hollow-titanium 24 swept wide-chord hollow titanium fan blades, with 8.7:1 by-pass ratio; five-stage low-pressure axial compressor; nine-stage high-pressure axial compressor, low-emissions single annular combustor, two-stage high pressure turbine, six-stage low-pressure turbine, boltless architecture, single crystal blades, split blade cooling and thermal barrier coatings.

PW4000 (2 units in A330, for 250..350 pax; 4 units in B747-400, for >400 pax), bypass ratio 5:1, fan diameter D_f=2.5 m, pressure ratio π_{fan}=1.7, π_{total}=32, 4 m long engine, take-off thrust 300 kN (90 kN at 12 km altitude), LP-shaft at 4000 rpm with 4 turbine-stages, HP-shaft at 10 000 rpm with 2 turbine-stages. Only 12% of total thrust is due to primary exhaust. Overall engine efficiency is η=0.35.

PW1000G family (from 2015) is intended for regional airline turboprops, with F=50..200 kN, bypass β=12, fan diameter D_f=2.1 m, with a gear stage to slow fan spinning, decreasing noise by 30 %.

Old Pratt & Whitney JT8D engine (used in B727, DC-9, MD-80, B737...), had a mass of 1500 kg, F_{TO}=100 kN, bypass ratio β=0.96, fan diameter D_f=1.25 m, $\dot{m}_{air}$ =150 kg/s, π_{total}=16, TSFC=21 (g/s)/kN. There were nine combustion chambers positioned in a can-annular arrangement, each with three air inlet hole sizes: the smallest was for cooling, the medium for burning, and the large for forming an air blanket.

CFM International

CFM International is a joint venture between GE Aviation USA and Snecma (France), formed in 1974 to build and support the CFM56 series of jet engines. The names of CFM International and the CFM56 product line are derived from the two parent companies' commercial engine designations: GE's CF6 and Snecma's M56. Up to 2011, more than 23 000 engines were produced. GE is responsible for the high pressure compressor, combustor and high pressure turbine, while Snecma is responsible for the fan, low pressure turbine, the gearbox, and the exhaust.

The CFM56 successor, the CFM Leap engine (2x for the new A320neo) has 150 kN, BPR=11:1, OPR=40:1, D_{fan}=2 m, compressor stages (fan/LPC/HPC) of 1:3:10, turbine stages (HPT/LPT) 2:7.

MTU Aero Engines
MTU is a German aircraft engine manufacturer and international partner to PW (e.g. in PW4000), GE-EA (e.g. GP7200), Eurojet (EJ200), and Europrop (TP400).

Europrop International GmbH (EPI) is a joint venture among four European aero-engine manufacturers (MTU, Snecma, Rolls-Royce, and ITP) with just one product: the Europrop TP400-D6 turboprop of 8200 kW, developed for the Airbus Military A400M aircraft (MTOM=141 000 kg). The TP400 is the most powerful single-rotation turboprop (and the third most powerful turboprop after the contra-rotating Kuznetsov NK-12 and Progress D-27). The engine has a twin-spool gas generator, with a third coaxial shaft connecting the low pressure power turbine to the 5.3 m diameter propeller (with eight blades made of composite), via an offset reduction gearbox. It has m_{eng}=1900 kg, $\dot{W}_{shaft}/m_{eng}$ =4.4 kW/kg, OPR=25, TET=1500 K, with a prop-torque of 100 kN·m and a BSFC=0.24 kg/kWh (the engine efficiency is $\eta_e=1/(h_{LHV}\cdot BSFC)=0.35$, and a fuel consumption of $\dot{m}_f$ =0.54 kg/s at maximum power. The IP compressor has five stages, and the HP compressor six. Both the HP and IP turbines are single stage, and the LP power turbine has three stages.

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