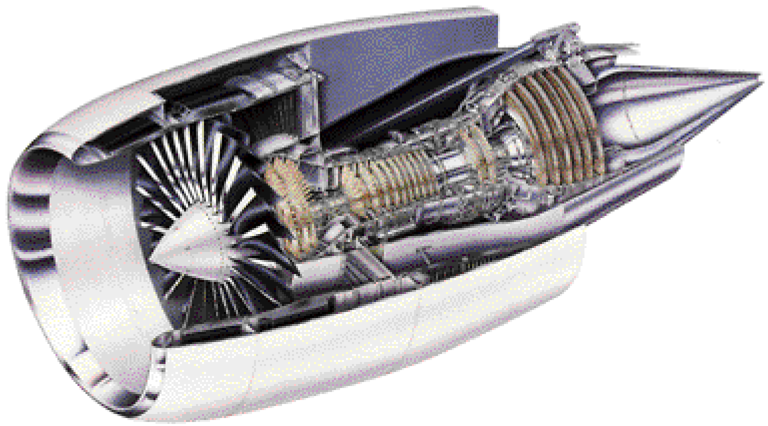
The GE90 - An Introduction



GE-90 TURBOFAN ENGINE (CUT-AWAY VIEW)

Built by General Electric in conjunction with SNECMA of France, IHI of Japan and FiatAvio of Italy, and first commissioned by the British Airways for its new fleet of Boeing 777s recently (September 1995), it is the most powerful commercial aircraft engine today. Certified at a Take-Off Thrust of 380 kN (85,000 lb.), only two engines suffice for a huge aircraft like the 777 with a seating capacity of 375 (weight approx. 230 tonnes). A derivative of the GE/NASA **E**nergy **E**fficient **E**ngine (**E^3**) program, it is also the most fuel efficient, silent and environment friendly engine of today. In addition to the highest thrust to be offered, the GE90 is expected to provide airlines with a 5-6% improvement in fuel burn, lower noise pollution, and NO_X emissions 33% lower than today's high bypass ratio engines.

This seminar attempts at highlighting the various aspects of the engine by presenting a brief insight into its features.

COMPARISON

HIGH THRUST CLASS TURBOFAN ENGINES (> 200 kN) (modified after [2])

	GE-90	CF6-50C2	CF6-80C2
Company	General Electric (USA)	General Electric (USA)	General Electric (USA)
In use since	September 1995	1978	October 1985
First flew on	Airbus A-340 & B-777	KC-10 (Military)	A-300/310, 747/767
Description	High Bypass TF	Two-Shaft High BPR TF	Two-Shaft High BPR TF
Weight (Dry)	---	3960 kg	4144 kg
Overall Length	4775 mm	4394 mm	4087 mm
Intake/Fan Diameter	3124 mm	2195 mm	2362 mm
Pressure Ratio	39.3	29.13	30.4
Bypass Ratio	8.4	5.7	5.05
Thrust at TO	388.8 kN	233.5 kN	276 kN
Thrust during Cruise	70 kN	50.3 kN	50.4 kN
S.F.C. (SLS)	8.30 mg/N-s	10.51 mg/N-s	9.32 mg/N-s
Air mass flow rate	1350 kg/s	591 kg/s	802 kg/s
Presence of FADEC*	Yes	No	Yes
Other information	33 % lower NO_x emission . Less noise than other TFs in its class (due to low fan tip speed)	TET of LPT is 1144 K.	Lower fuel burn (s.f.c.) than other engines, long life, high reliability.

	RB-211-524G/H	Trent-882	JT-9D-7R4
Company	Rolls Royce (UK)	Rolls Royce (UK)	Pratt & Whitney (USA)
In use since	February 1990	August 1994 (Cert.)	February 1969 (first)
First flew on	747-400 & 767-300	Boeing 777	Boeing 747/767, A310
Description	Three-Shaft Axial TF	Three Shaft TF	Twin-Spool TF
Weight (Dry)	4479 kg	5447 kg	4029 kg
Overall Length	3175 mm	4369 mm	3371 mm
Intake/Fan Diameter	2192 mm	2794 mm	2463 mm
Pressure Ratio	33	33+	22
Bypass Ratio	4.3	4.3+	5
Thrust at TO	269.4 kN	366.1 kN	202.3 kN
Thrust during Cruise	52.1 kN	72.2 kN	176.3 kN
S.F.C.	15.95 mg/N-s (cruise)	15.66 mg/N-s (cruise)	10.06 mg/N-s
Air mass flow rate	728 kg/s	728+ kg/s	687 kg/s
FADEC (Y/N)	No	Yes	No
Other information		Most powerful conventional a/c engine in contract (till Sept. '95) in the world (Trent 772)	

***FADEC - Fully Automated Digital Engine Control**

- gives improved fuel consumption.
- better engine control and reduces pilot work load by interacting with aircraft computers.
- lower aircraft operating costs.

LOW THRUST CLASS TURBOFAN ENGINES (< 200 kN) (modified after [2])

	CFM56-5C2	JT-8D-17R	V 2500-A1
Company	CFM International (France) & GE (USA)	Pratt & Whitney (USA)	Intl. Aero Engines (USA)
In use since	Late 1992	February 1970	July 1988
First flew on	Airbus A-340	Boeing 727/737 & DC-9	Airbus A-320
Description	Two Shaft Subsonic TF	Axial Flow Twin-Spool TF	Twin Spool Subsonic TF
Weight (Dry)	2492 kg (Bare Engine) 3856 kg (approx.)	1585 kg	2242 kg (Bare Engine) 3311 kg (with powerplant)
Overall Length	2616 mm	3137 mm	3200 mm
Intake/Fan Diameter	1836 mm	1080 mm	1600 mm
Pressure Ratio	37.4	17.3	29.4
Bypass Ratio	6.6	1.00	5.42
Thrust at TO	138.8 kN	72.9 kN	111.25 kN
Thrust during Cruise	30.78 kN	18.9 kN	21.6 kN
S.F.C.	16.06 mg/N-s	23.37 mg/N-s	16.29 mg/N-s
Air mass flow rate	466 kg/s	148 kg/s	355 kg/s
FADEC (Y/N)	Yes	No	Yes
Other information			

GE-90 TURBOFAN CYCLE ANALYSIS

Following are the results of a simple high bypass ratio turbofan engine cycle analysis carried with the help of a computer program. The theory of the analysis can be found in [3]. A more extensive and accurate analysis can be obtained from [4]. The available data on the GE90 engine was merely limited to its take-off thrust, bypass ratio (BPR) and overall pressure ratio (OPR). The rest of the data is tentative and is assumed on the basis of other similar GE engines (like CF6-80C2 and CFM56) with the appropriate improvements considered.

ENGINE DATA

Intake efficiency = 0.980
Fan polytropic efficiency = 0.930
Compressor polytropic efficiency = 0.910
Turbine polytropic efficiency = 0.930
Isentropic nozzle efficiency = 0.950
Mechanical efficiency = 0.990
Combustion pressure loss (ratio) = 0.050
Fuel combustion efficiency = 0.990

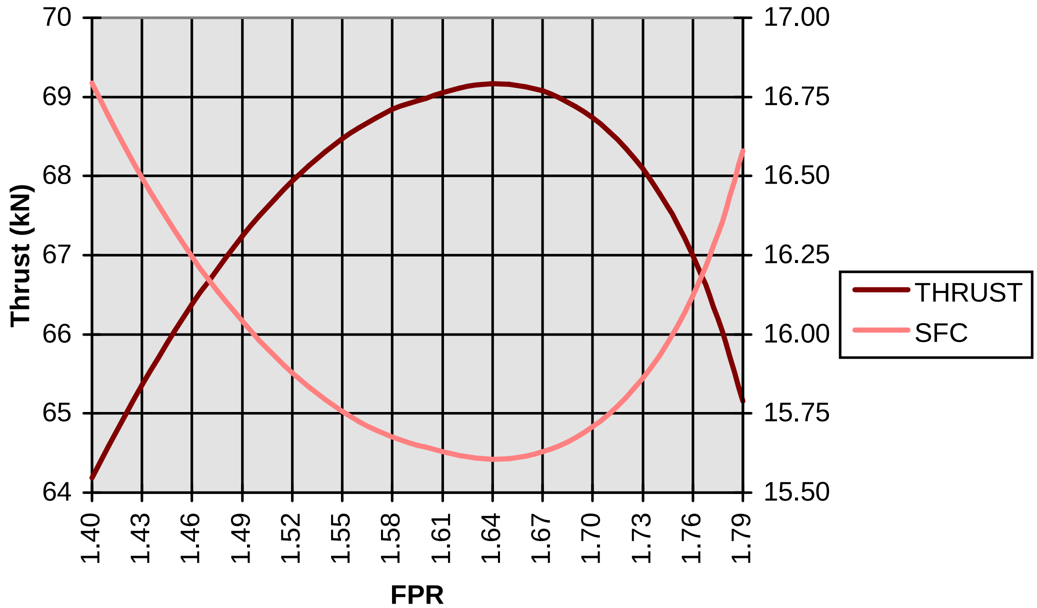
Area of hot nozzle = 1.0111 m^2
Area of cold nozzle = 3.5935 m^2

	Design Point (Cruise)	**Off-Design Point (Take-off)**
Height (km)	10.668	0.000
Mach No.	0.850	0.000
RAMPR	1.590	1.000
FPR	1.650	1.580
LPCPR	1.140	1.100
HPCPR	21.500	23.000
OPR	40.440	39.970
P_a (bars)	0.239	1.014
T_a (K)	218.820	288.160
C_a (m/s)	252.000	0.000
BPR	8.100	8.400
TIT (K)	1380.000	1592.000
m_a (kg/s)	576.000	1350.000
THRUST (kN)	69.200	375.300
m_f (kg/s)	1.079	2.968
SFC (mg/N-s)	15.600	7.910
Sp. Thrust (N-s/kg)	120.100	278.100

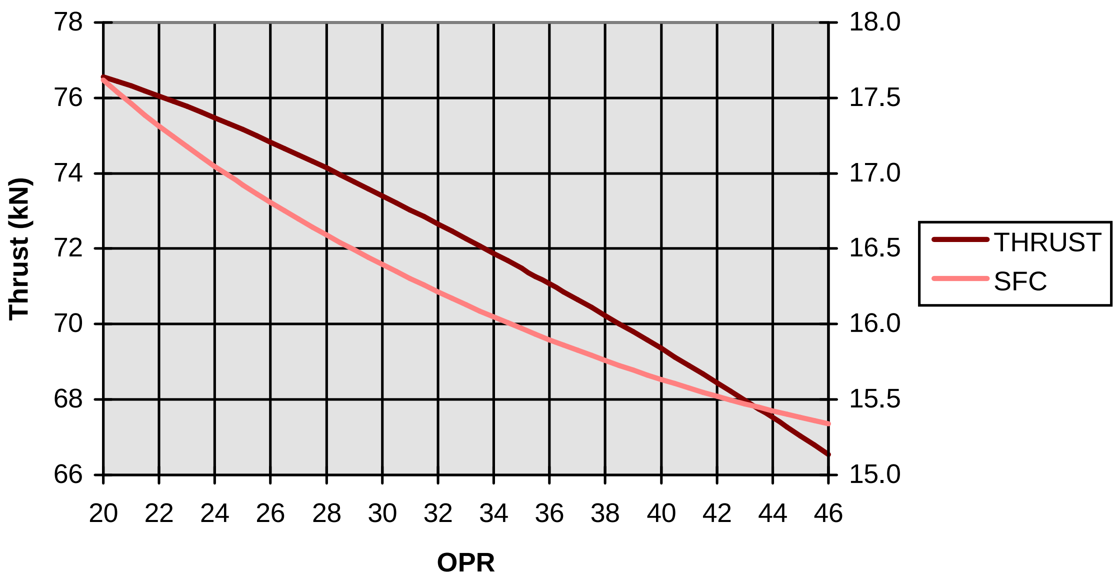
The computed value of the cruise thrust is found to be in close agreement with the thrust required by the Boeing 777 aircraft with two GE90 engines which is around 65-70 kN per engine.

GRAPHS FOR DESIGN POINT OPERATIONS (CRUISE)

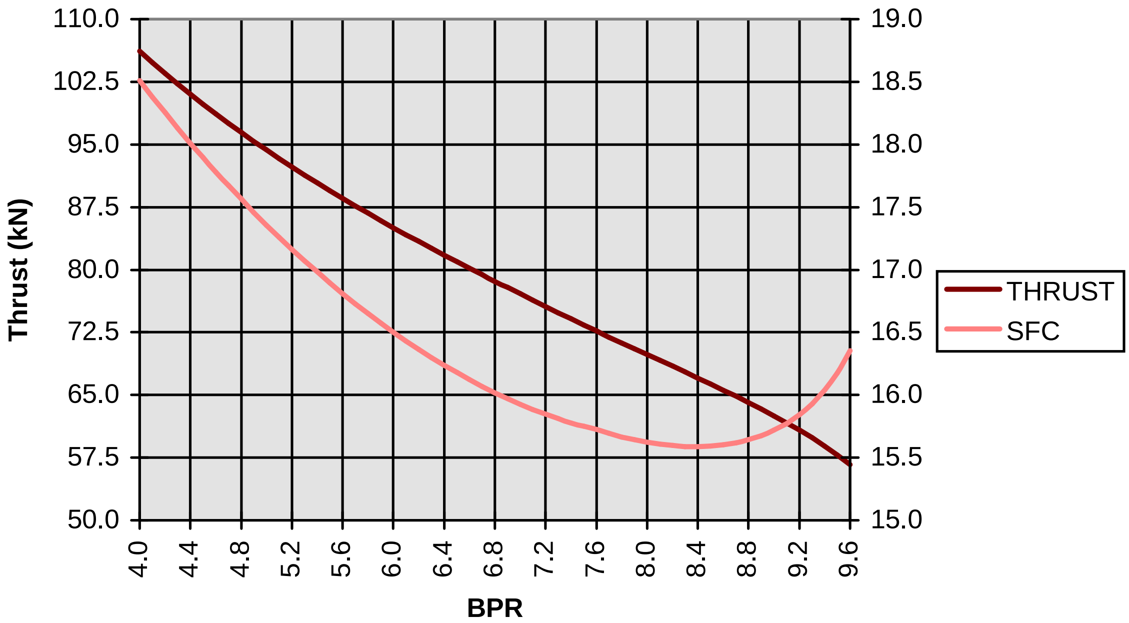
Thrust & SFC vs FPR



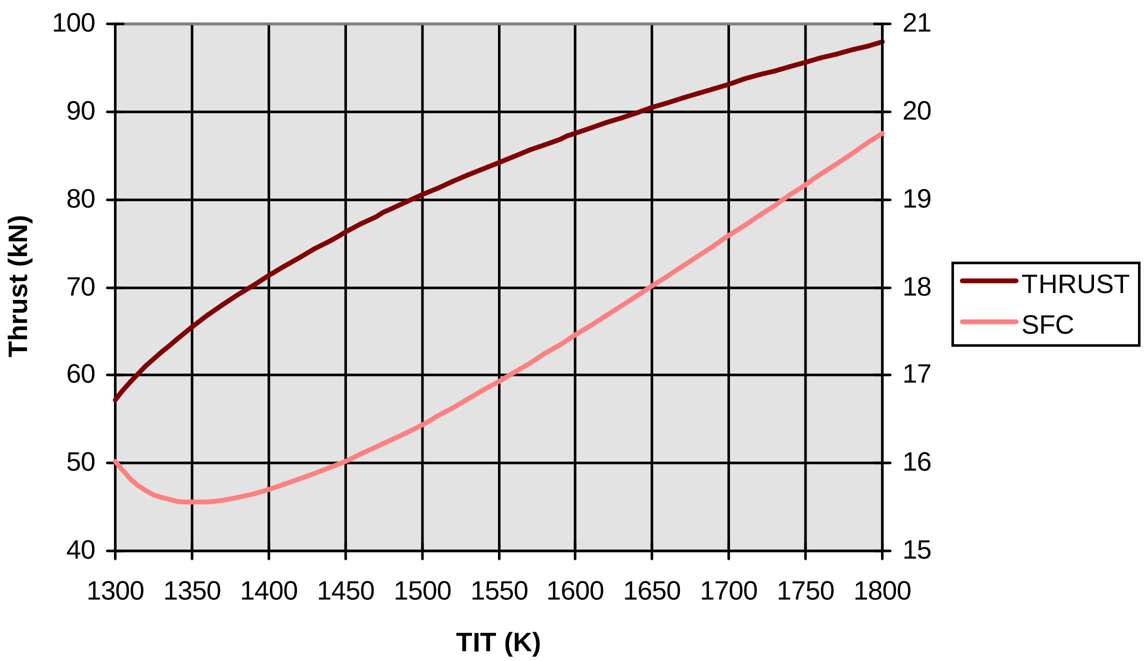
Thrust & SFC vs OPR



Thrust & SFC vs BPR



Thrust & SFC vs TIT



CERTIFICATION ([1] and [2])

MILESTONES

Date	Event
November 1992	First core test
March 1993	First engine to test with 377.8 kN thrust
April 1993	First engine to test with 468.5 kN thrust
December 1993	First GE90 flying testbed on Boeing 747
November 1994	GE90 certifies at 388.8 kN thrust
December 1994	First Boeing 777 flight test
August 1995	Boeing 777/GE90 aircraft certification
September 1995	Boeing 777/GE90 entry into service

GE90 Ground and Flight Testing -

With FAA certification of the GE90, GE Aircraft Engines brought to close one of the most extensive ground and flight test programs ever undertaken by an engine manufacturer.

GE announced the development of the GE90 in January 1990. In November 1992, the first full-scale engine core went to test; the first full engine followed in March of 1993. Since that time, GE and its revenue sharing participants have run a total of 13 development engines which have verified the engine's inherent design benefits. Overall, the engines have logged more than 5,000 hours, including 228 flight hours on GE's modified Boeing 747 flying test bed.

GE90 endurance engines completed more than 14,000 cycles and demonstrated excellent section durability. Seven engines have operated at more than 100,000 lb. (444.5 kN) of thrust, with one achieving a record-breaking 110,000 lb. (489 kN) of thrust. In fact, GE90 development engines have sustained thrust levels in excess of 100,000 lb. (444.5 kN) for more than 65 hours.

As part of the required certification testing, the GE90 successfully completed both the 2.5 and 8 lb. (1.13 and 3.63 kg) bird ingestion tests on the engine's composite blades.

In October 94, four 2.5 lb. birds were ingested with the engine running at speeds required to produce 85,000 lb. (377.8 kN) of thrust at takeoff on a hot day. There was no thrust loss and the engine responded to all throttle commands during the required 20 minutes of operation following the ingestion. All fan blades were in excellent condition and have continued to run in other engine tests.

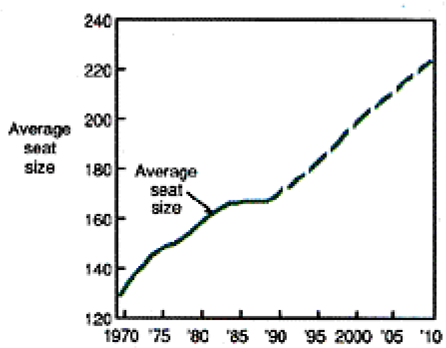
In mid-November 94, GE conducted the fan bladeout test with the FAA present. The release blade was detonated at a fan speed of 2,485 rpm, 10 rpm over the target, with the engine generating more than 105,000 lb. (466.8 kN) of sea level static (SLS) corrected thrust. The engine mount system performed as designed and the test demonstrated fan blade containment. The ruggedness of the composite fan blade was successfully demonstrated, and the observed trailing blade damage matched pre-test analysis, verifying the inherent benefits of the composite blade design.

The GE90 flew for the first time in late 1993 installed on the 747 flying testbed. Throughout the first phase of testing, the engine accumulated nearly 228 hours in 45 flights. The engine performed exceptionally well, demonstrating performance levels that were better than specification and provided pilots unrestricted throttle movement throughout the flight envelope.

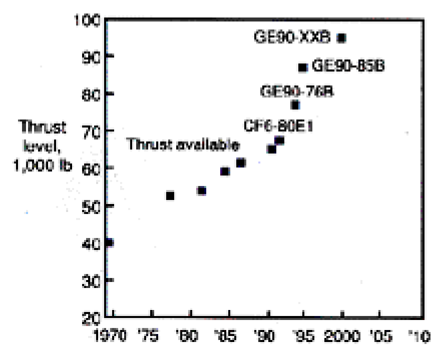
WHY AN ALL-NEW ENGINE?

Requirement by Market

Historically, aircraft have grown in weight and thrust requirements. Today, the market favors heavier and longer range aircraft with thrust growth built in.



Growth Chart 1



Growth Chart 2

The above growth charts show that trend favors GE90-powered large widebody aircraft.

Positioned for the Airline's Future

- Common engine for entire families of new, larger aircraft.
- New widebody aircraft demand 20-30% higher thrust than today's engines.
- Aircraft historically require 20-30% additional thrust for increases in TOGW.

Modern cycle design has built-in total performance advantages

- 10% better SFC than today's engines.
- High thrust growth with commonality.
- Low noise and emissions.

Reliability of Proven Technology incorporating "Lessons Learned".

GE90 DESIGN

The GE90 is designed for :

- Thrust Growth.
- Engine commonality for the 777 Airplane Family.
- Fuel Efficiency.
- 180-Minute ETOPS (Extended Twin OPerationS).

- Low Emissions.
- Low Noise.
- Reduced Operating Cost.

Cycle Selected for significant fuel savings.

- Bypass ratio optimized.
- Overall pressure ratio optimized.
- Designed for lowest SFC and fuel burn.

Designs selected for maximum airline benefit.

- Designed and demonstrated technologies for high reliability.
- Builds on CF6 and CFM56 reliability.
- ETOPS approval.
- Operator developed maintenance procedures.
- Designed for low noise and low emissions.
- Designed for Lowest Operating Cost.

Engine Sized For Future Aircraft Requirements.

- Initial certification at 84,700 lb. (376.5 kN) thrust - February 1995
- First growth certification at 92,000 lb. (408.9 kN) thrust - May 1996.
- Potential to grow to 120,000 lb. (533.4 kN).

HIGH THRUST AND TEST EXPERIENCE

Summary

- Over 145 Hours at > 422.3 kN
- Over 95 Hours at > 435.6 kN
- Over 75 Hours at > 440.0 kN
- Over 65 Hours at > 444.5 kN
- 20 Hours of Continuous Running on 900-105/1A at > 444.5 kN

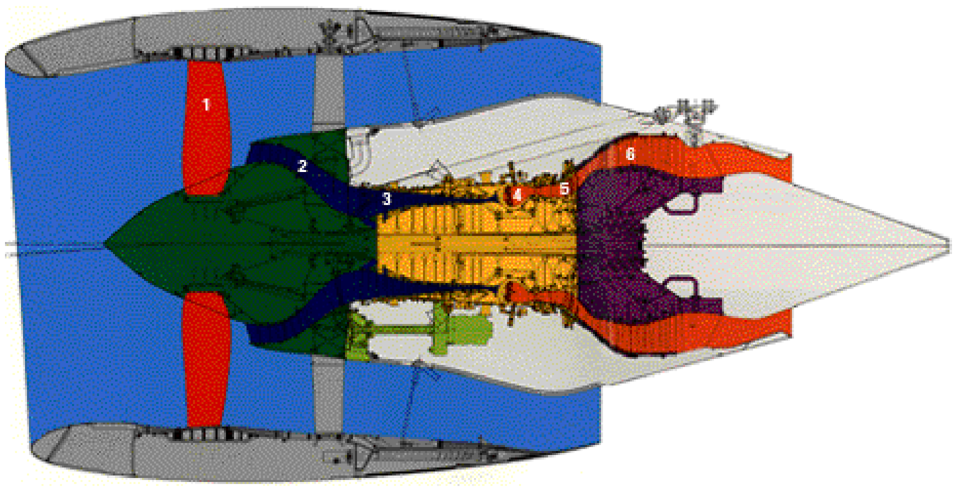
Note **:** Sea Level Static (SLS) Corrected Thrust Levels

Eight GE90 engines have operated at or above 445 kN of SLS Thrust.

Various tests carried out

- Fan Mapping.
- Booster Stress Survey.
- Overspeed Certification (490.3 kN).
- “Dress Rehearsal” for Triple Redline Block Test.
- 1.13 kg Bird Certification / Blade Out Certification.

THE ENGINE AND ITS COMPONENTS ([2])



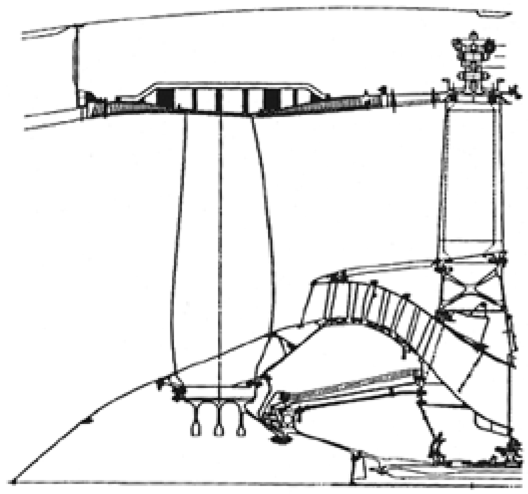
GE-90 TURBOFAN ENGINE (CROSS-SECTIONAL VIEW)

The following are the main components of the engine -

1. Composite fan
2. Low Pressure Compressor (LPC) / Booster
3. High Pressure Compressor (HPC)
4. Dual Dome Combustor
5. High Pressure Turbine (HPT)
6. Low pressure Turbine (LPT)

COMPOSITE FAN

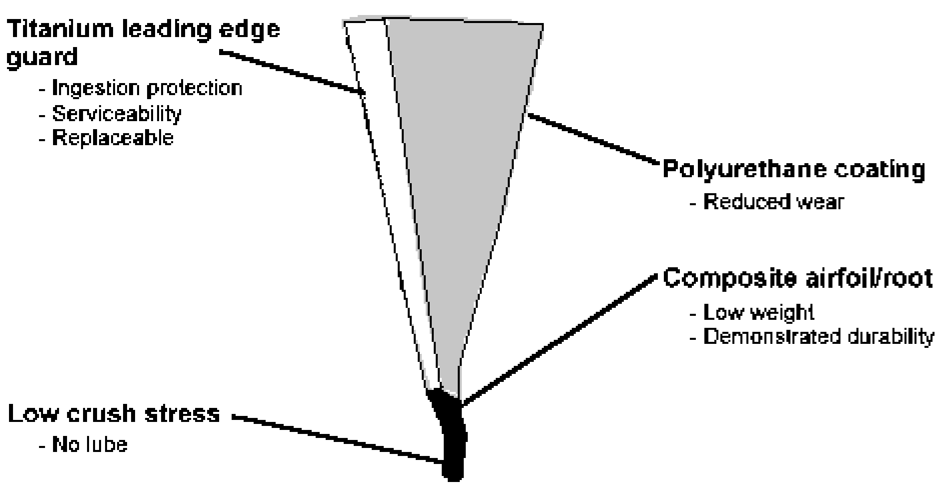
GE90 Fan Design



Fan Diagram

- 22 composite wide-chord blades and platforms.
- Large fan diameter for higher air mass flow.
- Fan geared - reduces fan tip speed thus producing less noise.
- Low tip speed and pressure ratio for quiet efficient operation.
- Lightweight tri-web disk for inspectibility and reduced weight.
- Hybrid (conical/elliptical) spinner for low core debris ingestion.
- Fan Pressure Ratio (FPR) about 1.60-1.65 (tentative).

GE90 Fan Blade



Fan Blade

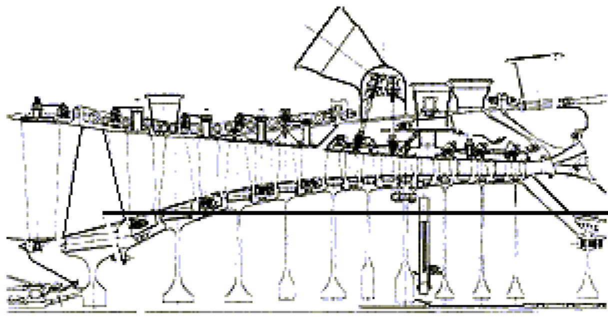
- Wide Chord Composite Fan - high performance and low weight.
- Environmental resistance - GE90 fan material system displays equal environmental resistance like those of current aircraft composites.

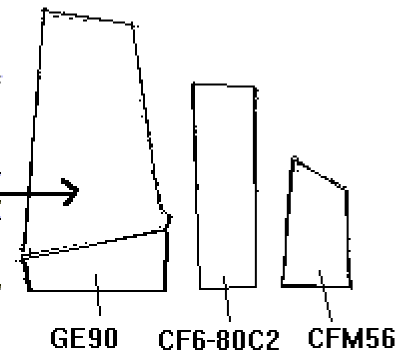
- GE90 fan composite material system demonstrated similar to those currently in service.
- Laminated specimens fully exposed to aircraft fluids typically maintained 95 percent base properties.
- Actual blade fully protected by polyurethane coating.
- No exposure to ultraviolet radiation.

Composite Fan Development History

- GE90 Composite Blade Benefits from 25 Years of Development.
- Materials, manufacturing and computing advances have provided the necessary technology.

COMPRESSOR





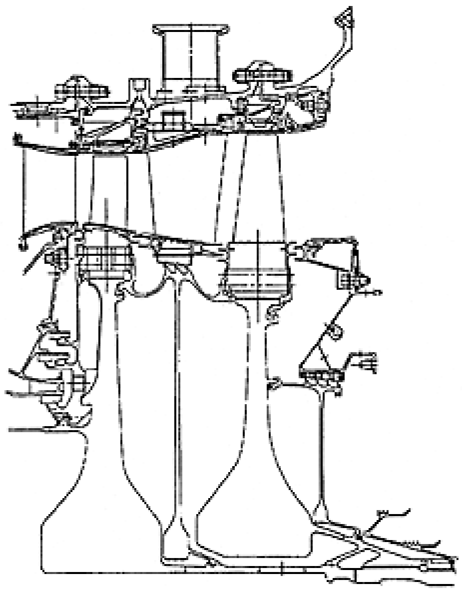
Compressor Diagram **First Stage HPC blade**

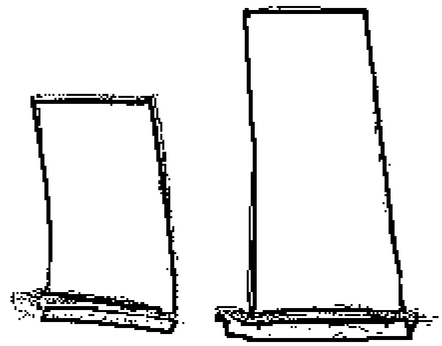
- Structure similar to successful CFM56.
- Compact engine construction.
- Rugged, low aspect ratio airfoils.
- Reduced part count.
- Reduced operating cost.
- Short LPC/booster - 3 stages.
- LPC Pressure Ratio (LPCPR) around 1.10-1.14 (tentative).
- Low LPT entry temperatures for thrust growth.
- 10 stage HPC with 23-to-1 Pressure Ratio (HPCPR).
- Scale-up of the NASA **E**nergy **E**fficient **E**ngine (**E^3)** demonstrated performance and operability in both test cell and flight test.

COMBUSTOR

- Dual dome annular combustor from successful advanced military programs.
- Reduced NO_X emission levels (as low as 10 ppm.).
- Reduced unburned hydrocarbon, carbon monoxide and smoke levels.
- Improved operability.
- Long-life liner construction.
- Dome aero-thermo tuned for power setting.
- Altitude re-light capability 30,000 ft (9.144 km) with margin.

TURBINE





Turbine Diagram **HP Turbine Blade - Stages 1 & 2 resp.**

- High Pressure Turbine incorporates proven design technology.
- 6-stage LPT and 2-stage HPT.
- Stiff, simply supported rotor system like CFM56 for dynamic stability.
- Boltless assembly airfoil and shroud cooling circuits modeled after successful CF6-80 design.
- Introduces film-cooled technology from proven turbine experience.
- Multihole turbine cooling technology - better cooling effectiveness.
- Successful CF6-80 designs and passive clearance control system features.
- Stage 1 HPT blade casting with laser drilled cooling hole pattern (Material N5).
- Stage 2 HPT blade with laser drilled cooling hole pattern (Material N5).
- Modular nozzle assemblies based on CFM56 and CF6-80 designs.

OTHER FEATURES ([2])

GE90 AND THE ENVIRONMENT

Reduced Emissions and Smoke

- Dual Dome Combustor.
- Reduced Noise.
- Low Fan Pressure Ratio and large aspect ratio low pressure turbine.
- Overall lower mission total fuel burn = Lower total mission pollutants.
- Higher thrust to core flow ratio.

GE90 Combustor Provides Improved Operability with Reduced Emission Levels

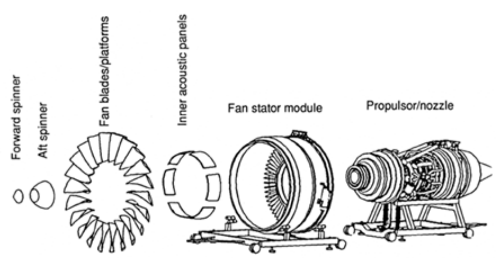
- Double Annular Combustor.
- Pilot dome optimized for operability - main dome optimized for high power.
- Emissions reduction Based on 15 years of NASA and Advanced Military Engine Development.
- Full-scale GE90 Testing.
- Exit temperature profiles meet design intent.
- Emission levels verified.

TRANSPORTABILITY

- Designed for Standard Engine Transport Methods.

GE90 Propulsor

- Smaller than the high bypass turbofans of today



Propulsor Smaller than CF6

GE90 Modular Design

- Allows replacement of propulsor only
- Separate Propulsor/Nozzle from Fan Stator Module
- Fan stator module remains at main base or with aircraft
- Removal and Replacement Time Estimated at Less than 6 Hours

FUTURE OF GE90 ([2])

THRUST GROWTH

GE90 components are sized for growth. If the market requires it, 110,000 lb. (511 kN) of thrust could be produced by a GE90 with further investment. The following are the ways General Electric intends to achieve the thrust increment -

- **376.5 kN Fan**
  Certification Engine.
  B777 “B” Market.

- **409 kN Fan**
  Improved LPT Materials.
  Increased HPT Cooling and 1st Stage Blade TBC.
  B777 “B” Market.
  B777 Stretch.

- **422.3 - 435.6 kN Fan**
  Improved Turbomachinery.

- **466.8 kN Fan**
  Higher P/P Fan with Destaged Core.

- **511.2 + kN TF**
  Higher Speed and P/P Fan with Destaged Core.

CONCLUSION

It is seen that GE90 is indeed the most powerful and efficient commercial transport engine of the 90's. It also has ample scope for thrust growth to keep up with the future requirements. Although unavailability of exact technical information on the engine such as its weight, pressure ratio, TIT, cruise thrust, s.f.c, etc. render the data in this report tentative, its comparison with other engines clearly shows that it is a class apart from them in terms of thrust and fuel efficiency.

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