Jet Engines-Powering Modern Airplanes

Jim Rauf

Jet Engines—the Power of Flight

- Introduction
- Aircraft Propulsion
- Wright brothers to WW II-piston engines/propellers
- WW II and inventions of the jet engine
- Jet engines-how they work
- Post war jet engine development-led by the military
- The first commercial jet engine powered aircraft-the Comet
- 707 and JT3D change the airline industry
- Concorde SST
- Development of increased jet engine efficiency
- Jet engine configurations
- Reliability-ETOPS
- Some current jet engines-military and commercial
- Some next generation jet engines-military and commercial
- Future jet engine concepts

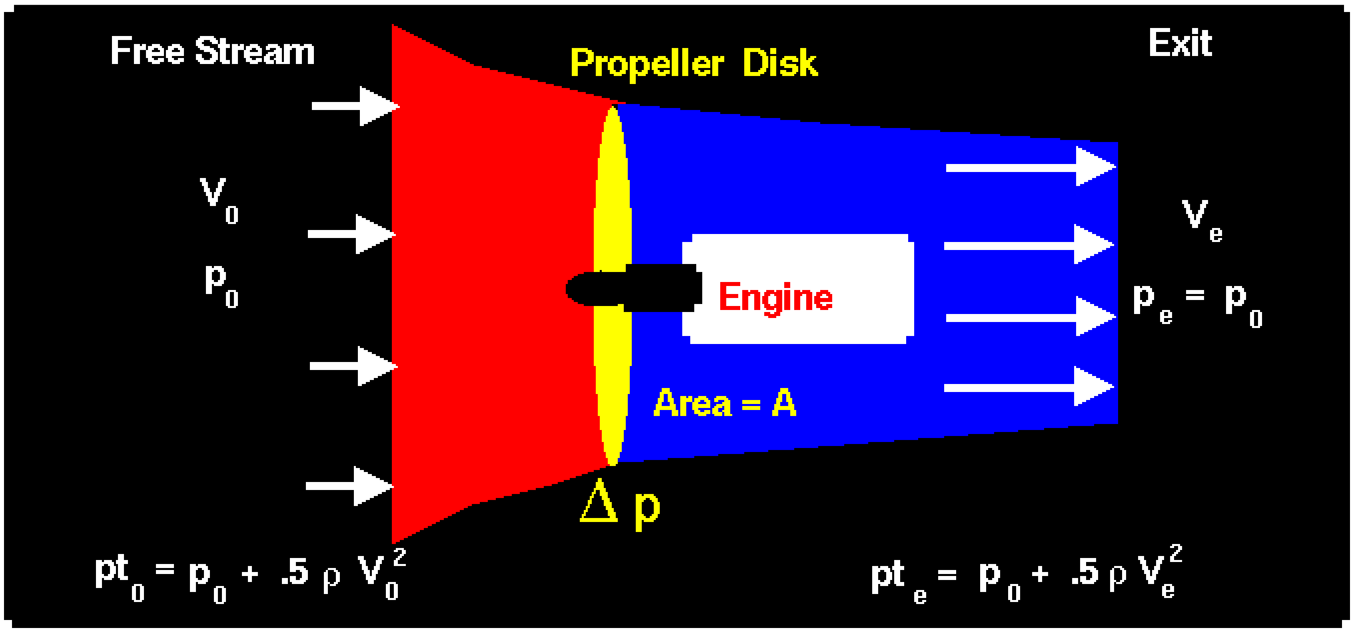
Introduction-Newton's Laws of Motion

1st "Every object persists in its state of rest or uniform motion in a straight line unless it is compelled to change that state by forces impressed on it."

2nd "Force is equal to the change in momentum (mV) per change in time.

3rd "For every action, there is an equal and opposite re-action."

Aircraft Propulsion-Propeller



ρ = density
p = pressure
V = velocity

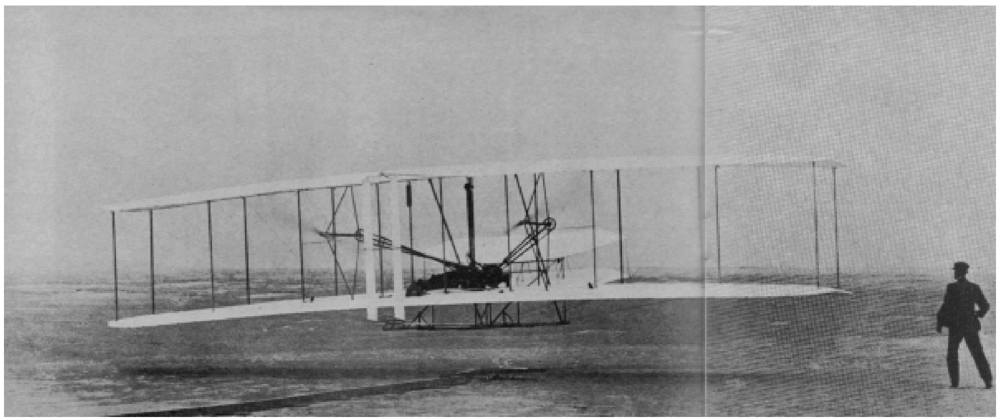
$$\text{Thrust} = F = A\,\Delta p$$

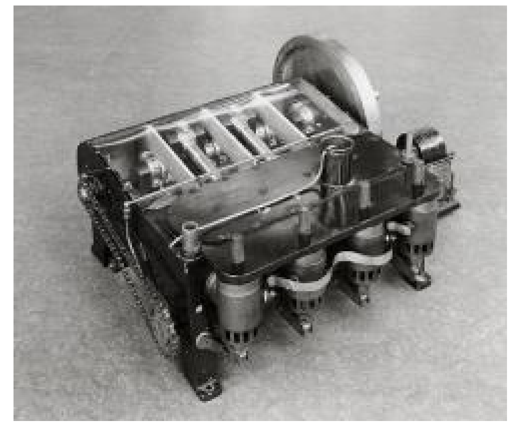
$$\Delta p = pt_e - pt_0 \qquad \Delta p = .5\rho\,(V_e^2 - V_0^2)$$

$$F = .5\rho A\,(V_e^2 - V_0^2)$$

Wright brothers to WW II-piston engines/propellers

- In 1903, the **Wright Brothers** flew, *The Flyer*, with a 12 horse power four cylinder gasoline fueled piston engine
- From 1903, the year of the Wright Brothers first flight, to the late 1930s the gasoline fueled reciprocating internal-combustion engine with a propeller was the sole means used to propel aircraft



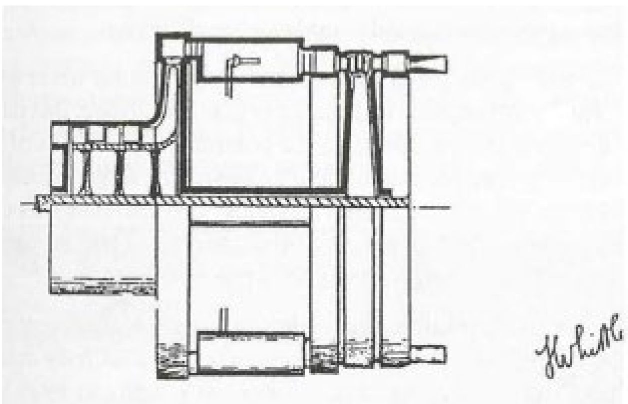



P51 Mustang 1942


DC3 airline introduction 1936

Jet Engines-Early History

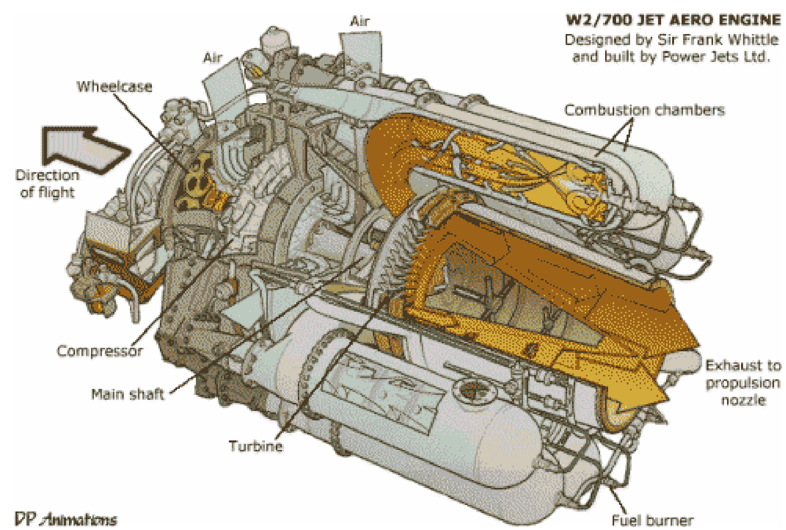
- **Frank Whittle** of the UK and **Hans von Ohain** of Germany are credited with inventing the jet engine
- Whittle's 1930 patent shows a compressor with two axial stages followed by a centrifugal stage, an axial cannular combustor with fuel nozzles and a two stage axial turbine.



- Whittle had great difficulty in getting support to pursue his revolutionary invention.
- He was able to successfully test the kerosene fueled W.1 in 1937, the World's first jet engine

Jet Engines-Early History

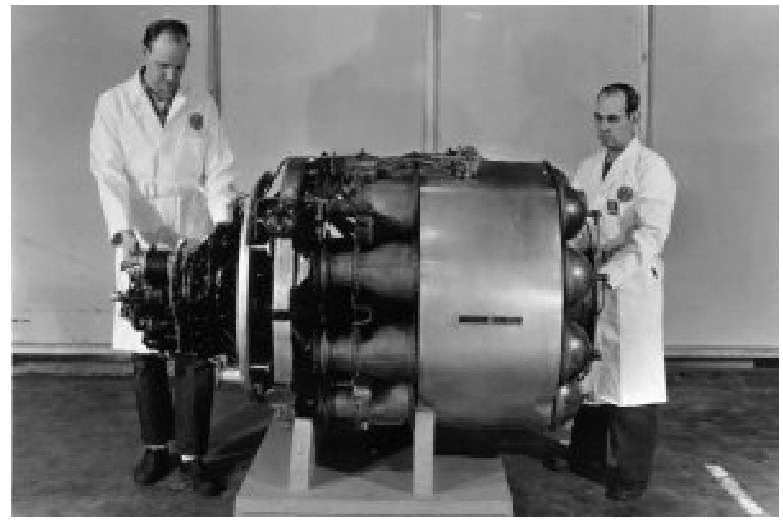
- The Whittle W1 engine was the first British jet engine to fly powering the Gloster E.28/39 on its maiden flight on May 15, 1941
- The improved W2 engine model incorporated a double sided centrifugal compressor, an axial reversed flow cannular combustor, a single stage axial turbine and produced a thrust of 1560 lb.
- The exhaust gas energy or specific power reached approximately 50 hp for each lb/sec of airflow.
- The Whittle W2 engine was renamed the Welland after the engine became the UK's first production jet engine



Jet Engines-Early History

- The W.1X and drawings of the W.2B production engine were delivered to the General Electric Company on October 1, 1941
- GE's improved and uprated version, the IA, powered the first U.S. jet aircraft, the Bell XP-59A Airacomet on October 2, 1942
- This effort resulted in producing the GE I-A, the first American jet engine ,a copy of the Whittle W.2B engine.

The Bell XP-59A Airacomet first flew on 1 October 1942, powered by two GE I-A engines.

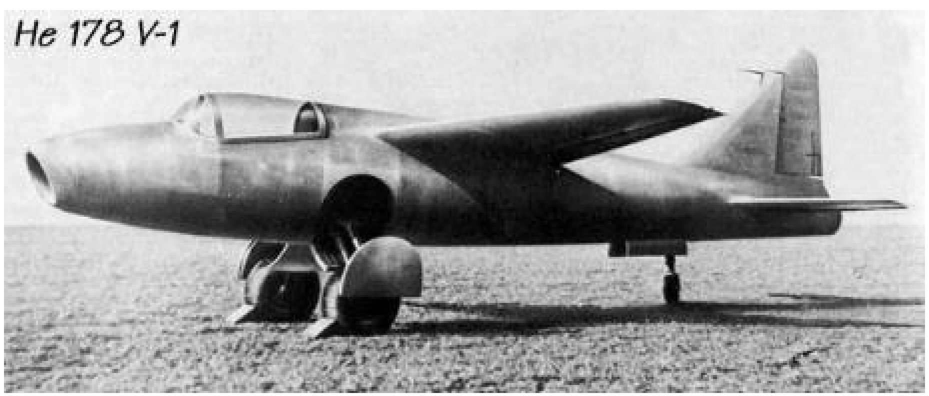


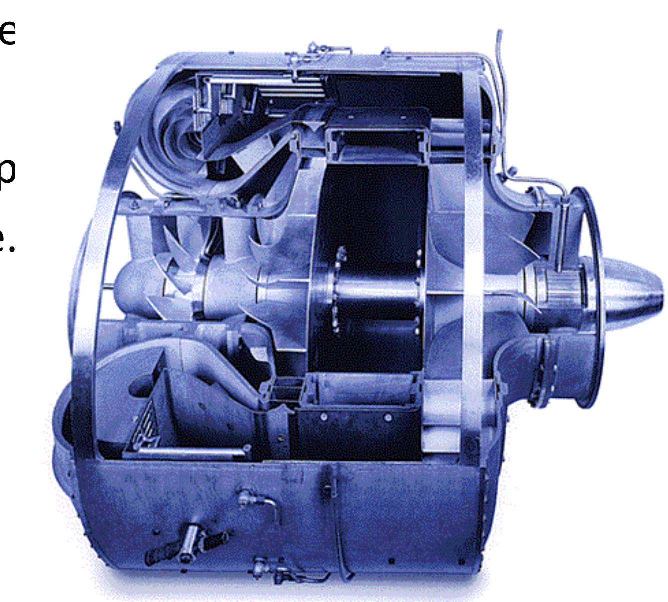
GE I-A engine

Whittle W2 Engine

Jet Engines-Early History

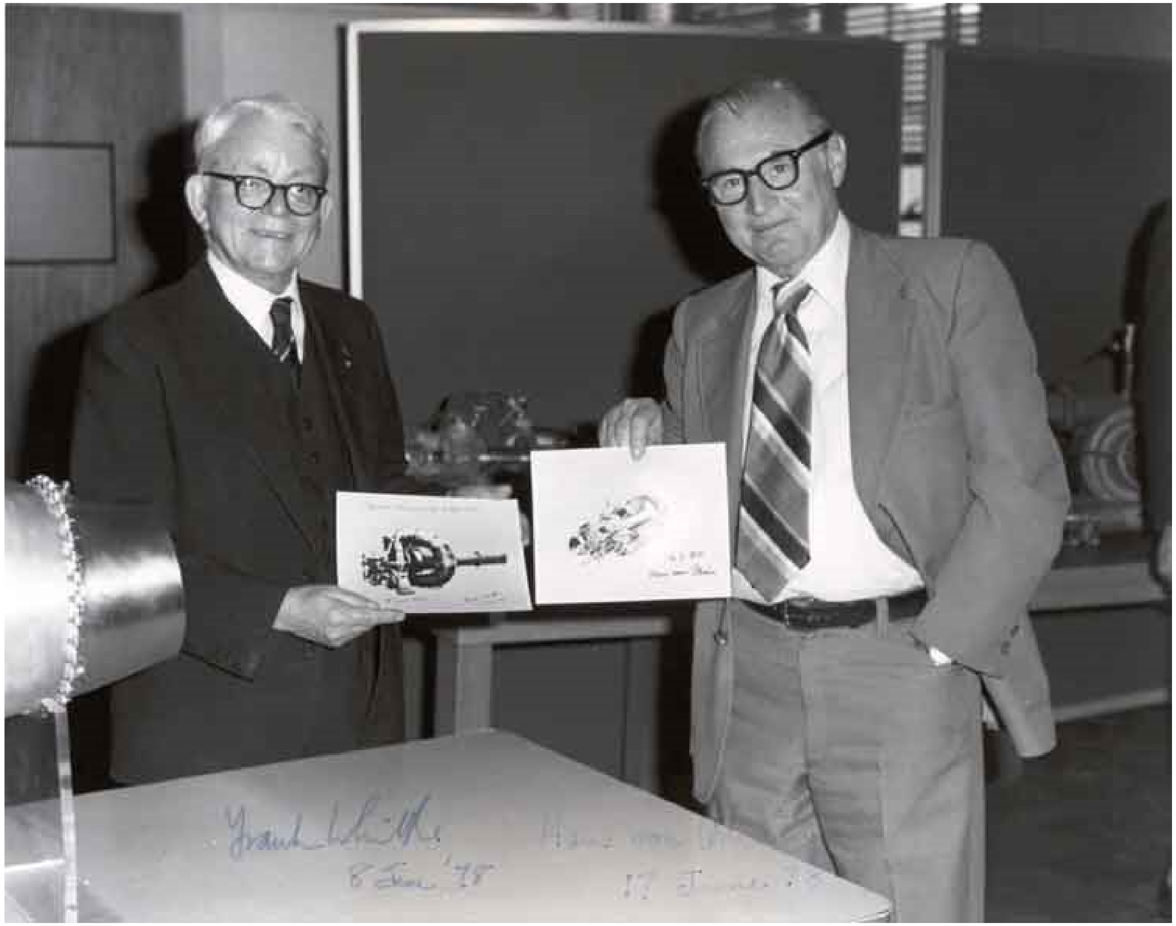
- Unknown to the Allies, Hans von Ohain, an engineering student, with continuing support from the Heinkel the aircraft company, had developed a petrol fueled jet engine by March 1938, shortly after Whittle.
- This resulted in the first jet powered flight in the summer of 1939 on the eve of World War II.
- The von Ohain engine had an axial flow inducer ahead of the centrifugal impeller stage, a reverse flow combustor and a radial inflow turbine.
- The exhaust gas energy was approximately 50 hp for each lb/sec of inlet airflow, similar to Whittle.





Hans von Ohain's jet engine He S 3B

Jet Engine Inventors

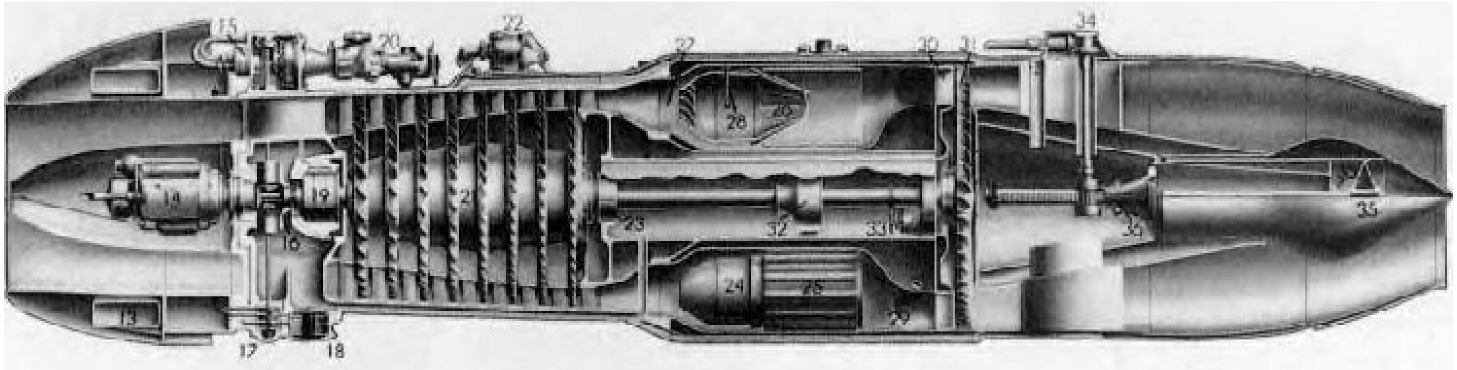


Frank Whittle and Hans von Ohain ~ 1978

Jet Engines-Early History

- During World War II, the Junkers Jumo engine powering the Messerschmitt Me 262 jet aircraft was the first jet fighter in service- April 1944
- The Jumo engines for this aircraft were mounted in nacelles rather than internal to the aircraft fuselage
- It used an axial flow compressor, axial flow turbine and straight through flow combustor to reduce frontal area

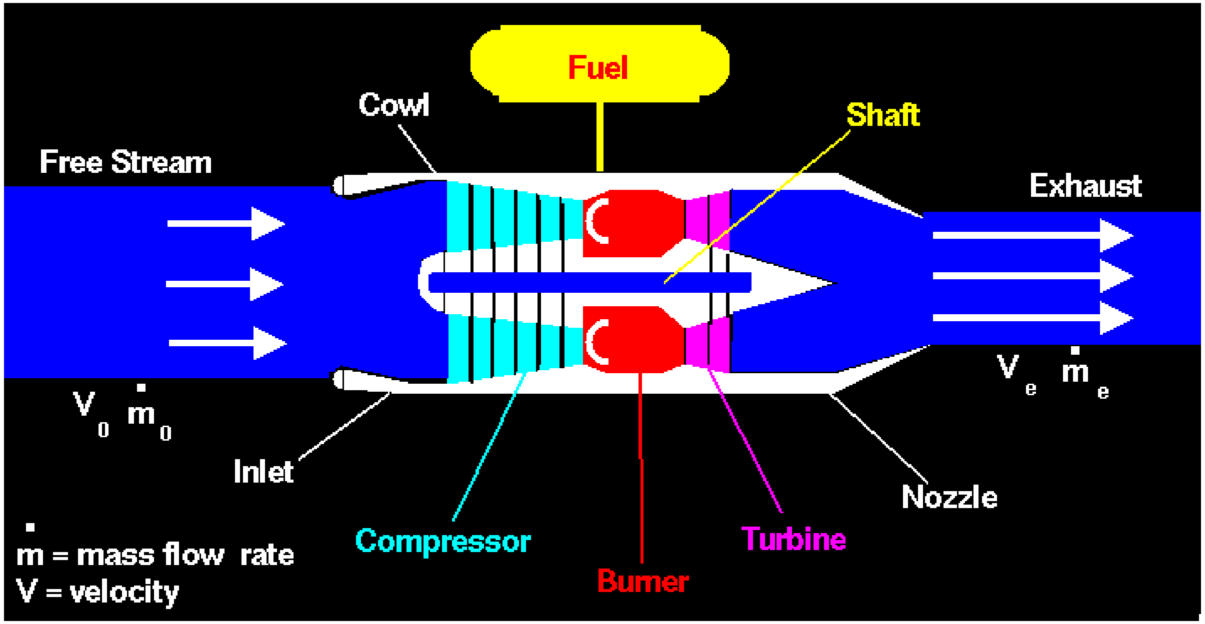
- This early configuration became a forerunner of how future jet engines would be configured relative to overall design arrangement.



Junkers Jumo 004 Turbojet

Jet Engines-How They Work

- A jet engine is an air breathing reaction engine that generates thrust by discharging a fast moving jet of gas
  - Jet engine are a special case of gas turbine engines
- The thrust is the result of Newton's 2nd and 3rd laws of motion

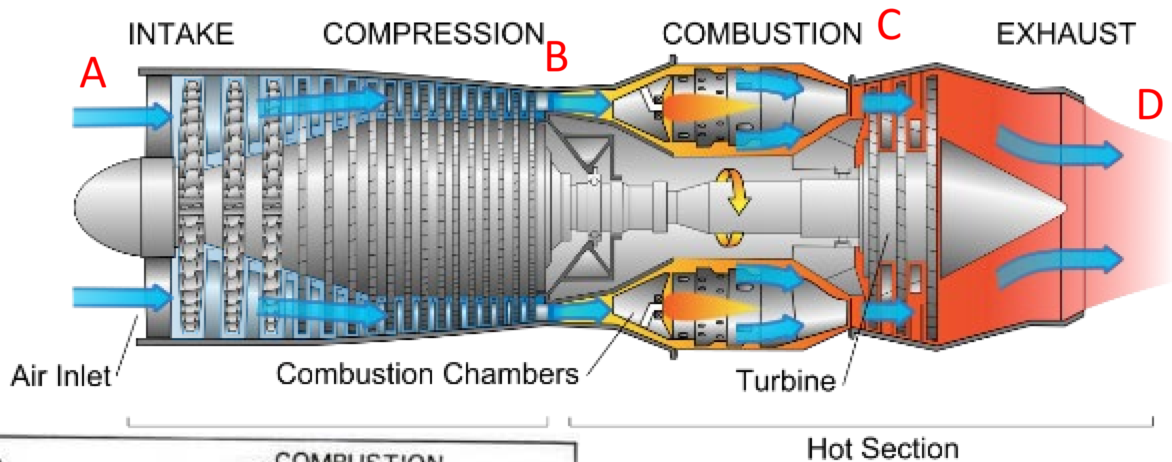


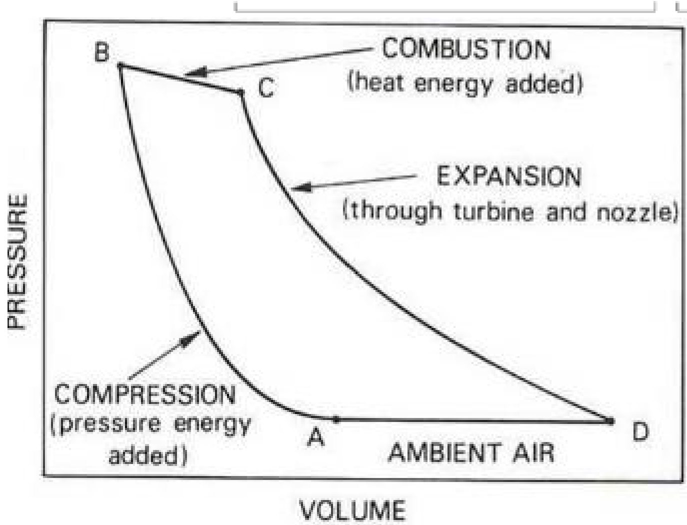
$$\text{Thrust} = F = \dot{m}_e V_e - \dot{m}_0 V_0$$

Jet Engines-How They Work

- There are several configurations of jet engines but they all have the Brayton cycle as the basis of their thermodynamic operation:
  - Turbojet
  - Turbojet with afterburner (augmenter)-military applications
  - Turbofan
  - Turbofan with afterburner (augmenter)-military applications
  - High bypass turbofan
  - Propfan
- Helicopters and propeller driven aircraft are powered by aircraft gas turbines:
  - Turboshaft engines-power rotor gearbox
  - Turboprop engines-drive propeller thru a gearbox

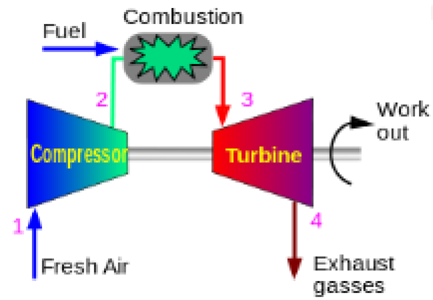
Jet Engines-How They Work

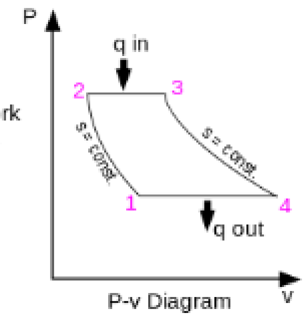


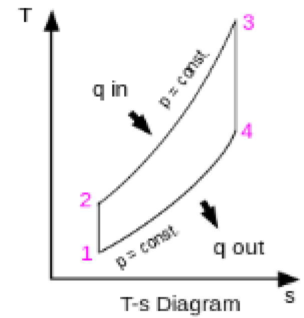


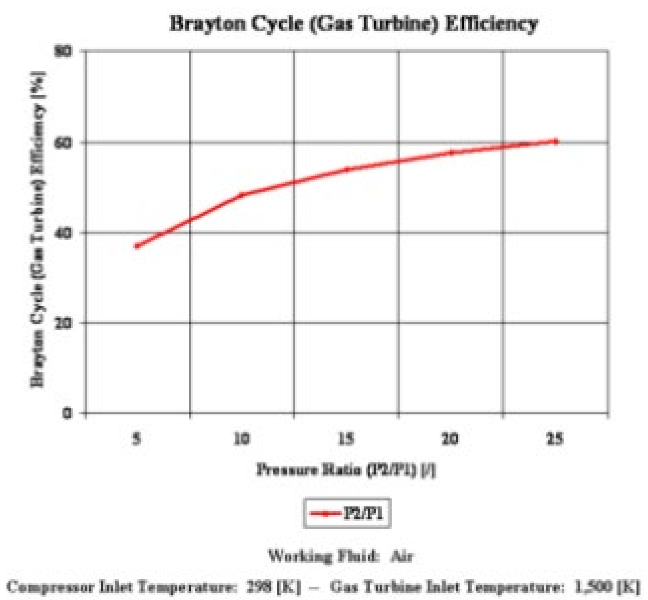
Energy in the hot gas "left over" after driving the compressor is converted into jet velocity that produces thrust

Jet Engines-How They Work-Efficiencies

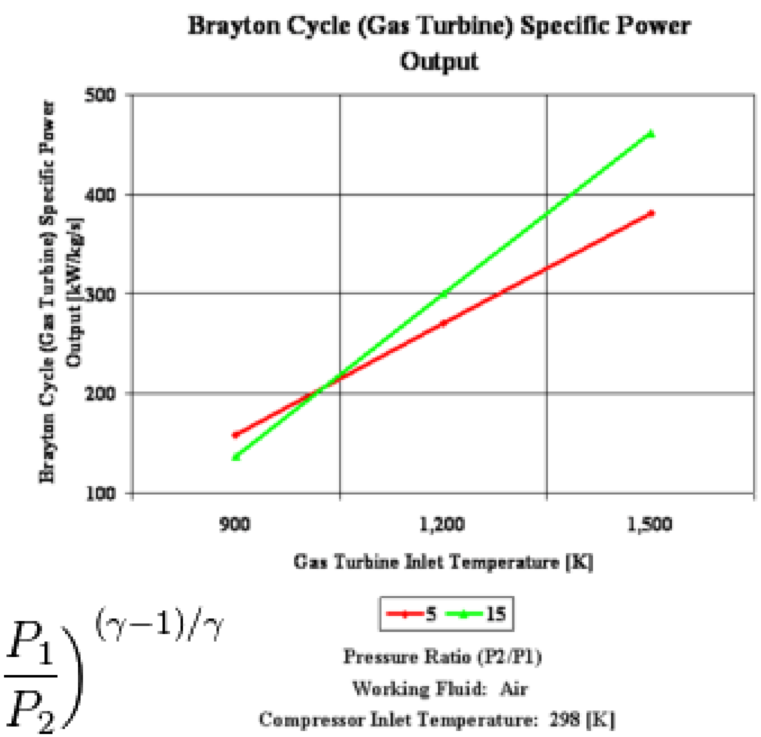






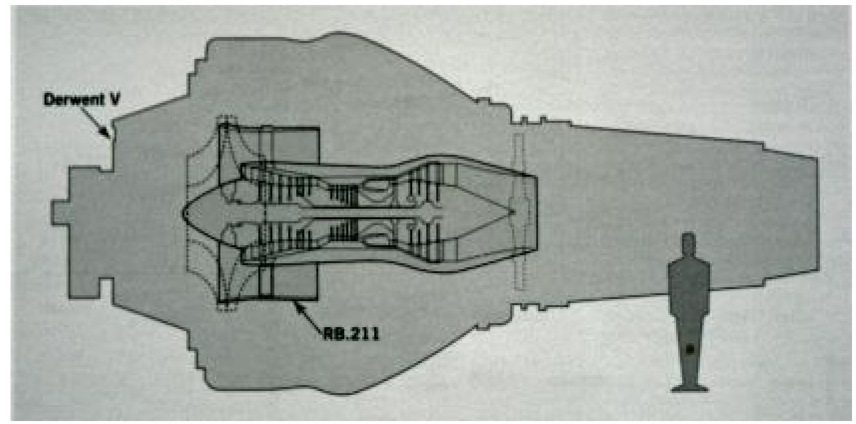


$$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{(\gamma-1)/\gamma}$$



Jet Engines-How They Work

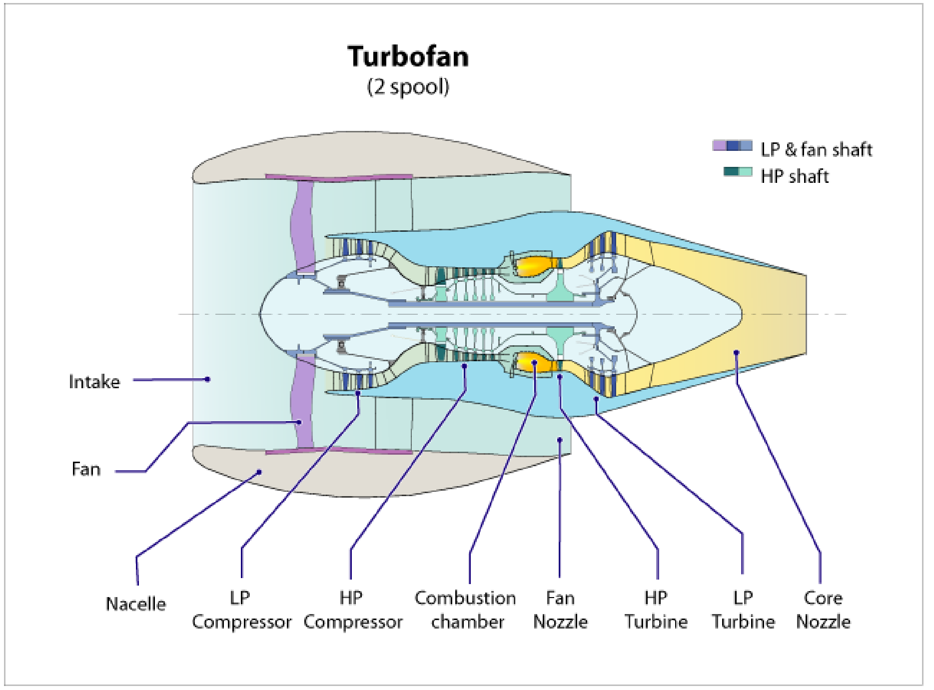
- **High thermal efficiency** depends on a high value of the temperature, a function of the pressure of the air at the exit of the compressor
- **High specific power** (higher power from a smaller engine) depends on a high value of the temperature at the turbine inlet
- The goal of jet engine designers over the years is to increase both the compressor pressure ratio and the turbine inlet temperature
  - Increased engine thermal efficiency
  - Smaller, lighter engines



RR Derwent V (1945) versus RR RB211 (1968) scaled to 50,000 lb thrust

Jet Engines-How They Work

- Major components
- Inlet
  - Sub sonic
  - Supersonic
- Compressor
  - Centrifugal
  - Axial
- Combustor
- Turbine
  - High pressure
  - Low pressure
- Exhaust
  - Nozzle
  - Afterburner
- Engine control system

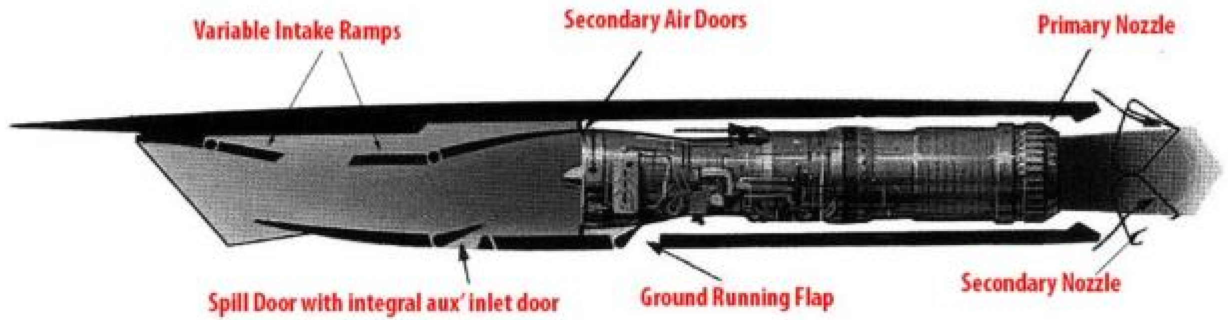


Jet Engines-How They Work-Inlet

- For **subsonic** aircraft, the inlet is a duct which is required to ensure smooth airflow into the engine despite air approaching the inlet from directions other than straight ahead
- This occurs on the ground from cross winds and in flight with aircraft pitch and yaw motions
- Air enters the compressor at about half the speed of sound
- Thus the internal profile of the inlet has to accommodate both accelerating and diffusing flow without undue losses

Jet Engines-How They Work-Inlet

- For **supersonic** aircraft, the inlet has features such as cones and ramps to produce the most efficient series of shockwaves which form when supersonic flow slows down.
- The air slows down from the flight speed to subsonic velocity through the shockwaves, then to about half the speed of sound at the compressor through the subsonic part of the inlet.
- The particular system of shockwaves is chosen, with regard to many constraints such as cost and operational needs, to minimize losses which in turn maximizes the pressure recovery at the compressor



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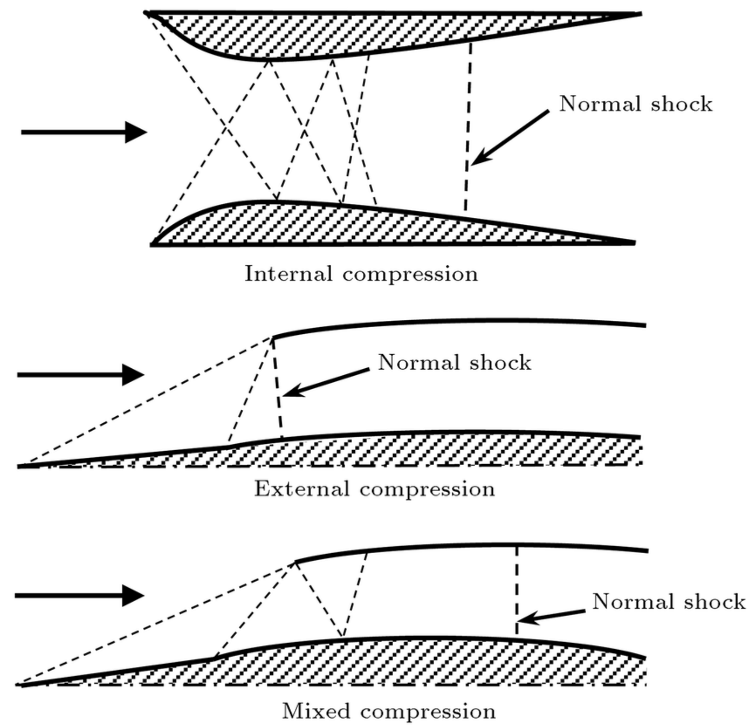
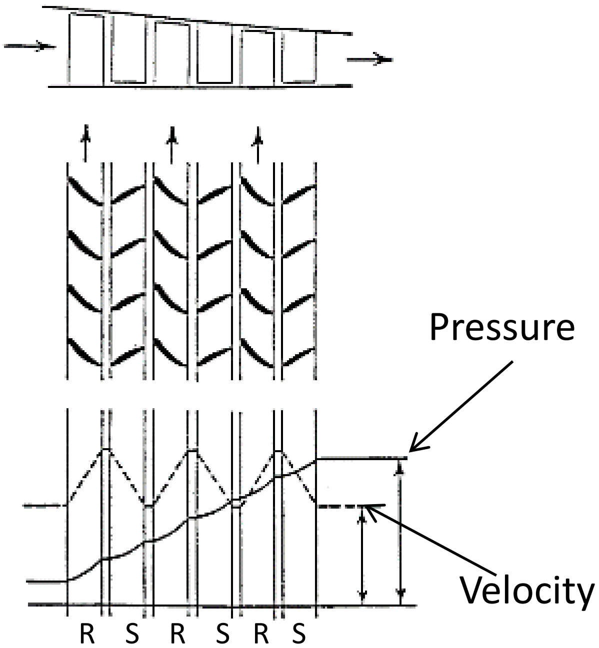


Jet Engines-How They Work-Compressor

- In a **centrifugal compressor**, energy is transferred from a set of rotating impeller blades to the gas
- The designation "centrifugal" implies that the gas flow is radial, and the energy transfer is caused from a change in the centrifugal forces acting on the gas
- Centrifugal compressors deliver high flow capacity per unit of installed space
  - Used in helicopter engines

Jet Engines-How They Work-Compressor

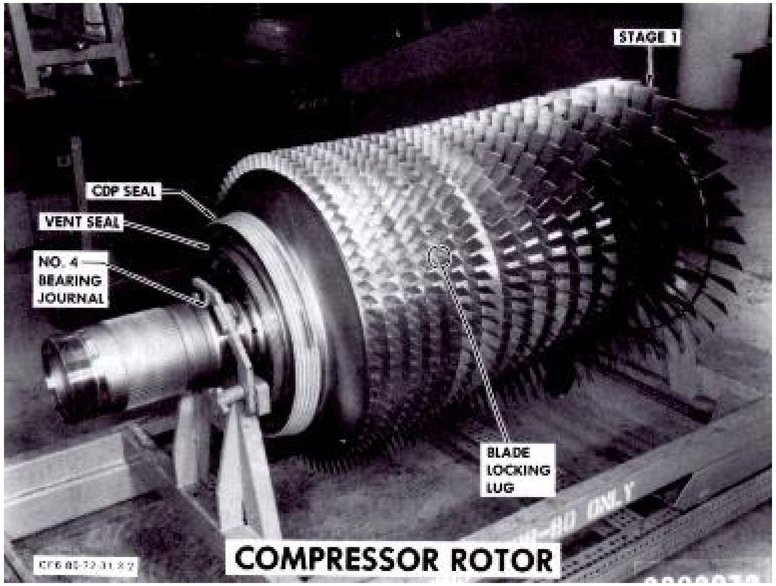
- **Axial compressors** consist of sequential sets of airfoils, blades, which are on a rotating structure, and other airfoils, vanes, which are attached to a stationary structure
- The rotating blades impart kinetic energy to the air, by increasing its tangential momentum
- In the rotating blades, and in the stationary vanes, this kinetic energy is converted to a static pressure rise by the diffusion process
- This process occurs in a single stage, and may be repeated in succeeding stages, until the goal pressure rise is realized



Jet Engines-How They Work-Compressor

- Compressor design is made difficult by the nature of the diffusion process
- The pressure rise from the diffusion opposes the flow of air
- At low rotating speeds, the compressor cannot put as much energy into the air as it can at high speeds- it cannot compress the air as much
  - The fixed and relatively small area of the rear stages limits the amount of air which can be pumped at the low pressures which can be achieved
  - At low speeds (off design) the front stages are back-pressured as they work to force the low-density air through the rear stages
- Variable geometry, usually in the front stages of a compressor, serves to limit the air flow, and to maintain acceptable efficiency levels, during low speed operation
  - Variable stator vanes- first used on the J79 turbojet–invented by Gerhard Neumann of GE are now used by most engine manufacturers
- Another way to divert the excess air at low speeds to reduce the back pressure on the front stages is to use bleed valves
  - This “wastes” the energy that was used to compress the bleed air

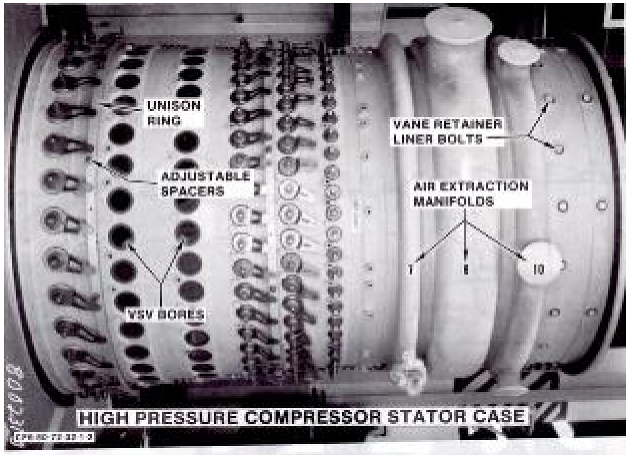
Jet Engines-How They Work-Compressor

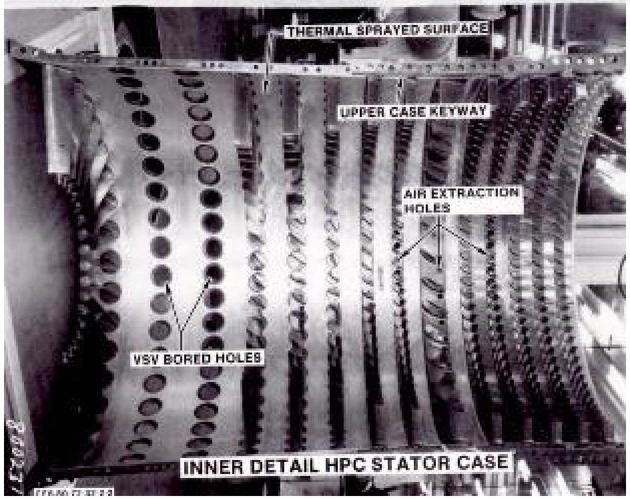


HPC

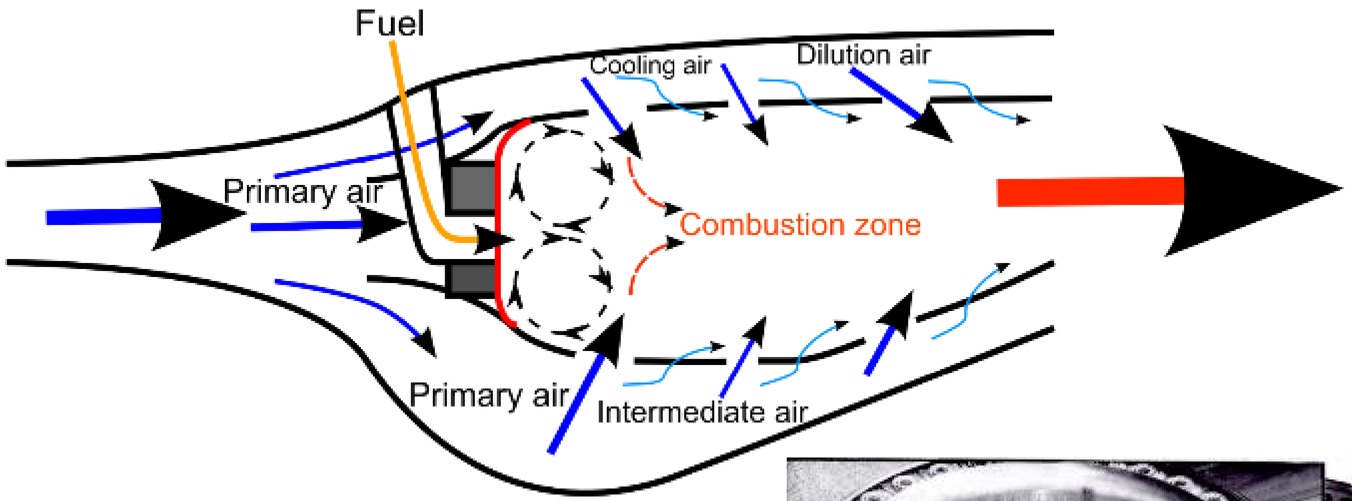
Air Flow in	264/116	pps
Pressure in	33/13	psia
Temperature in	252/133	F
No. Stages		14
No.blades	807	
Blade height	7.45-1.25	in
N2	10550/9768	
"g" field	50,000	
Air Flow out	257/113	Lb/sec
Pressure out	433/178	psia
Temperature out	1083/868	F

CF6-80A3 HP Compressor





Jet Engines-How They Work-Combustor

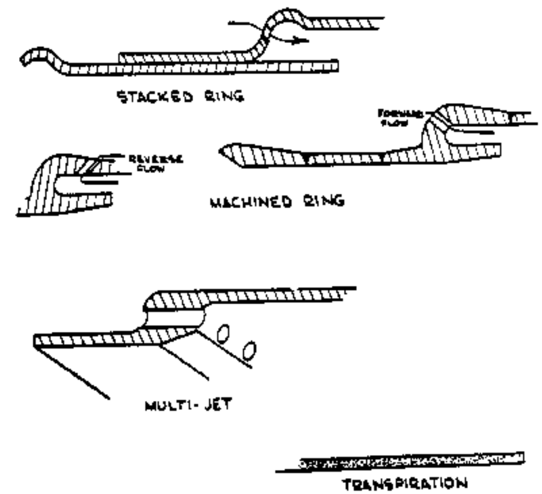


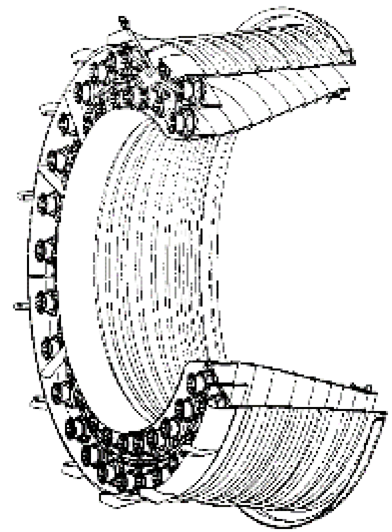
CF6-80A combustor

Air Flow in	257/113	Lb/sec
Pressure in	433/178	psia
Temperature in	1083/868	F
Fuel flow	17750/6696	Lb/hr
Air Flow out	250/110	Lb/sec
Pressure out	412/170	psia
Temperature out	258/1943	F

Jet Engines-How They Work-Combustor

- Since flame fronts generally travel at just Mach 0.05 and air flow out of the compressor is at a higher speed the air must be slowed in a diffuser before it enters the combustor
- Since the turbine materials cannot withstand stoichiometric temperatures (a complete combustion of fuel and air), some of the compressor air is used to quench the exit temperature of the combustor to an acceptable level
- Some of the air not used in the combustion process is used to cool the metal combustor liner



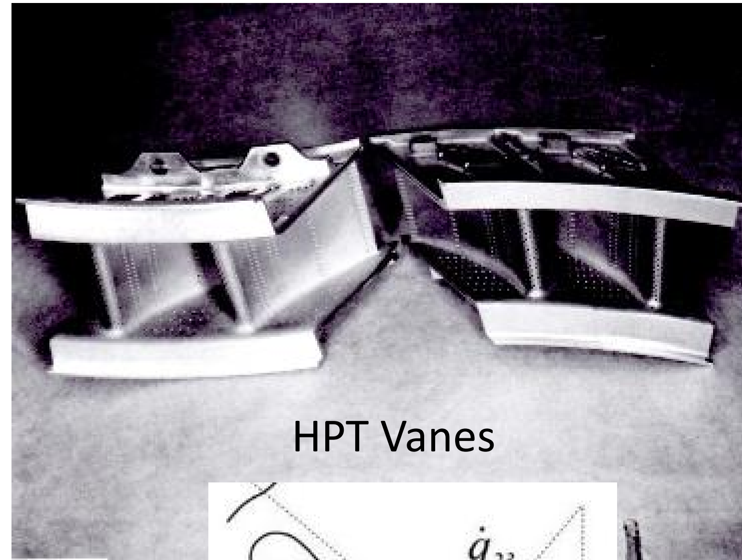


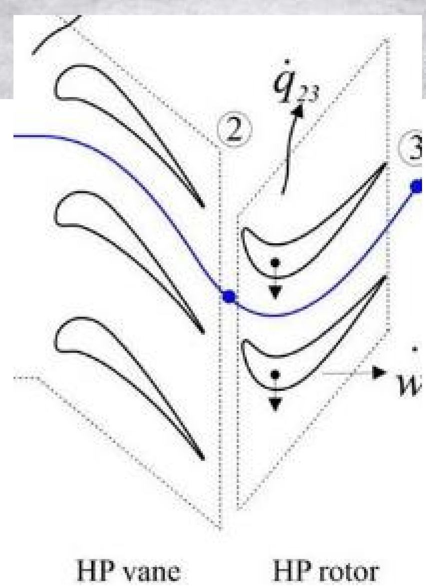
Jet Engines-How They Work-HP Turbine

- The **high pressure turbine** is a series of bladed disks that act like a windmill, extracting energy from the hot gases leaving the combustor
- The energy is used to drive the compressor
- Energy not extracted from the hot gas is available to provide thrust
- High pressure turbines are usually one or two stages depending on how much energy is needed to drive the compressor
- Cooling air, bled from the compressor, may be used to cool the turbine blades, vanes and disks to allow higher turbine entry gas temperatures
  - The higher the turbine inlet temperature, the higher the specific power of the engine

Jet Engines-How They Work-HP Turbine

- The HP turbine is the opposite of the HP compressor in that the pressure and temperature decrease as the hot gas flows thru the turbine
- The turbine is taking energy out of the gas-to power the compressor - whereas the compressor is putting energy into the air
- Hot gas flows thru a row of stationary vanes where it is accelerated due to the decreasing flow area
- The gas then impinges on the row of rotor turbine blades causing them to move while the gas looses energy (temperature and pressure)
- In a jet engine not all the energy in the hot gas is imparted to the rotating turbine
- The remaining energy is available to generate thrust by accelerating the gas thru the exhaust nozzle



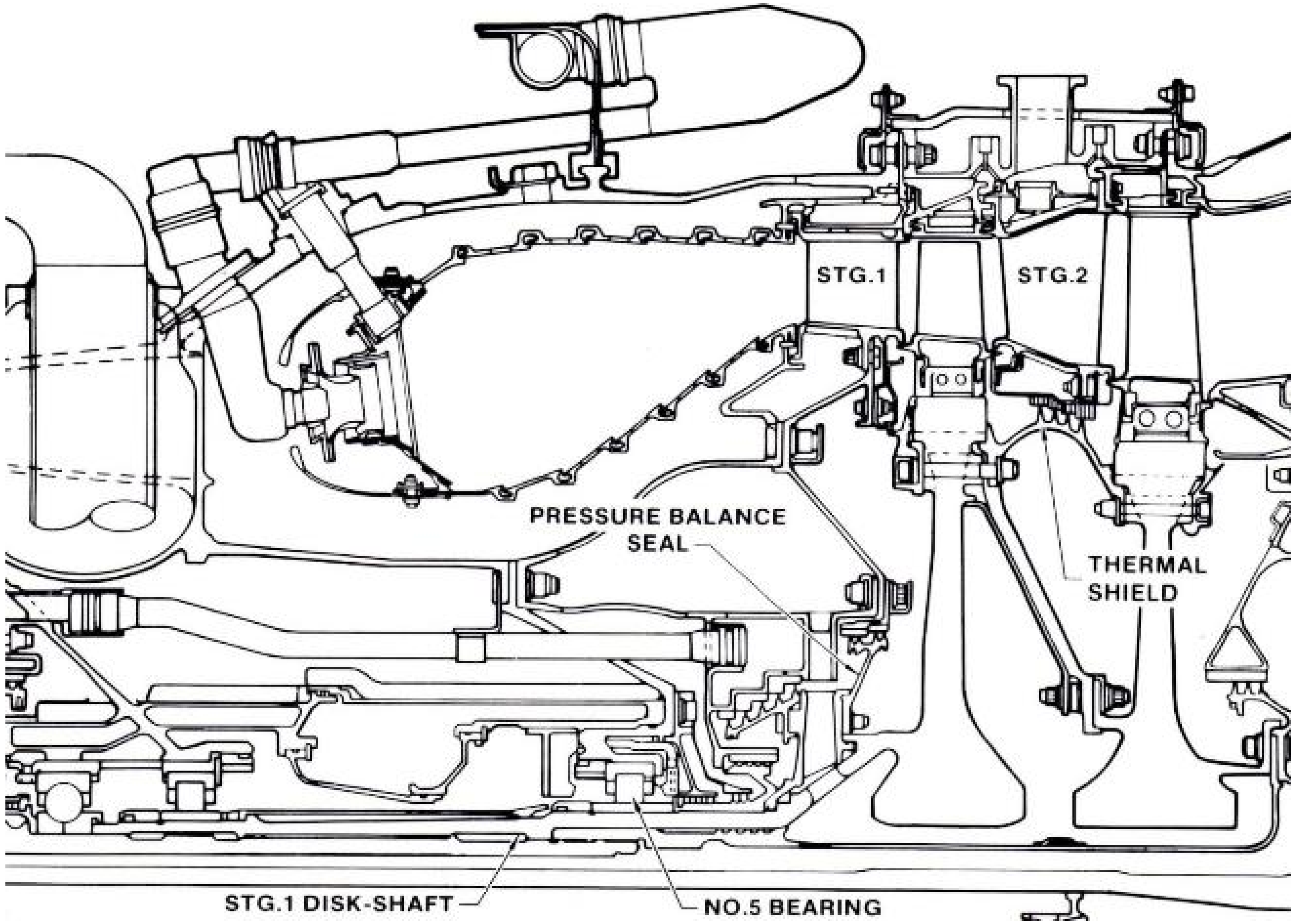


Jet Engines-How They Work-HP Turbine

- To maximize the specific power of the engine, the turbine must be operated at as high a temperature as possible, consistent with the engine's material capability and the required operating life
- The turbine airfoils (stator vanes and rotor blades) are cooled with air extracted from the compressor
  - Maximum temperature of the cooling air ~1000F
- The cooling air removes heat from the HPT airfoils by flowing thru internal passages in the airfoils and then flowing over the airfoil surfaces forming a "film" of relatively cool air which "insulates" the airfoils from the hot gases of the HPT

Cooled HPT stage 1 blades

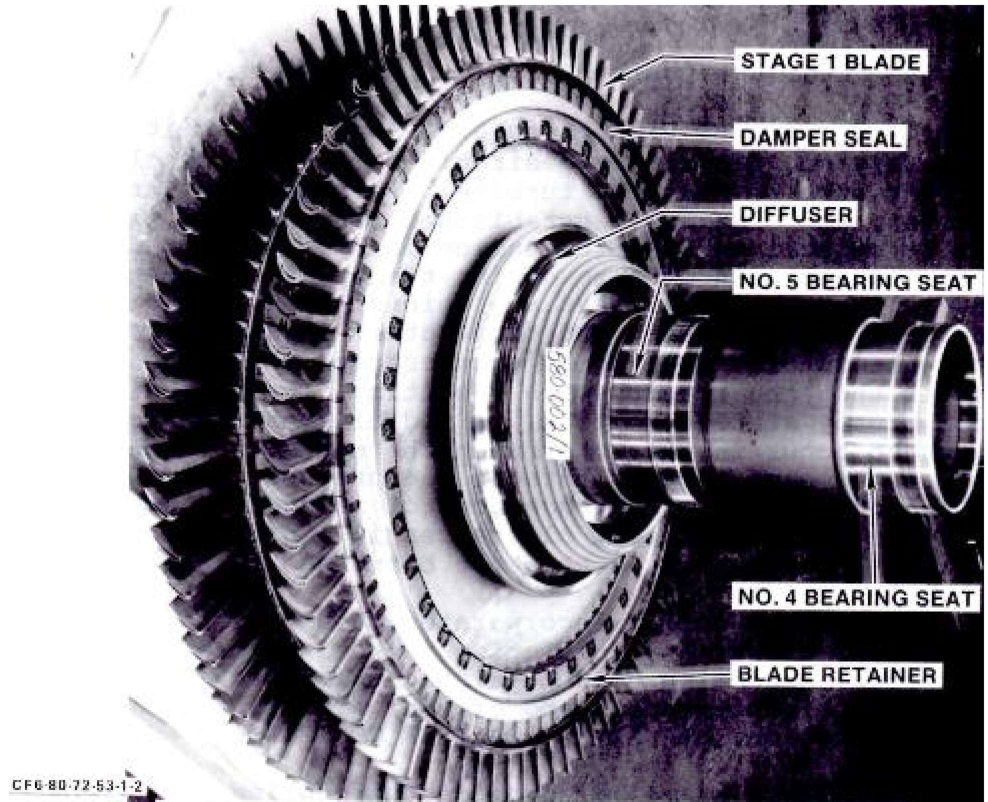
Jet Engines-How They Work-HP Turbine



Jet Engines-How They Work-HP Turbine

HPT		
Air Flow in	250/110	Lb/sec
Pressure in	412/170	psia
Temperature in	2258/1943	F
No. Stages	2	
No.blades	80/74	
Power	**76,000/30,000**	**HP**
Blade height	2.18/3.60	inch
N2	10550/9768	RPM
"g" field	50,000	
Air Flow out	267/117	Lb/sec
Pressure out	92/38	psia
Temperature out	1483/1248	F

High rotational speeds lead to high "G " fields and high mechanical stresses



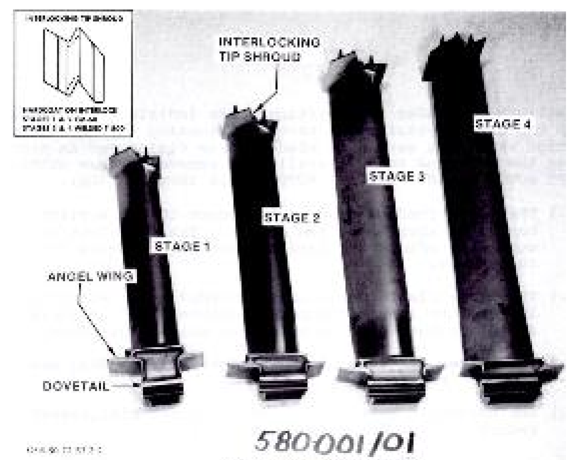
HIGH PRESSURE TURBINE ROTOR ASSEMBLY

Jet Engines-How They Work-LP Turbine

- **Low pressure turbines** drive low pressure compressors and fans of turbofan engines
- They extract energy for the hot gas after it leaves the high pressure turbine
- LP turbines typically run at lower speeds and have more stages than HP turbines
  - The amount of energy in the gas is less
  - The LP compressors and fans operate at lower rotational speeds
- LP turbines extract energy for the hot gas flow in the same way the HP turbine do
- LP turbine blades are much longer than HP turbine blades
  - Rotational speeds are lower
  - Gas temperatures and pressures are lower
- LP turbine airfoils are either not cooled or in some cases cooled with a simple cooling circuit

CF6-80A3 LPT

Air Flow in	267/117	pps
Pressure in	92/38	psia
Temperature in	1483/1248	F
No. Stages	4	
No.blades	432	
Blade height	6.15-10.40	
N1	3678/3525	
"g" field	15,000	
Air Flow out		pps
Pressure out	23/9	psia
Temperature out	959/772	F



LPT ROTOR BLADES

Jet Engines-How They Work-Exhaust Nozzle

- The **exhaust nozzle** converts energy available in the hot gas into a high speed jet by

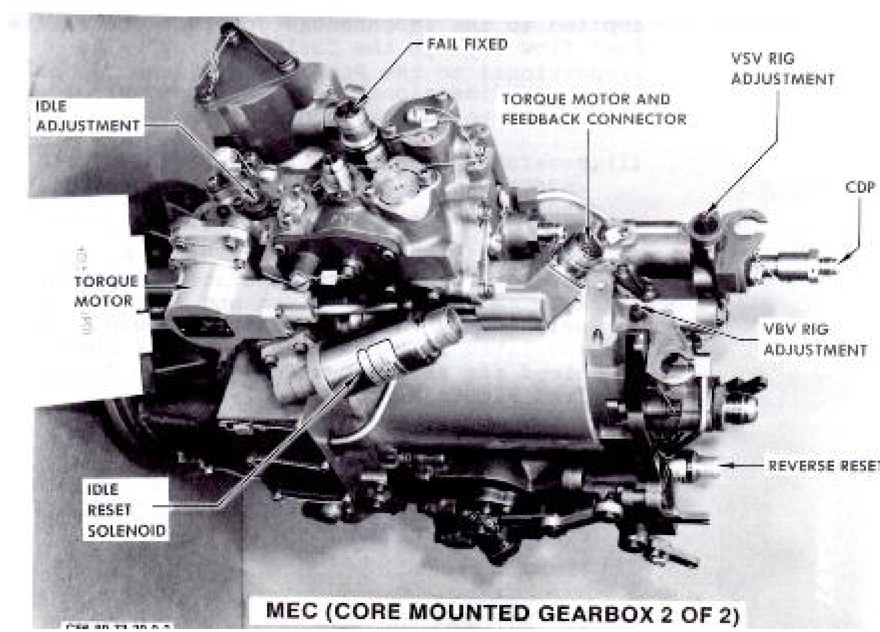
  accelerating the gas
- The gas pressure, and shape of the nozzle determines the velocity of the gas's jet velocity
- Convergent nozzles can accelerate the gas to sonic velocity
- Convergent-divergent nozzles can accelerate the gas to supersonic velocity
- Afterburning engines have variable area exhaust nozzles
  - Variable throat area or variable throat and exit areas

Jet Engines-How They Work-Exhaust Nozzle

Exhaust Nozzle		
Air Flow in	267/117	pps
Pressure in	23/9	psia
Temperature in	1419/1232	R
Air Flow out	267/117	pps
Pressure out	22.5/9.1	psia
Temperature out	1418/1232	R
Fan jet velocity	1404/1656	Ft/sec

Jet Engines-How They Work-Controls

- Basic **Control System** goal is to reliably deliver engine thrust
- Engine thrust is controlled by fan speed, N1
- The control systems attain the required N1 settings by controlling the engine transiently within safe operating boundaries
  - From start-up to shutdown
- The Control System also provides functions to optimize engine efficiency (SFC) and temperature
- The control system maintains engine speed within certified limits
  - Redline N1
  - Redline N2
  - Maximum Ps3
  - Minimum N2

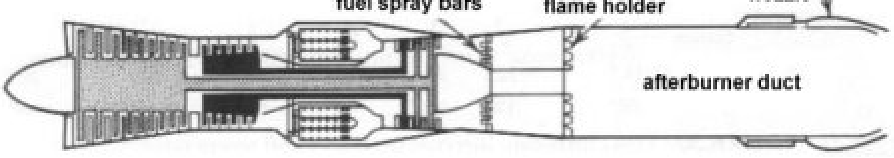


Jet Engines-How They Work-Controls

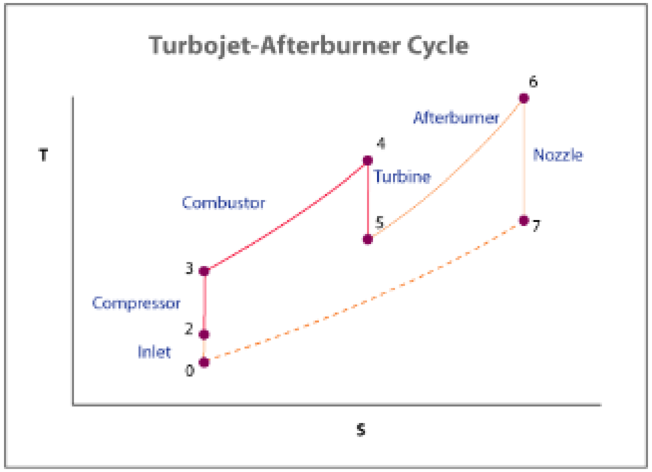
- Engine control determines-from throttle position setting and engine parameters from sensors(temperatures, pressures ,fuel specific gravity , etc):
- Engine fuel flow-from fuel pump
- Variable geometry
  - Variable stator vanes (VSVs)
  - Variable bleed valves (VBVs)
  - Thrust reversers
- Performance enhancements
  - HPT active clearance control (HPT ACC)
  - LPT active clearance control (LPT ACC)
  - Compressor active clearance control (COM ACC)
  - Undercowl cooling air
  - Aircraft generator heat exchanger air source (IDG)
  - Bore cooling control (BCV)
  - Start and transient bleed

Jet Engines-How They Work-Afterburner

- An **afterburner** injects additional fuel into the exhaust gas of a turbojet or turbofan engine to provide additional thrust from military engines
- Afterburning provides a significant increased thrust at the cost of very high fuel consumption and inefficiency
- It is used for supersonic flight, takeoff and for combat situations



Turbojet with Afterburner



Post war jet engine development

- The allies studied the German jet engines
- Engine designers adopted the Junkers Jumo **axial compressor** configuration for fixed wing aircraft
  - Smaller diameter engines-lower frontal area –less aircraft drag
  - Ability to increase compressor pressures by adding stages
- After WW II military fighter aircraft adopted turbojet power plants
- Manufacturers included Pratt & Whitney , General Electric, Westinghouse, Curtiss Wright , Rolls Royce, Bristol Sidley , de Havilland
  - Military supported research and development of jet engine technology
- Improvements in materials technology allowed increases in jet engine rotor speeds and operating pressures and temperatures

- Application of jet engines to commercial aviation followed military applications
- Slightly modified military engines-
  - **Pratt & Whitney** J57 became the JT3 and JT3D
  - **GE** J79 became the CJ805
- Engines based on military engines-
  - GE **CF6-6** based on **TF39** engine for C5A transport
  - PW **JT9D** based on PW's proposed engine for C5A transport
- Engines designed and developed for commercial applications came later
  - **GE90**
  - **PW4000**
  - **RB211**

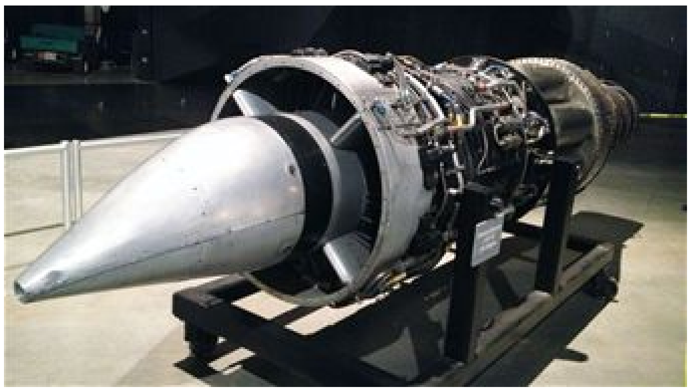
Post war jet engine development

- The **General Electric/Allison J35** was originally developed by General Electric in was the United States Air Force's first axial-flow compressor engine
- The J35 was fairly simple, consisting of an eleven-stage axial-flow compressor and a single-stage turbine
- With the afterburner, which most models carried, it produced a thrust of 7,400 lbf first run in 1946

Type: Afterburning turbojet
Length: 195.5 in including afterburner
Diameter: 43 in
Dry weight: , 2,930 lb including afterburner
Compressor: 11-stage axial compressor
Combustors: Eight tubular inter-connected combustion chambers
Turbine: Single-stage axial
Maximum thrust:
5,600 lbf at 8,000 rpm
7,400 lbf with afterburner
Overall pressure ratio: 5:1
Air mass flow: 91 lb / sec at take-off power
Specific fuel consumption: 1.1 lb/lb/hr
Thrust-to-weight ratio: 2.53 lbf/lb
Maximum operating altitude: 50,000 ft (15,000 m)
Cost: US$ 46,000 each

Post war jet engine development

- The **J47** was developed by GE from the earlier **J35** engine and was first flight-tested in May 1948 as a replacement for the J35 used in the North American XF-86 Sabre
- More than 30,000 engines of the basic J47 type were built before production ended in 1956
- The J47 powered USAF aircraft: F-86, XF-91, B-36, B-45, B-47 and XB-51

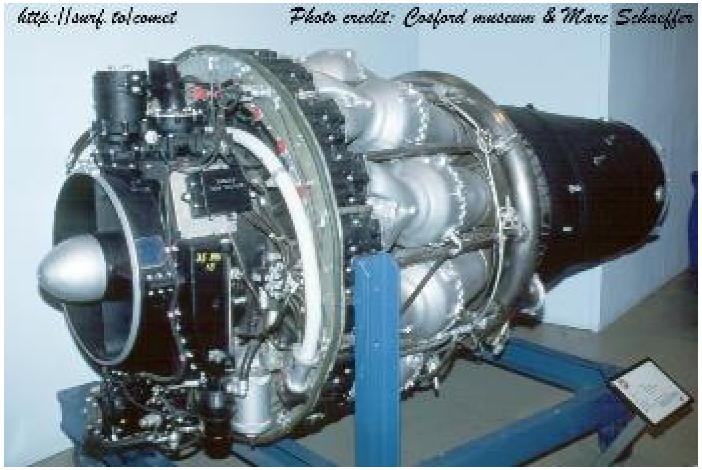


Model: J47-GE-25
Compressor: 12-stage axial
Turbine: Single-stage axial
Weight: 2,707 lbs.
Thrust: 5,670 lbs.
Maximum rpm: 7,950
Maximum operating altitude: 50,000 ft.

F-86

The first commercial jet engine powered aircraft-the Comet

- The de Havilland DH 106 Comet was the first production commercial jet aircraft
- Developed and manufactured by de Havilland in the UK
- Comet 1 prototype first flew on 27 July 1949 and entered service in 1952
- It was powered by four de Havilland Ghost turbojet engines buried in the wings



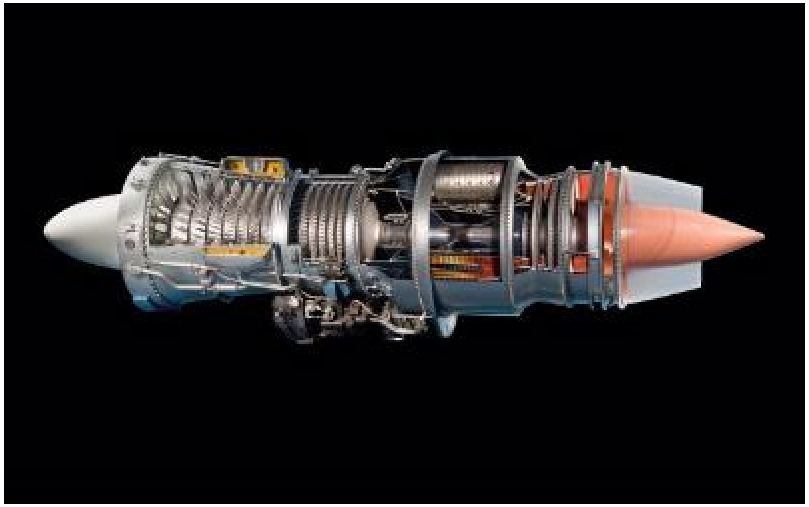
de Havilland Ghost the world's first jet engine to enter airline (BOAC) service

Type: Turbojet
Length: 121 in
Diameter: 53 in
Dry weight: 2,218 lb
Compressor: Single stage centrifugal flow
Combustors: 10 chambers
Turbine: Single-stage
Maximum thrust: 5,000 lbf at 10,250 rpm
Overall pressure ratio: 4.6
Specific fuel consumption: 1.02 lb/hr/lbf

Pratt & Whitney J57

- The J57 (JT3) Engine was the first Pratt & Whitney-designed turbojet
- The J57 was a twin-spool, axial flow configuration, a substantial departure from earlier centrifugal-flow designs
  - J57 had afterburner versions
- May 1953, a J57-powered North American F-100 Super Sabre became the first production aircraft to exceed the speed of sound in level flight
- Pratt & Whitney had leapfrogged the industry with its first turbojet design

F-100



JT3 was a turbojet engine

Pratt & Whitney J57/JT3 Turbojet

- **Length:** 136.77in
- **Diameter:** 38.8in LP compressor inlet
- **Dry weight:** 3495lb
- **Compressor:** all-axial,
- 9-stage LP compressor,
- 7-stage HP compressor
- **Combustor:** cannular, 8 flame tubes
- **Turbine:** all-axial
- 1 stage HP turbine
- 2-stage LP turbine

- **Takeoff thrust:** 12030 lbf @ Take-off, SLS
- **Max Cruise thrust:** 3550lbf M0.85,35000ft
- **Overall pressure ratio:** 12.5:1
- **Air mass flow:** 180 lb/s
- **Specific fuel consumption:**
- 0.785 lb/hr/lbf @ Take-off, SLS
- 0.909 lb/hr/lbf @Max Cruise
- **Thrust-to-weight ratio:** 3.44

707 and JT3 change the airline industry

- In October 1958, the commercial version of the J57, the JT3, brought American passengers into the jet age of travel with the inaugural flight of a Pan American World Airways Boeing 707 from New York to Paris
- Four engines, each rated at 13,000 pounds of thrust, reached a cruising speed of 575 miles per hour, 225 miles per hour faster than the newest propeller-driven airliner of that time
- The J57 and JT3 were so far ahead of the competition that virtually every aircraft manufacturer in the United States designed an airplane around them
- A total of 21,186 of these turbojets were built for commercial and military applications before the last one was shipped in 1965

Rolls-Royce RB.80 Conway Turbofan

- The first by-pass engine (or turbofan) in the world to enter service
- Development started at Rolls-Royce in the 1940s, but it was used only briefly in the late 1950s and early 1960s before other turbofan designs were introduced that replaced it
- **Length:** 134.21 in
- **Diameter:** 37.6 in
- **Dry weight:** 4,500 lb
- **Compressor:** axial flow; 7-stage LP, 9-stage HP
- **Combustors:** cannular
- **Turbine:** axial flow; 1-stage HP, 2-stage LP
- **Performance**
- **Maximum thrust:** 17,150 lb
- **Bypass ratio:** 0.25
- **Specific fuel consumption:** 0.87

The sfc of the de Havilland Ghost was 1.02

Pratt & Whitney JT3D

- Pratt & Whitney began developing its first production turbofan—the JT3D—during the late 1950s
- It was a low-bypass-ratio engine built around the J57's service-proven core. The JT3 made its first flight on a Boeing 707-120 aircraft on June 22, 1960
- Shortly thereafter, McDonnell Douglas selected it for versions of the DC-8
- Airplanes Powered

  Boeing 707-120B

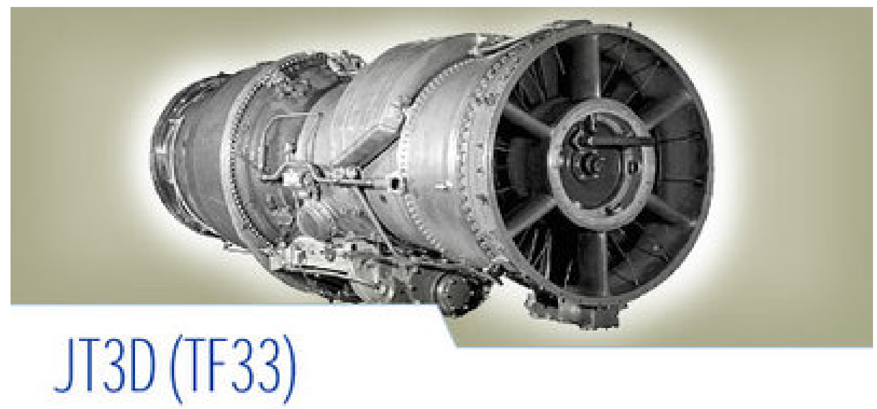
  Boeing 707-320B,C

  Boeing 707-323C

  McDonnell Douglas DC-8-50

  McDonnell Douglas DC-8-60

  McDonnell Douglas DC-8F



- **Length:** ~138in
- **Diameter:** ~51.57in fan tip
- **Dry weight:** ~4360lb bare engine
- **Compressor:**
- 2-stage fan,
- 6-stage IP compressor
- 7-stage HP compressor
- **Combustors:** cannular, 8 flame tubes
- **Turbine:**
- 1stage HP turbine
- 3-stage LP turbine

- **Maximum thrust:** 17,000 lbf Take-off
- **Overall pressure ratio:** ~12.5:1
- **Bypass ratio** 1.42:1
- **Air mass flow:** 432lb/s
- **Turbine inlet temperature:** ~1150K @Take-off,SLS
- **Specific fuel consumption:**
- ~0.78 lb/(lbf·hr) @ 4000lbf thrust
  M 0.82,35000ft,ISA
- **Thrust-to-weight ratio:** 3.9 bare engine

Rolls-Royce/Snecma Olympus 593

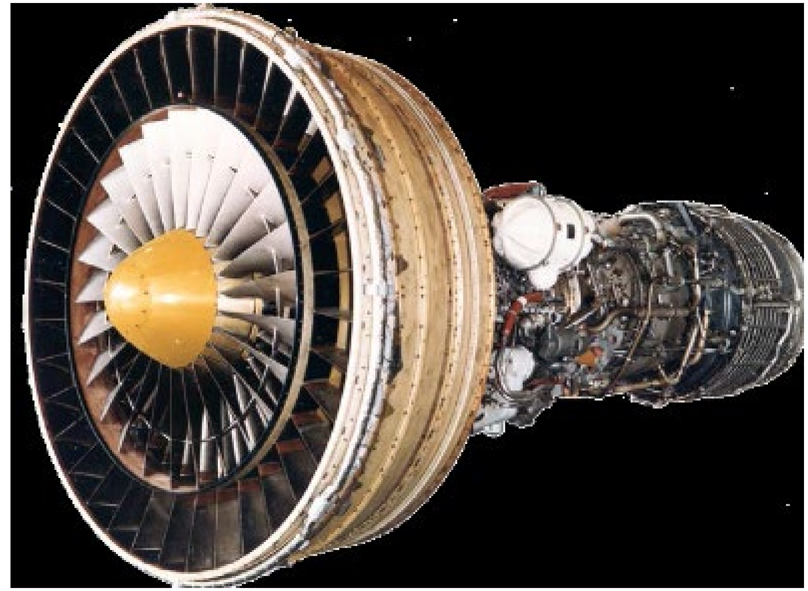
Type: turbojet
Length: 13 ft 3 in
Diameter: 47.75 in
Dry weight: 7,000 lb
Compressor: Axial flow
 7-stage low pressure
 7-stage high pressure
Combustor: Nickel alloy construction annular chamber, 16 vaporizing burners, each with twin outlets
Turbine: 1 stage high pressure
1 stage low pressure
Maximum thrust: 31,350 lbf
38,050 lbf with afterbuner*
Overall pressure ratio: 15.5:1
Air mass flow: 410 lb/sec
Specific fuel consumption: 1.39 lb/(lbf·h) at sea level
 1.195 lb(lbf·h) cruise
Thrust-to-weight ratio: 5.4:1

* Afterburner used for take off and during trans sonic flight up to Mach 1.7

Concorde SST 1969-2003

First High Bypass Fan Engine-- GE TF39

- **Type:** Turbofan
- **Length:** 312 in
- **Diameter:** 97 in
- **Dry weight:** 8000 lb
- **Compressor:** 1 stage fan
- 5 stage low pressure compressor
- 16 stage high pressure compressor
- **Combustors:** Annular
- **Turbine:** 2 stage high pressure turbine
- 6 stage low pressure turbine.
- **Maximum thrust:** 43,300 lbf
- **Overall pressure ratio:** 25:1
- **Fuel consumption:** ~1549lb/s
- **Specific fuel consumption:** 0.313 lb/lbf-hr
- **Thrust-to-weight ratio:** 5.4:1



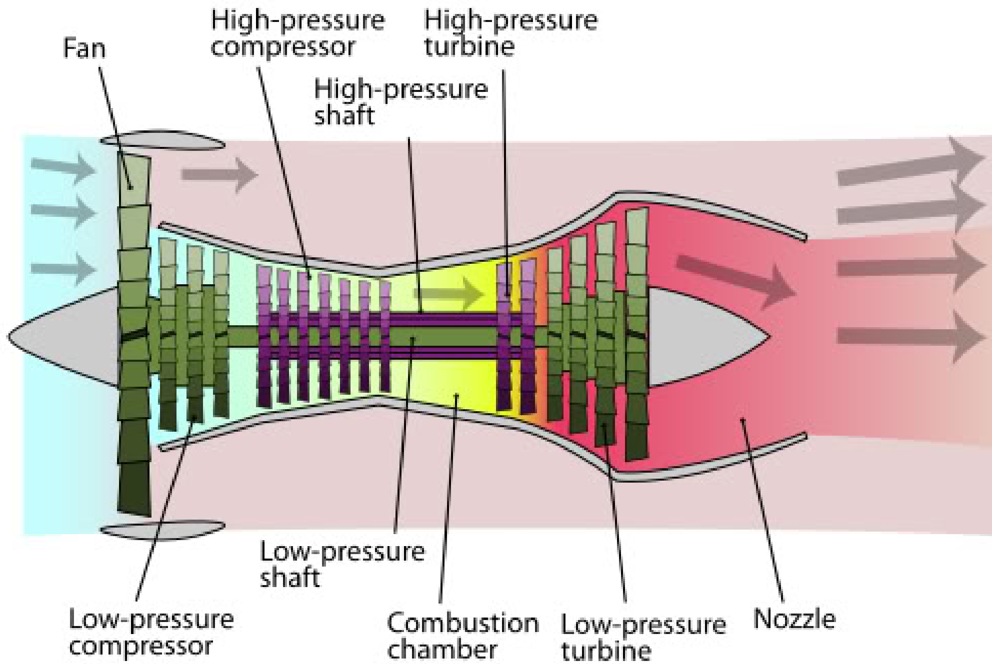
Lockheed C5A

First Commercial High Bypass Fan Engine—P&W JT9D

- **JT9D-7**
- **Type:** High bypass two-spool turbofan engine
- **Length:** 128.2 in
- **Diameter:** 92.3 in (Fan tip)
- **Dry weight:** 8,608 lb
- **Compressor:** 1-stage Fan,
- 3-stage LP compressor
- 11-stage HP compressor
- **Combustors:** Annular combustion chamber
- **Turbine:** 2-stage HP turbine
- 4-stage LP turbine
- **Maximum thrust:** 46,300 to 50,000 lbf take-off
- **Overall pressure ratio:** overall 23.4:1 (Fan 1.64:1)
- **Bypass ratio:** 5.0:1
- **Specific fuel consumption:** ca 0.6 lb/lbf/hr at M0.8 at 35,000 ft
- **Thrust-to-weight ratio:** 5.4 to 5.8

Engines for first 747 “Jumbo jets”

Turbofan Engine



- Some of the air that passes thru the fan bypasses the compressor combustor and turbine of the "core engine"
- The bypass air provides thrust in addition to the thrust provided by the "core engine"
- Turbofans achieve lower fuel consumption than turbojets

Jet engine basic principles

- **CFM56-7B**

https://www.youtube.com/watch?v=_LaKlE2h3Jw

Extended Twin Operations-ETOPS

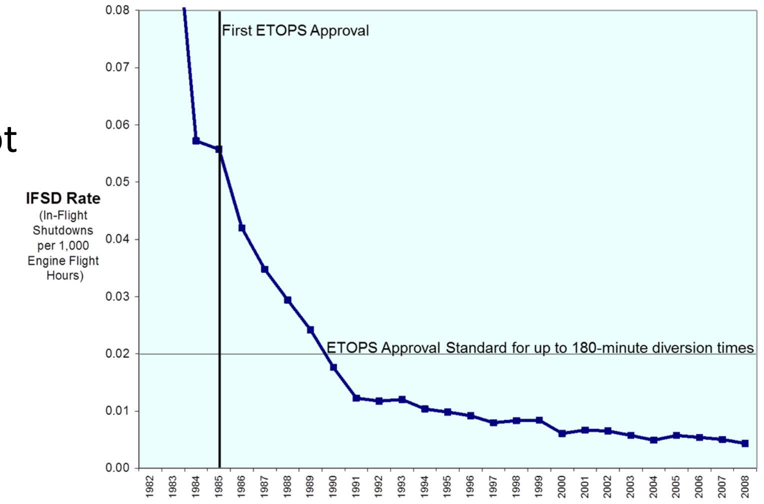
- In 1953 the **FAA**, introduced the "60-minute rule" for 2-engine aircraft
- The flight path of twin-engine aircraft could not be further than 60 minutes' flying time , with one engine not operating , from an adequate airport
- 1985 **FAA** gave 90 minute (later120 minute) ETOPS rating to **TWA 767**
  - Other two engine aircraft and airlines followed

  Current ETOPS rules:

  Less than 0.05 IFSD/1000 hrs 120 minutes

  Less than 0.02 IFSD/1000 hrs 180 minutes

  Less than 0.01 IFSD/1000 hrs up to 330 minutes
- **777** and **787** approved for 330 minute ETOPS



Some current jet engines-commercial-GE CF6-80C2

CF6-80C2

CF6-80E1 $19 million

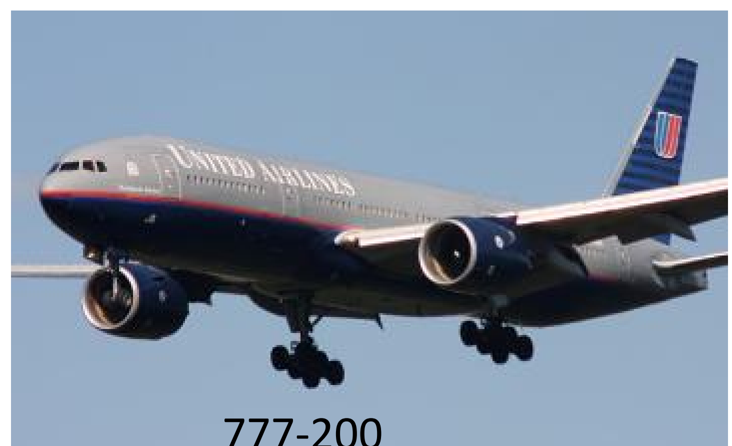
- **General characteristics**
- **Type:** Turbofan
- **Length:** 183 in
- **Diameter:** 105 in
- **Dry weight:** 8,966 - 9,047
- **Compressor:** 1 stage fan
- 3 stage low pressure
- 14 stage high pressure axial compressor
- **Combustors:** annular
- **Turbine:** 2 stage high pressure
- 4 stage low pressure turbine
- **Maximum thrust:** 52,500 - 61,500 lbs
- **Overall pressure ratio:** 29.2:1 - 31.1:1
- **Bypass ratio:** 4.24 - 4.4
- **Thrust-to-weight ratio:** 5.6:1 - 6:1

Airbus A310
Boeing 747
Boeing 767
McDonnell Douglas MD-11

Some current jet engines-commercial-PW4084

- Specifications (PW4084)
- **Type:** Two spool high bypass ratio Turbofan
- **Length:** 163.1 in
- **Diameter:** 112 in (fan)
- **Dry weight:**
- **Compressor:** 1 stage fan
- 5 stage low pressure compressor
- 15 stage (5 variable) high pressure compressor
- **Combustors:** Annular
- **Turbine:** 2 stage high pressure turbine
- 5 stage low pressure turbine
- **Maximum thrust:** 74,000–98,000 lbf
- **Overall pressure ratio:** 32.0:1 – 35.4:1
- **Bypass ratio:** 5.3:1
- **Turbine inlet temperature:** 707
- **Thrust-to-weight ratio:** 6–7

Pratt & Whitney 4084



777-200

Some current jet engines-commercial-GE90

GE90-115B

Fan/compressor stages	1/3/10
HP turbine/LP turbine	2/6
Max diameter inch	135
Length inch	287
Max thrust at Sea Level lbs	115,300
Overall Pressure Ratio	42

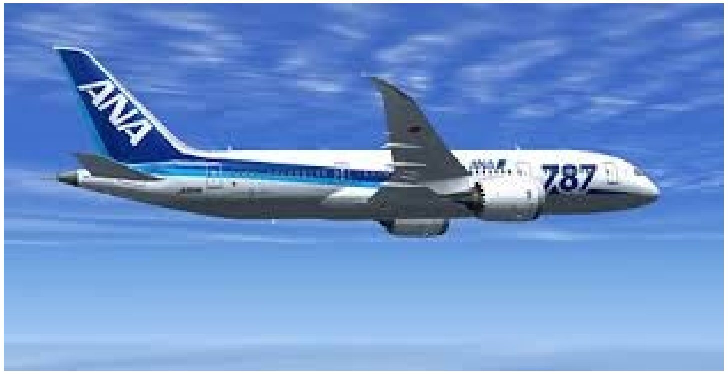
777-300ER

Some current jet jet engines- commercial-GE9X

•100,000 lbs. thrust class
•133" diameter composite fan case
•16 composite fan blades
•11-stage high pressure Compressor
  pressure ratio 21:1
•TAPS (twin annular pre-swirl) combustor for greater efficiency and low emissions
• Ceramic matrix composite (CMC) material in the combustor and turbine
•Overall engine pressure ratio of 60:1 – highest in the history of aviation---- P3~880 psi

EIS 2020

Some current jet engines- commercial-RR- Trent 1000



787

Type: Three-shaft
Bypass ratio: 11–10.8:1
Length: 186.5 in
Diameter: 112 in Fan
Dry weight: 12,710 lb
Compressor: Single stage LP,
eight-stage IP,
six-stage HP compressor
Combustors: Tiled combustor
Turbine: Single-stage HP turbine,
single-stage IP turbine
six-stage LP turbine
Maximum thrust: 53,000–75,000 lbf
Overall pressure ratio: 52:1 (Top-of-Climb)
Air mass flow: 2,840 lb per second
Thrust-to-weight ratio: 6.189:1

Roll Royce uses a three shaft design

Some current jet engines- commercial-CFM- LEAP

- **LEAP-**
- A320neo/737 Max/Comac C919
- **Type:** Twin-spool, high bypass turbofan
- **Length: 129 in**
- **Fan dameter:** 78 in
- **Dry weight:**
- **Compressor:** Single-stage fan, 3-stage low pressure compressor, 10-stage high pressure compressor
- **Combustors:** annular
- **Turbine:** Two-stage high pressure turbine, 7-stage low pressure turbine
- **Performance**
- **Maximum thrust:** 18,000-32,900 lbf.,
- **Overall pressure ratio:** 40:1
- **Bypass ratio:** 9:1-11:1

Replaces CFM56 engines

737 MAX 8 EIS 2018

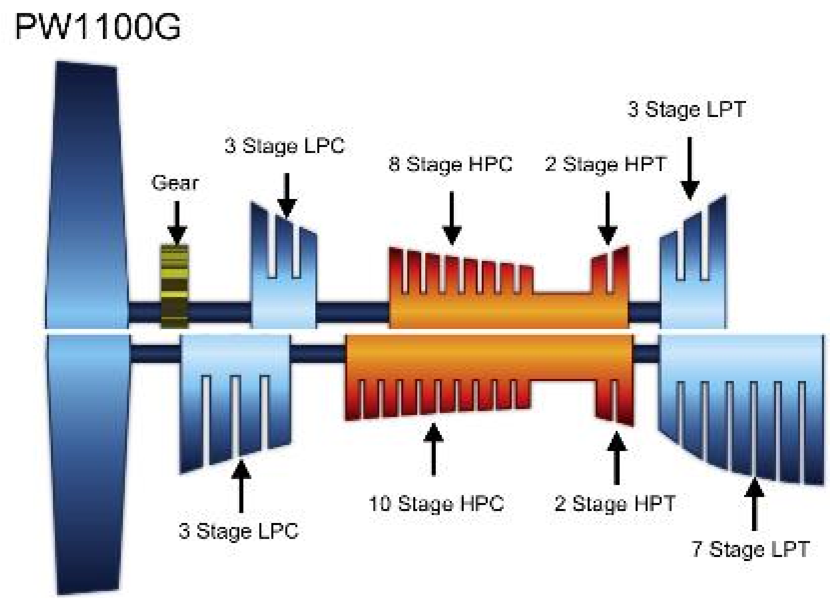
A320neo EIS late 2015

Some current jet engines- commercial-PW1100G

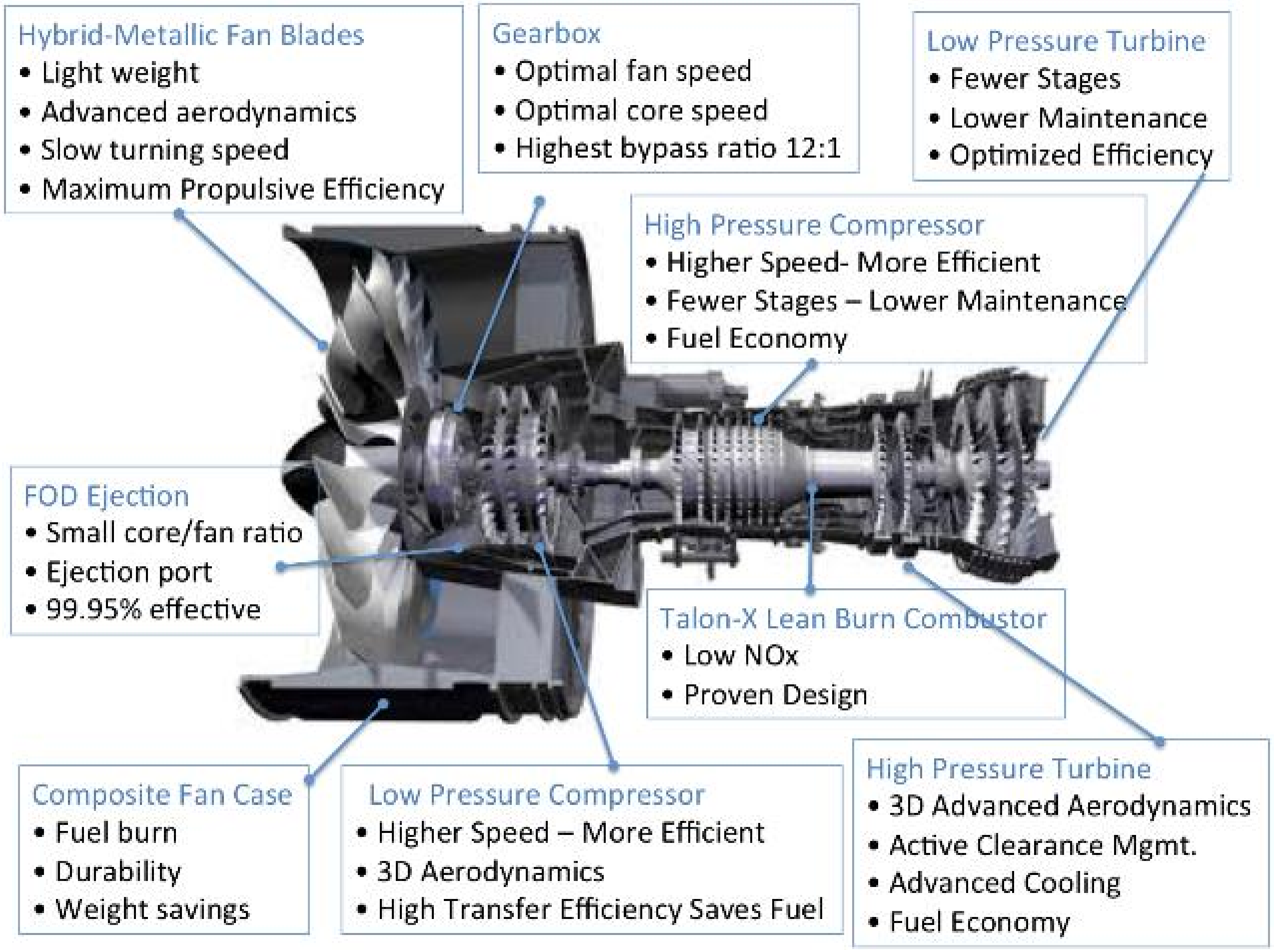
PW is taking a new approach to turbofan engine design-a “geared fan”

PW1100G on test

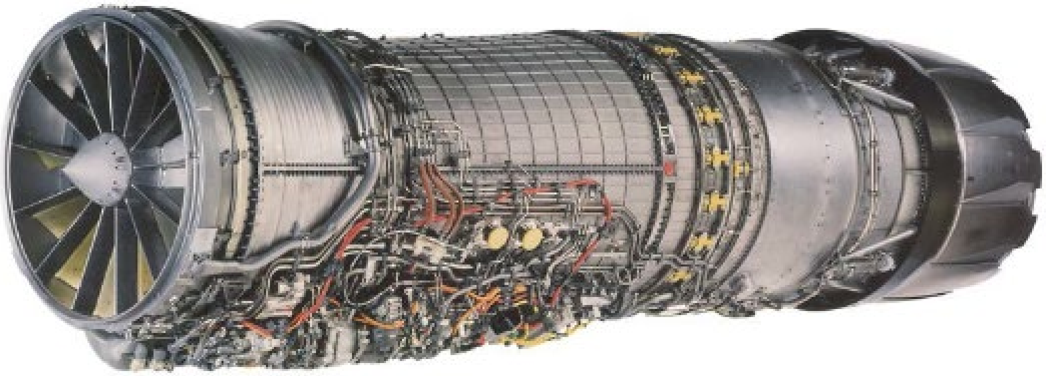
A320neo EIS late 2015



Some current jet engines-commercial-PW1100G



Some current jet engines-military-GE-F110



Performance Specifications
(Sea level/standard day)

F110-GE-129	**English**
Thrust class	29,000 lb
Length	181.9 in
Airflow	270 lb/sec
Maximum diameter	
Bypass ratio	0.76

F110-GE-129
turbofan engines

F-15

F-16

F-2

Some current jet engines-military-GE-F414

F414-GE-400

Performance Specifications
(Sea level/standard day)

Thrust class	22,000 lb
Length	154 in
Airflow	170 lb/sec
Maximum diameter	35 in
Inlet diameter 31 in	
Pressure ratio 30:1	30:1
Thrust-to-weight class	9:1

F/A-18E/F Super Hornet

EA-18G Growler

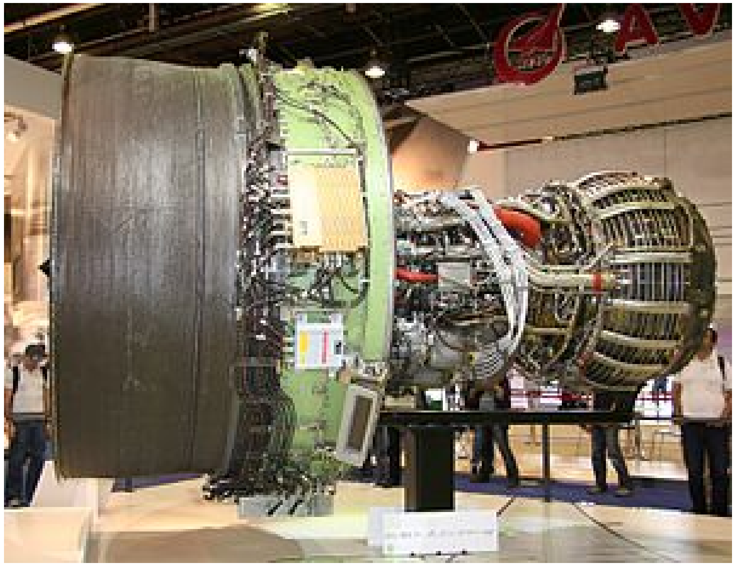
F414 Fighter Engine

- **Manufacturer:** General Electric Co.
  Thrust: 22,000 pounds
  Overall Pressure Ratio at Maximum Power: 30
  Thrust-to-Weight Ratio: 9
  Compressor: Two spool, axial flow, 3-stage fan
  LP-HP Compressor Stages: 0-7
  HP-LP Turbine Stages: 1-1
  Combustor Type: Annular
  Engine Control: FADEC
  Length: 154 in
  Diameter: 35 in
  Dry Weight: 2,445 lbs
  Applications: F/A-18E/F Super Hornet
- **Price/Unit Cost:** $4.32 million (in 2014)
  First Run: 1993
  First Flight: November 29, 1995

F/A-18E/F Super Hornet

Some current jet engines-commercial- GEnx-1B

Type: Turbofan
Length: 184.7 in
Diameter: 111.1 in
Dry weight: 12,822 lb
Compressor: Axial, 1 stage fan,
4 stage low pressure compressor,
10 stage high pressure compressor
Combustors: Annular
Turbine: , 2 stage high pressure turbine, 7 stage low pressure turbine
Maximum thrust: 63,800 lbf
Overall pressure ratio: 41
Thrust-to-weight ratio: approx 5:1



GEnx 1B $27 million

Engine for 787 and 747-8

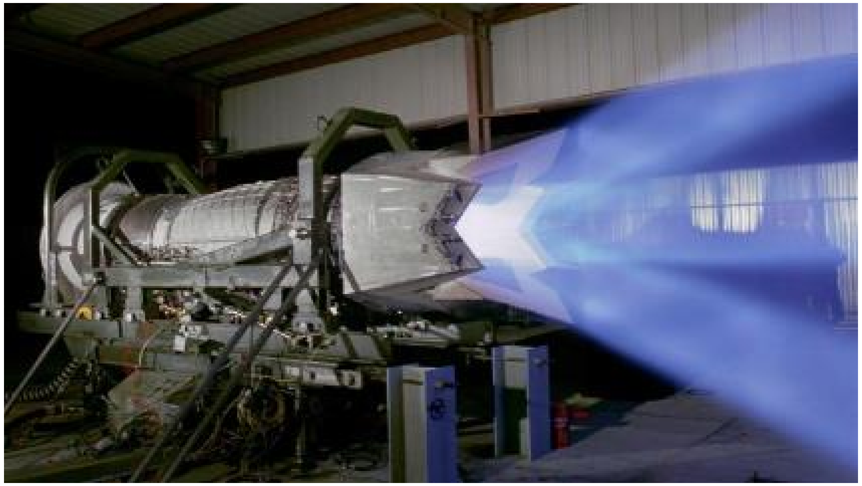
Some current jet engines-commercial- PW 2037

- Fan tip diameter: 78.5 in
- Length, flange to flange: 141.4 in
- Takeoff thrust: 37,250–43,000 lb
- Flat rated temperature: 87°F
- Bypass ratio: 6.0
- Overall pressure ratio: 27.6–31.2
- Fan pressure ratio: 1.74

The PW2000 engine entered revenue service in 1984 as the first commercial engine with FADEC (Full-Authority Digital Electronic Control) technology

Some current jet engines-military-PW-F119

F119



Type: Twin-Spool,
Augmented Turbofan
Thrust class: 35,000 Pound
Engine Control: Full-Authority Digital Electronic Control
Compression System: Twin Spool/Counter Rotating/Axial Flow/Low Aspect Ratio
Combustor: Annular
Turbine: Axial Flow/
Counter-Rotating
Nozzle: Two Dimensional Vectoring
Convergent/Divergent

F-22

Some current jet engines-military-PW-F100

F100-PW-220

Thrust: 23,770–29,160 lb
Weight: 3,740 lb
Length: 191 in
Inlet Diameter: 34.8 in
Maximum Diameter: 46.5 in
Bypass Ratio: 0.36
Overall Pressure Ratio: 32 to 1
-

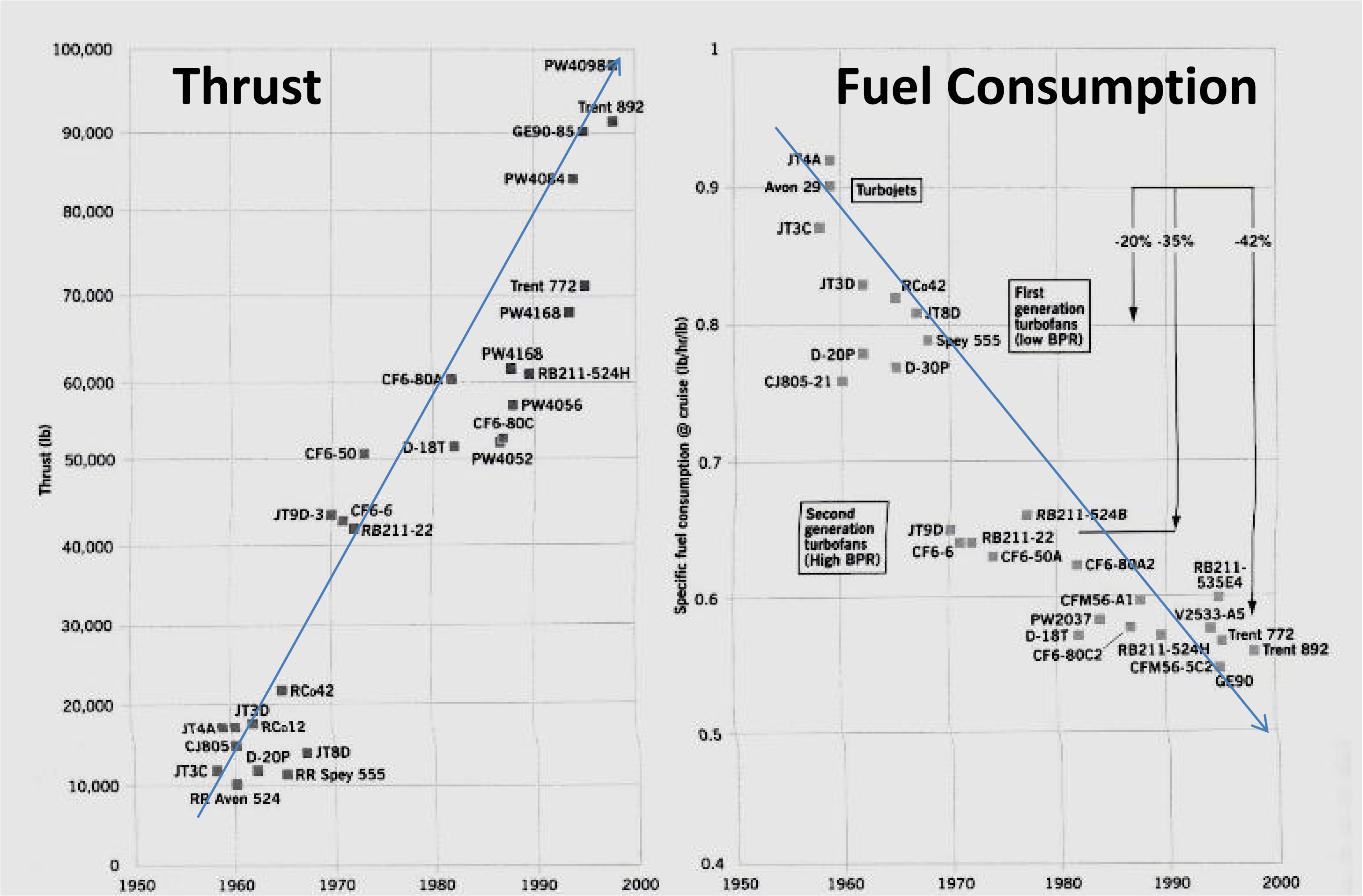
F-15 Eagle

F16

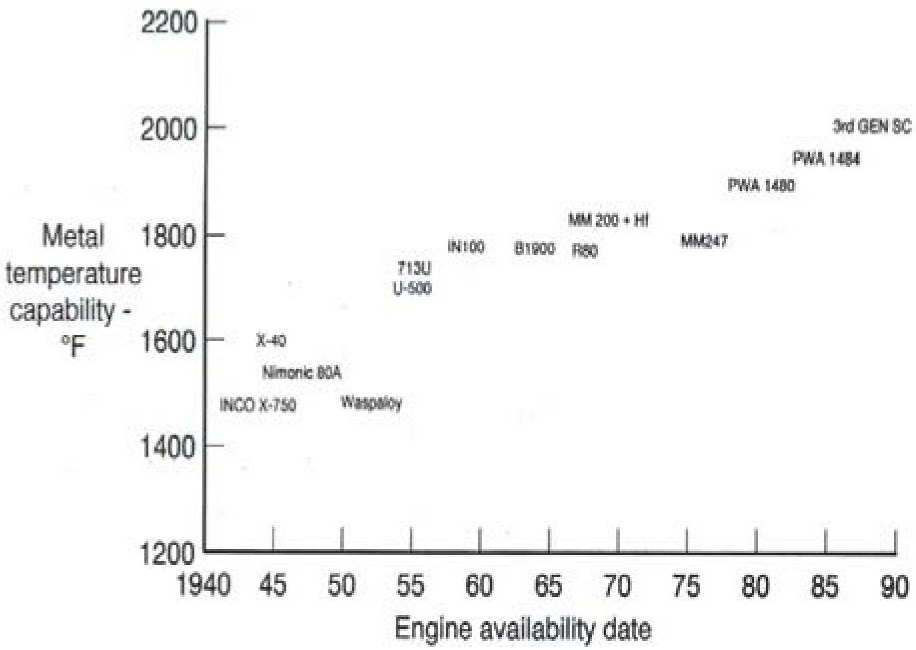
Some current jet engines-military-PW-F135

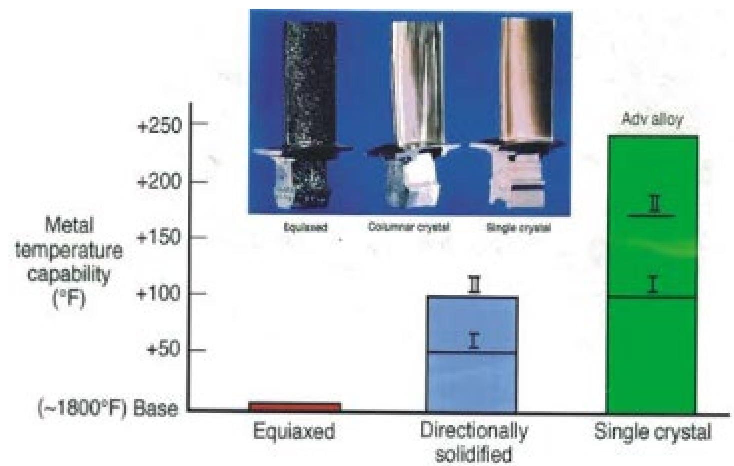
- **Pratt&Whitney F135**
- **Type:** Afterburning Turbofan/ also partially turboshaft
- **Length:** 220 in
- **Diameter:** 51 in
- **Dry weight:** 3,750 lbs
- **Compressor:** Axial 3 stage low-pressure compressor, 6 stage high-pressure compressor
- **Combustors:** Short, annular combustor
- **Turbine:** Single stage high pressure turbine, two stage low pressure turbine
- **Maximum thrust:** 43,000 lbf
- max, 28,000 lbf intermediate
- **Specific fuel consumption:** 0.886 lb/(hr·lbf) (w/o afterburner)
- **Thrust-to-weight ratio:** 11.467

Commercial Jet Engine Development

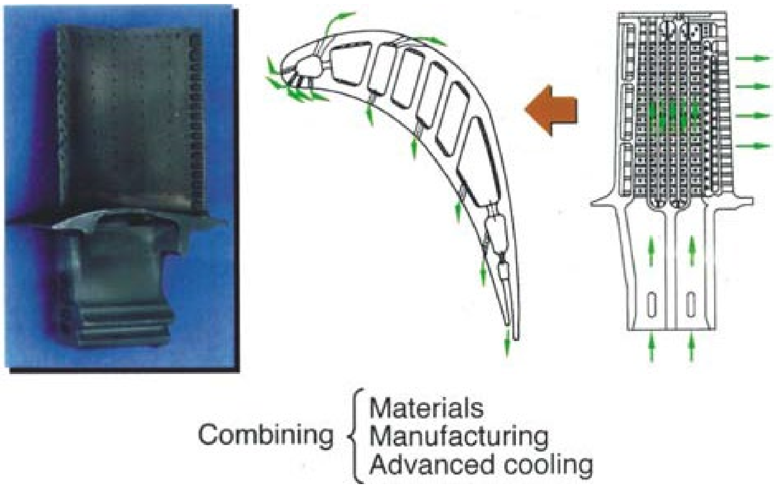


Jet engine materials improvements

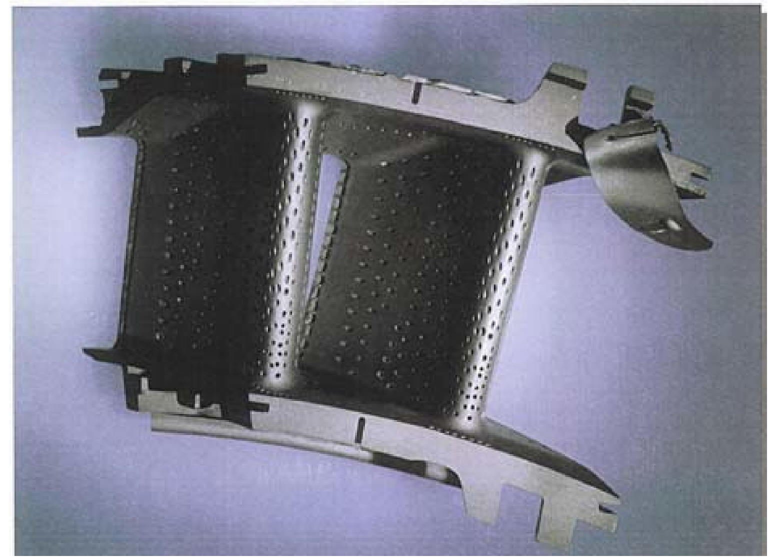




Jet engine materials improvements

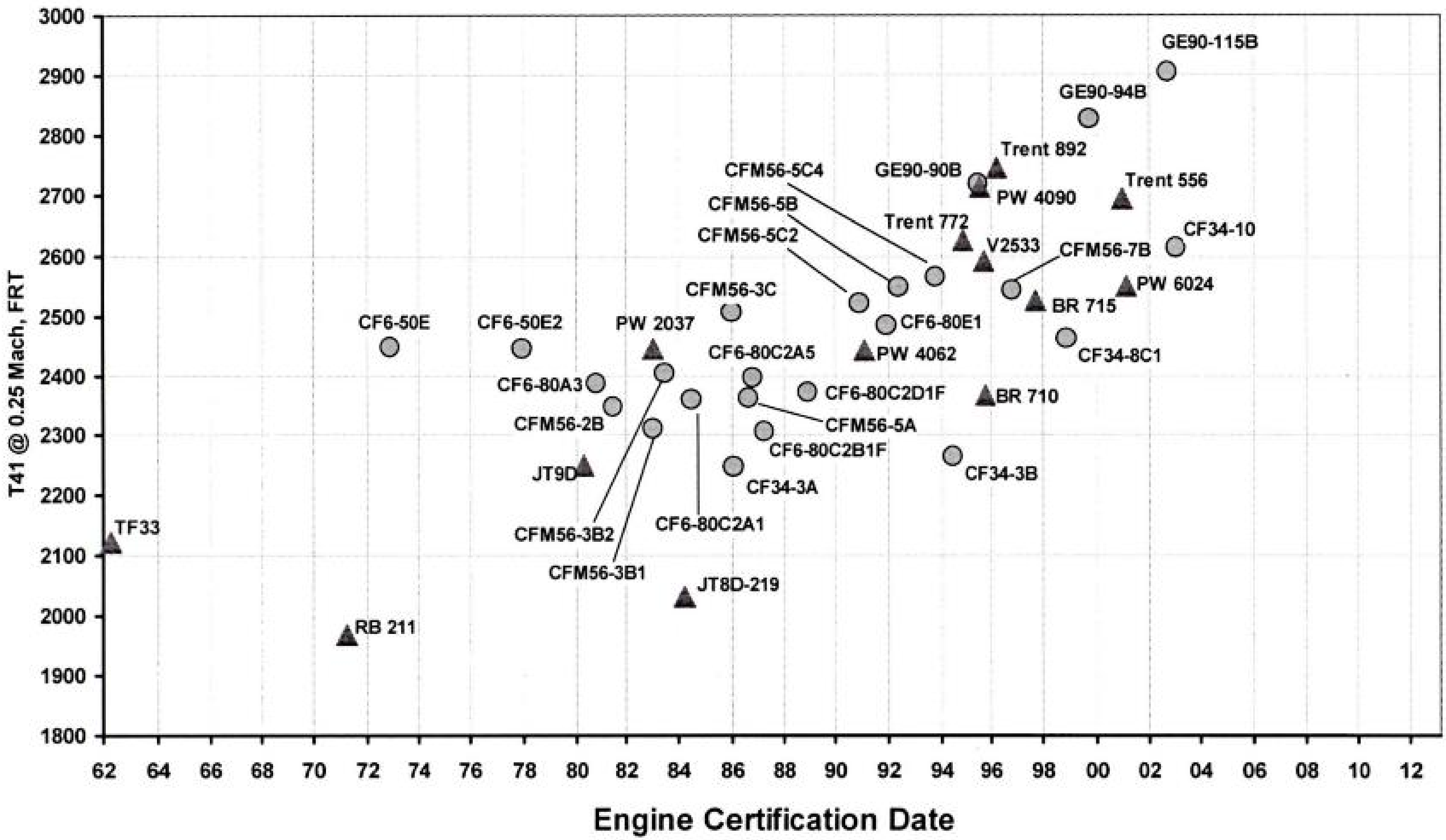


Single Crystal Turbine Blade with Film And Convection Serpentine Cooling

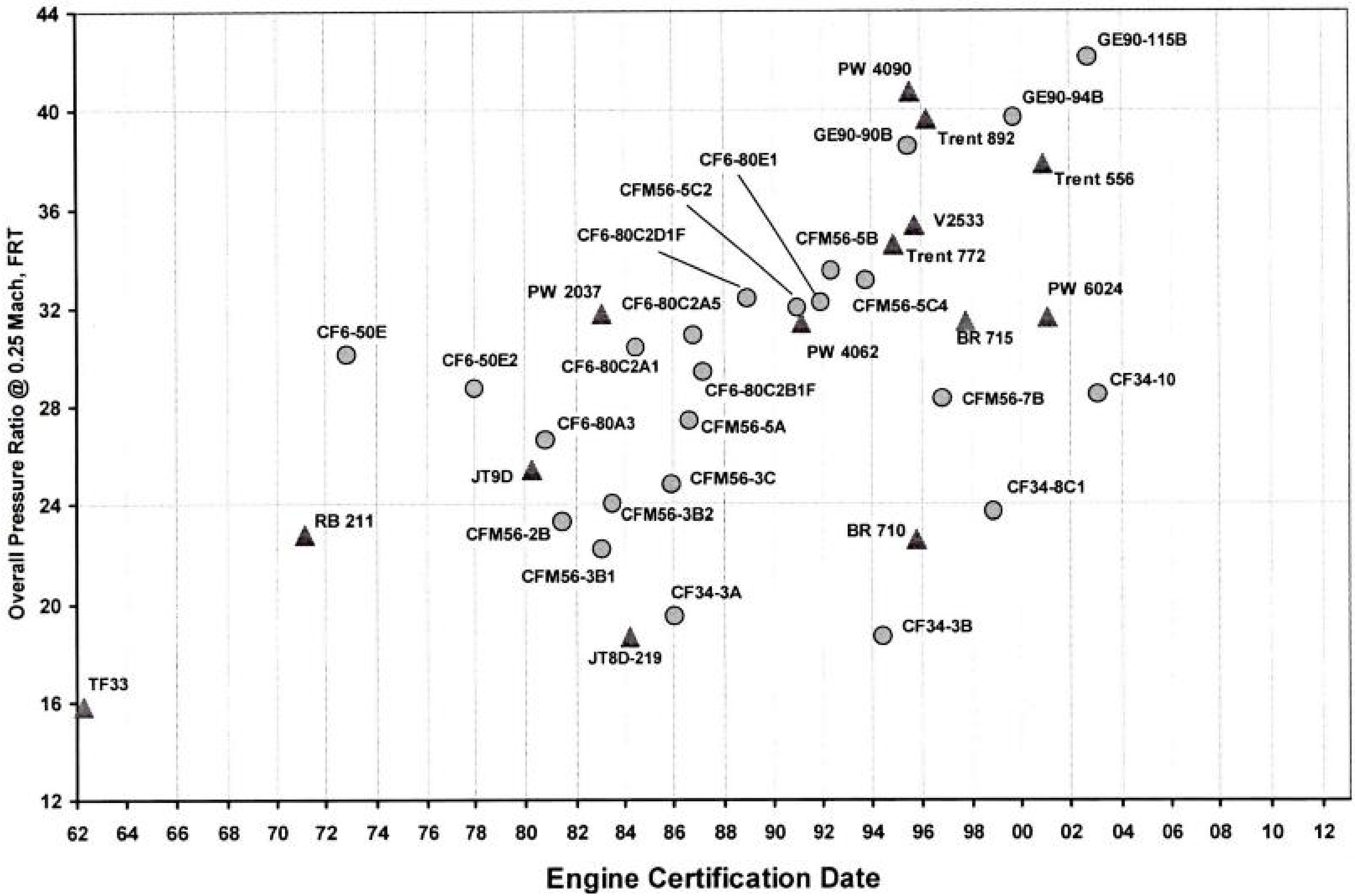


Single Crystal Turbine Vanes Using Film And Convection Cooling

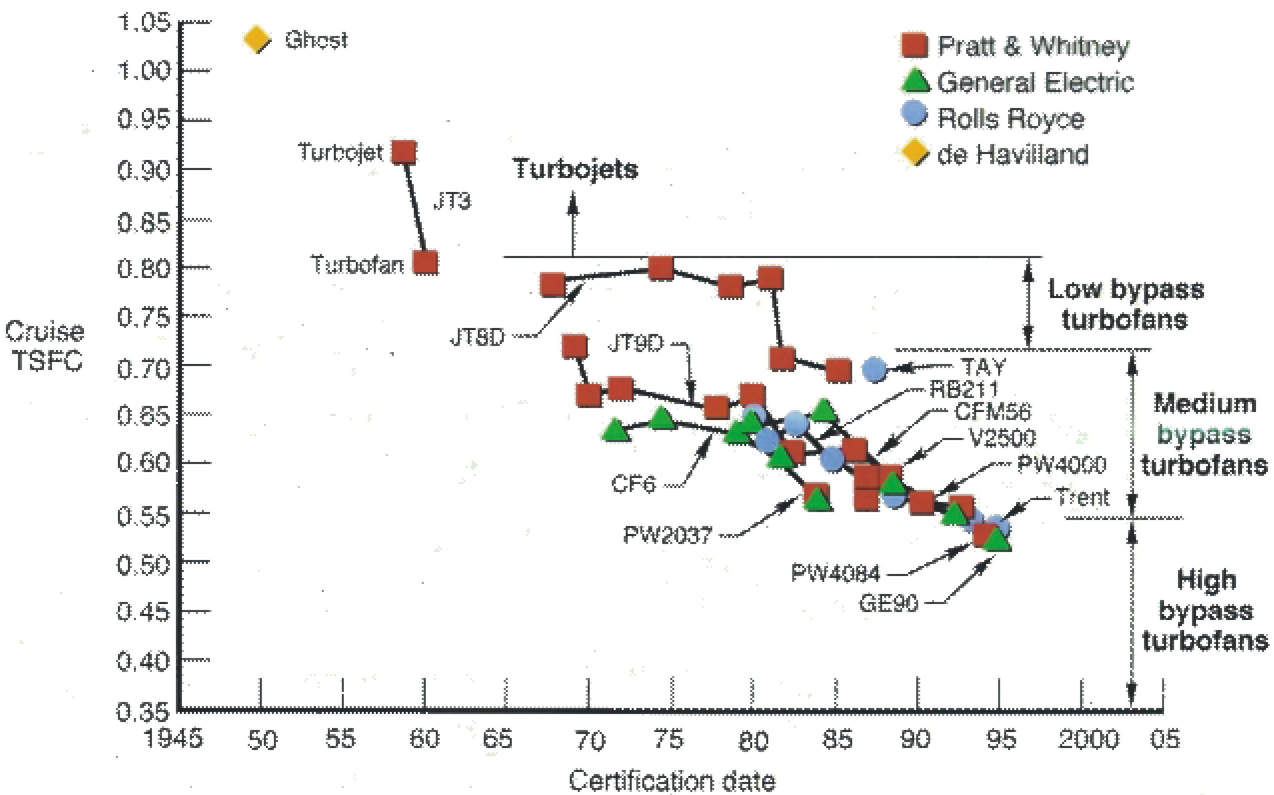
Engine Temperature Trend



Engine Pressure Ratio Trend



Commercial Jet Engine Development



Transport Engine Performance

Future jet engine concepts-Prop fans

Prop fans or open rotor engines offer high propulsive efficiency and lower fuel consumption

GE demonstrated the concept in the mid 1980's

Noise and engine installation are two challenges

GE and Rolls Royce are studying open rotor engines

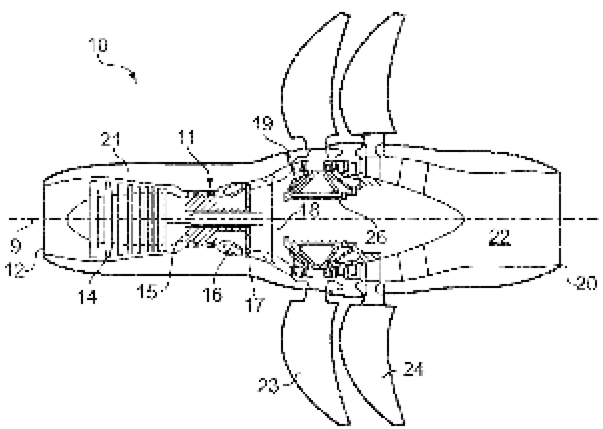


FIG. 1

RR concept

Future jet engine concepts-Variable cycles and Hybrids

- GE and Rolls-Royce are under contract to design such an engine for the US Air Force featuring variable bypass flows and ultra-high pressure ratios
- That ultra-high pressure, variable-cycle engine will mark the peak of gas turbine efficiency
- One concept that promises improvements in efficiency is the hybrid turboelectric concept uses gas-powered generators to supply electricity to motors, driving fans that produce thrust
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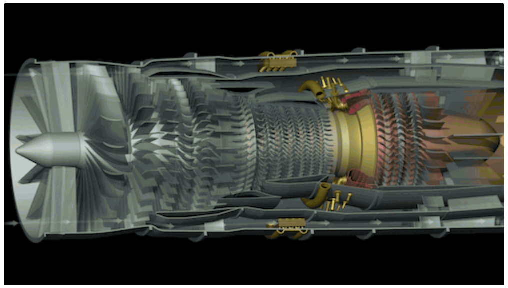
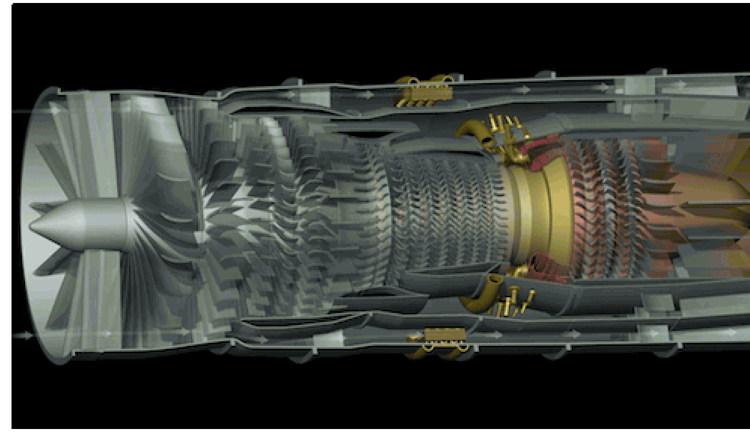
- A combination conventional turbofan coupled with an electrically driven fan (powered by batteries) might make sense for a 737/A320 type short haul aircraft
  - Turbofan power plus electric fan for takeoff
  - Turbofan power only for cruise



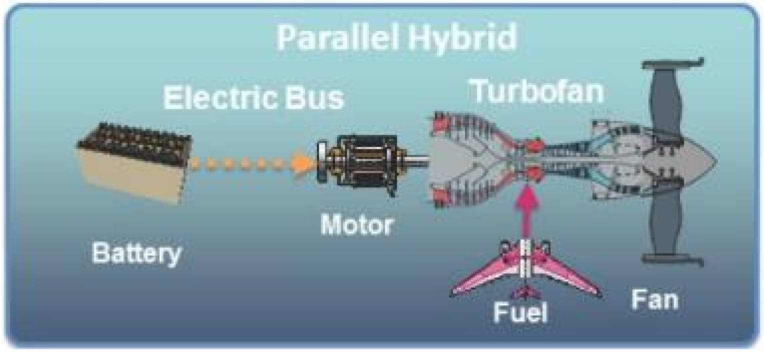
Future jet engine concepts-Variable cycles

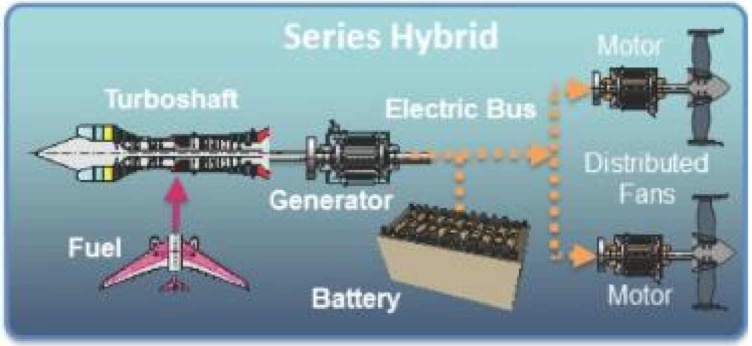
- Variable cycle or "adaptive cycle" engines
- Can switch between high power and high efficiency modes
- Engine's architecture shifts air flow between the core, the main bypass, and a third stream to achieve thrust, optimal performance, and fuel efficiency
- The high-pressure core exhaust and the low-pressure bypass streams of a conventional turbofan are joined by a third, outer flowpath that can be opened and closed in response to flight conditions
- For takeoff, the third stream is closed off to reduce the bypass ratio
- This sends more of the airflow through the high-pressure core to increase thrust
- When cruising, the third bypass stream is opened to increase the bypass ratio and reduce fuel consumption



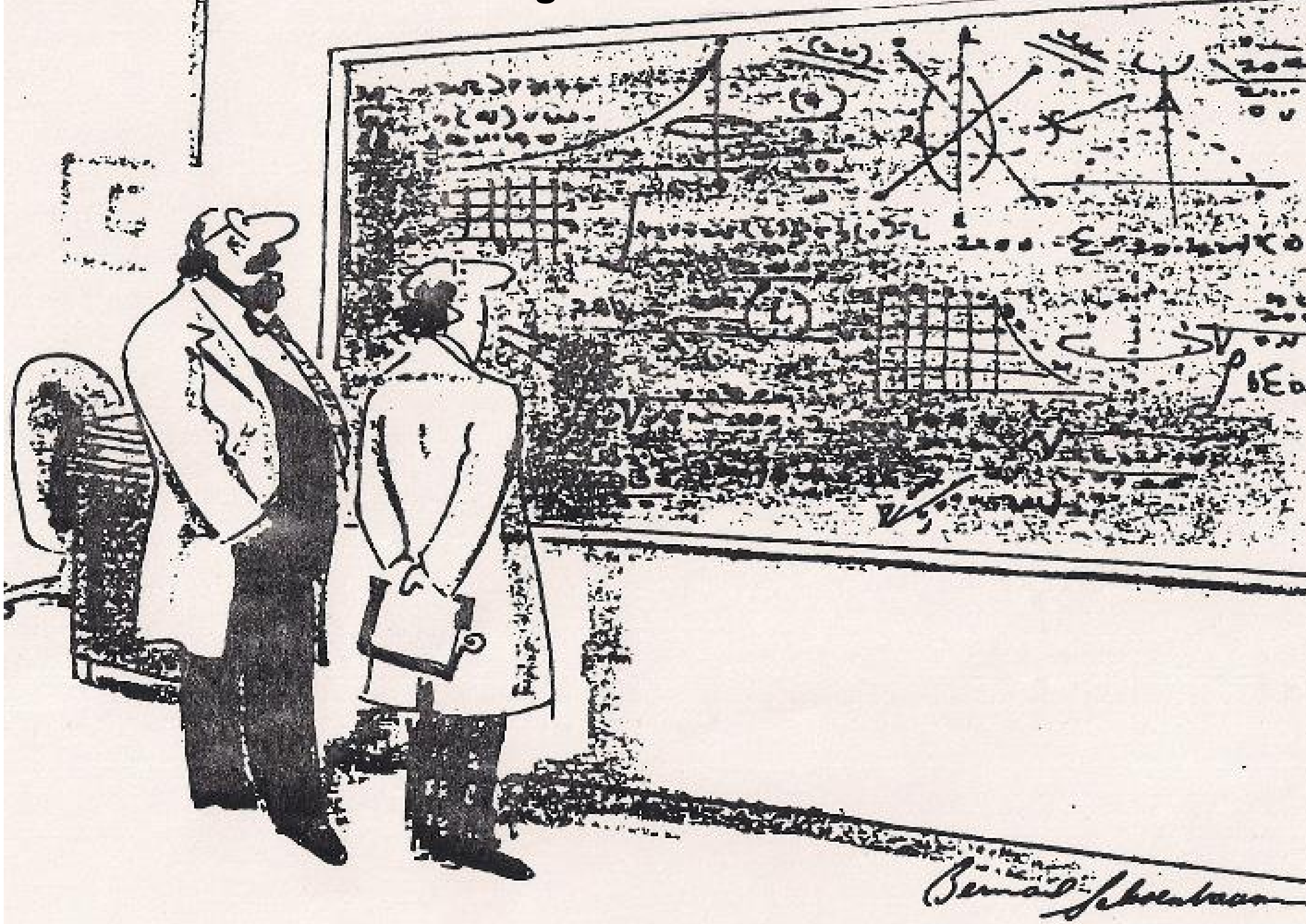
Future jet engine concepts- Hybrid Electrics

- The hybrid systems use gas turbine engines for propulsion and to charge batteries; the batteries also provide energy for propulsion during one or more phases of flight
- A parallel hybrid system, a battery-powered motor and a turbine engine are both mounted on a shaft that drives a fan, so that either or both can provide propulsion at any given time
- A series hybrid system, only the electric motors are mechanically connected to the fans; the gas turbine is used to drive an electrical generator, the output of which drives the motors and/or charges the batteries





Jet Engines



"Oh, if only it were so simple."

Jet Engines-Powering Modern Airplanes