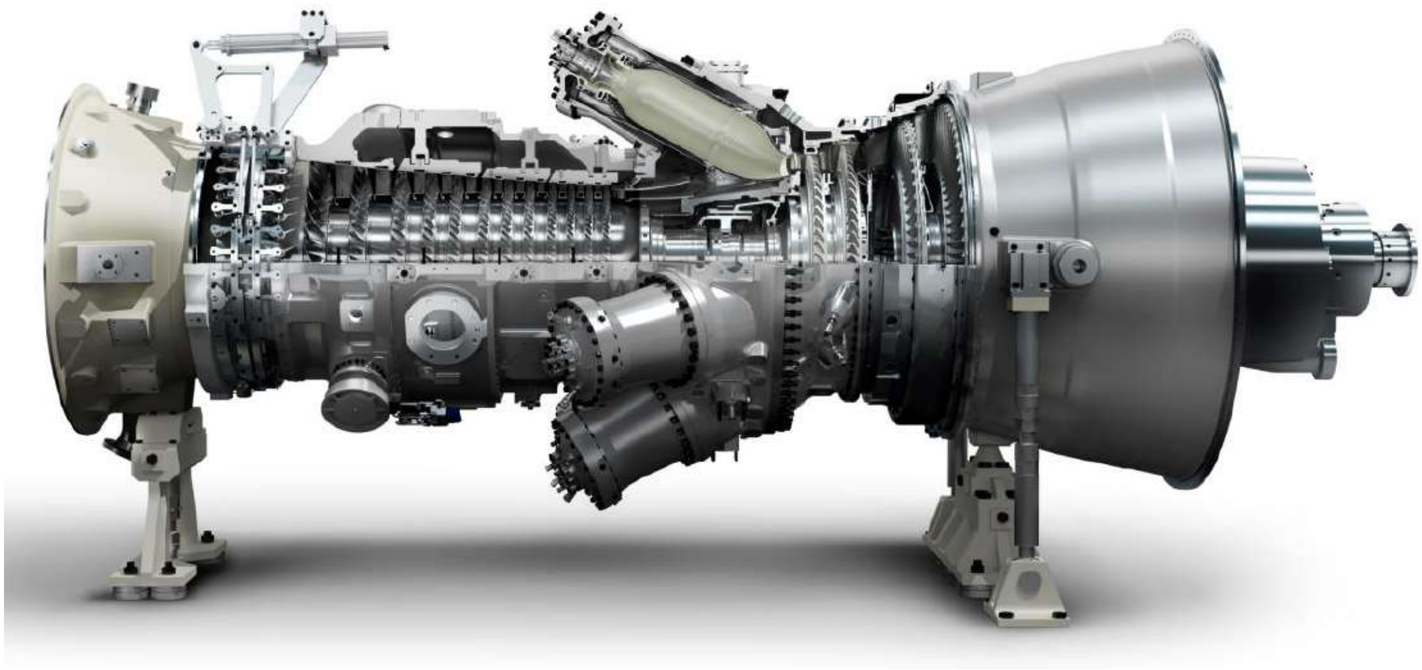
MJ2430 - Thermal Turbomachinery
MJ2244 – Airbreathing Propulsion II

Introductory Lecture



Jens Fridh, KTH

2019-01-15

Course Team

- Examiner
  - *Assc. Prof. Paul Petrie-Repar*

- Main lecturers
  - *Jens Fridh, course responsible MJ2430*
  - *Nenad Glodic, course responsible MJ2244*

- Lab/Course Assistants
  - *Silvia Trevisan*
  - *Arijit Sinha Roy*

- Guest lecturer
  - *Simon von Eckerstein (SIT)*

Agenda

- Course content
  - subjects covered in course
- Course concept
- Administrative aspects
  - Enlisting, schedule, lab, self-assessments etc.
- **Introduction to thermal turbomachines**

Course content

- Advanced course on thermal turbomachinery
  Used in propulsion, power generation, mechanical drive

- Orientation in engineering curriculum
  Thermodynamics, fluid dynamics
  ↓
  Turbomachinery, MJ2429 (period 1, 2)
  Jet propulsion, MJ2241 (period 2)
  ↓
  Thermal turbomachinery, MJ2430 (period 3)
  Air breathing propulsion II, MJ2244 (period 3)

GE GeNX

- Goals
  (To understand the basic principles turbomachinery)
  To understand turbomachinery flow in 2D/3D manner
  To be able to perform preliminary 3D design on turbomachinery
  To discuss specific subjects of thermal turbomachines on an advanced level
  To be aware of current developments and about future challenges

This course!!!

- 20 lectures/seminars with calculation examples

  Department lecturers + guest lecturers

- Laboratory exercise →1 ECTS

  MJ2430 / MJ2244: Measurement of the Steady and Unsteady Loading in a Flutter Cascade, *short lab report compulsory*

  MJ2244: one additional demonstration lab (small jet engine lab)

- Study visit Monday 4 March (Siemens, Finspong), enlisting via Canvas, *await confirmation*

- The courses Thermal Turbomachinery MJ2430 and Airbreathing Propulsion II MJ2244 are to a high degree co-taught (only register to one!)
  - MJ2244 Airbreathing Propulsion II course (Nenad… talk!)

    Same content as MJ2430, except for 1-2 additional lectures (focus on turbofan engines) and one additional demonstration lab (small jet engine lab). MJ2244 students will have access to MJ2430 canvas site.

  - Articles and additional material will be made available throughout the course that are of relevance for either or both of the courses

Administrative

- Enlisting

  Prerequisite to follow the course

  All students register (KTH course web… *my pages*)… to have access to Canvas course web. If not done, please do as soon as possible…first self-assessment on Friday!

- Course's webpages

  Canvas → event "MJ2430-VT18 Thermal Turbomachinery"

  MJ2244 will share the same event, separate section

- Lecture schedule

  Refer to KTH schedule generator

  Up-to-date schedule is maintained in the course web page (Canvas)

  All time indications: GMT+1 (Stockholm time)

- Exams

  MJ2430 / MJ2244 seperate exams on same date: Fri 15 March, 8:00 – 11:00, 2019, 3 hour session, Canvas-based: Kloker, Butter, Toker, Trötter

The exam (5 ECTS)

- Theory questions

  Multiple choice, multiple correct answers possible

- Calculation problems

  You will be asked to do a preliminary design of a turbomachine component

- Material allowed

  Summary of equations from course Canvas site

  Handheld calculator (no mobile, no laptop, no Excel, no Matlab or the like

  Dictionary (free of notes)

- Grading scale →

  Absolute scale

- Bonus points

  From (optional) self-assessments

From %	To %	Grade
92	100 (+ bonus points[3])	A
80	91	B
68	79	C
56	67	D
50	55	E
40	49	FX
0	39	F

Self-assessments

- Self-assessments

  One self assessment at the end of each week (total 7)

  Online in Canvas, not compulsory but recommended

  One week submission time (usually Friday to Friday)

  For a 75% correct self assessment, one bonus point (percentage point) is given for use in the exam (total 7 bonus points)

- Use of bonus points

  Bonus points are counted if the exam is passed (i.e. >50% correct)

  Amount to about 7-8% of the exam points (about one grading step)

Previous course evaluation

What was the best aspect of the course?

What was the best aspect of the course? (I worked: 6-8 timmar/vecka)
The fact that we had the recorded lectures in case we missed one. The content overall was very interesting too

What was the best aspect of the course? (I worked: 9-11 timmar/vecka)
Excursion to Finspang
The lectures and the study visit

What was the best aspect of the course? (I worked: 12-14 timmar/vecka)
laboratories
The Siemens visit!

What was the best aspect of the course? (I worked: 15-17 timmar/vecka)
Theoretical lectures very clear

What would you suggest to improve?

What would you suggest to improve? (I worked: 6-8 timmar/vecka)
Maybe more exercises related to structural dynamics

What would you suggest to improve? (I worked: 9-11 timmar/vecka)
more exercise solving and more exercises and respective solutions available. the test not being multiple choice with discount, and the exercise part not to be on bilda, but written instead. better explanation and assistance with the lab.

What would you suggest to improve? (I worked: 15-17 timmar/vecka)
More exercise sessions

What advice would you like to give to future participants?

What advice would you like to give to future participants? (I worked: 6-8 timmar/vecka)
Follow the recorded lectures if you miss one and also do the self assessments

What advice would you like to give to future participants? (I worked: 9-11 timmar/vecka)
attend class, do exercises and attend study visit

What advice would you like to give to future participants? (I worked: 15-17 timmar/vecka)
Study constantly

Is there anything else you would like to add?

Is there anything else you would like to add? (I worked: 15-17 timmar/vecka)
No

Have a question?

- This is normal

- Do the following

  Ask your fellow students

  Always welcome to approach teacher during lecture breaks or via Canvas

Course Literature

- Course material pdfs (main)
  - Contains a short version of material gone through in lectures
  - All documents on Canvas → Course material

- Additional reading: Cohen - Gas Turbine Theory
  - Useful additional book, when interest in thermal turbomachines exists

- Preporatory knowledge: Dixon – Fluid Mechanics and Thermodynamics of Turbomachinery
  - Useful text book, especially for those who plan to work with fluid machines in the future.
  - Note: also available as e-book at https://www.kth.se/kthb (free from inside KTH)

INTRODUCTION TO TURBOMACHINES!

Relevance of Turbomachines

- Thermal turbomachines are the back-bone of modern society
  - Used in air transport as prime mover (aircraft engines)
  - Used in the majority of thermal power generation applications (gas turbines, steam turbines…)
  - Used in mechanical drive applications where reliability and space-saving counts (gas networks, oil platforms)

- Thermal turbomachines are of extremely big importance for shaping a sustainable society

  No matter what is around the corner in terms of primary energy sources being used, thermal turbomachines will be part of the game (solar power plants…)

Relevance of Turbomachinery

- Thermal turbomachinery is the most common type of machine used in propulsion

- Most of the world's electricity production involves thermal turbomachinery

- Turbomachinery is often used as mechanical drive at remote locations (oil platforms, gas pumping stations)

- Turbomachinery is the prime mover in air transport (aircraft engines) and plays also a major role in sea (marine gas turbines, turbochargers) and in land-based transport (turbochargers)

  → airbreathing propulsion

What is ”Airbreathing propulsion”?

- Airbreathing propulsion denotes any kind of propulsion in which the surrounding air is used as base working fluid

- In a turbomachine

Compressor:	air
Combustion chamber:	air/fuel mixture
Turbine:	combustion gases

  → Air has a role as oxidizer in the process

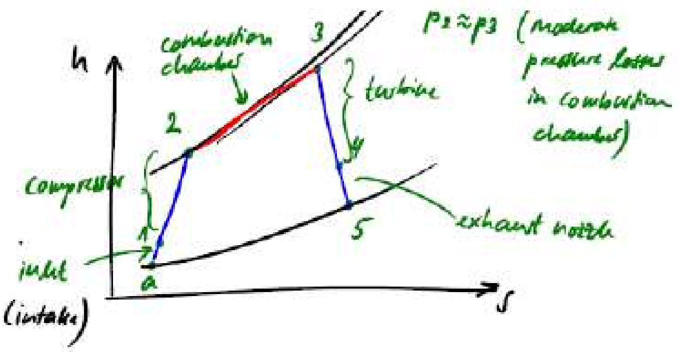
- Note: even an internal combustion engine based propulsion device falls into the category ”airbreathing propulsion”

  The focus here is however put on turbomachinery given its relevance

Turbomachines in propulsion

- Thermal turbomachines are widely used in airbreathing jet propulsion

- Propulsion principle
  - Acceleration of a certain gas
  - Energy from combustion (chemical to mechanical conversion)
  - Airbreathing propulsion: air in, fuel on board, air & combustion gas out
  - (Rocket propulsion: fuel & oxidizer on board, combustion gas out)



Turbojet cycle
Joule-Brayton

A comparison

- CFM56-7B, 1995

  Weight: 2365 kg

  Power: 17 MW

  P/W: 7 kW/kg

  Continuous motion

- Koenigsegg Agera R, 2012 (V8)

  Weight: 200 kg

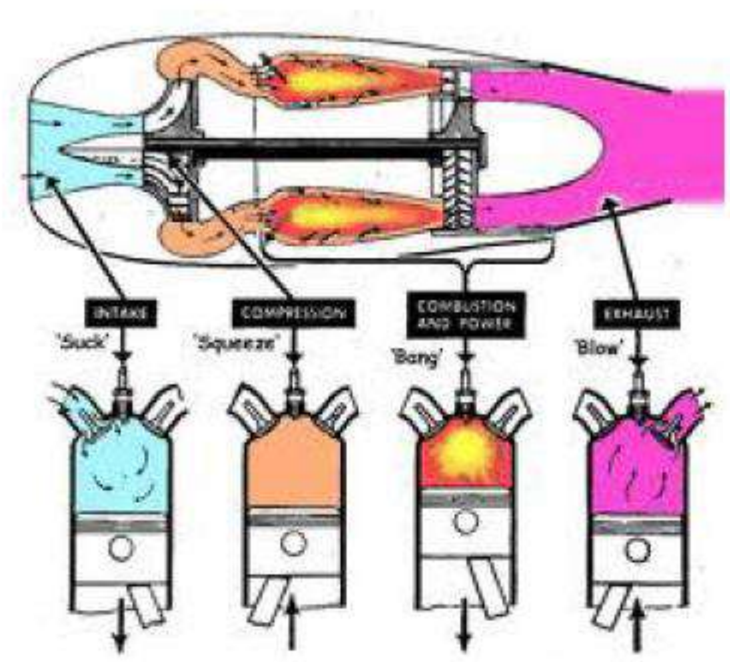
  Power: 0.84 MW (1140 hp on E85)

  P/W: 4 kW/kg…*with turbochargers!!!*

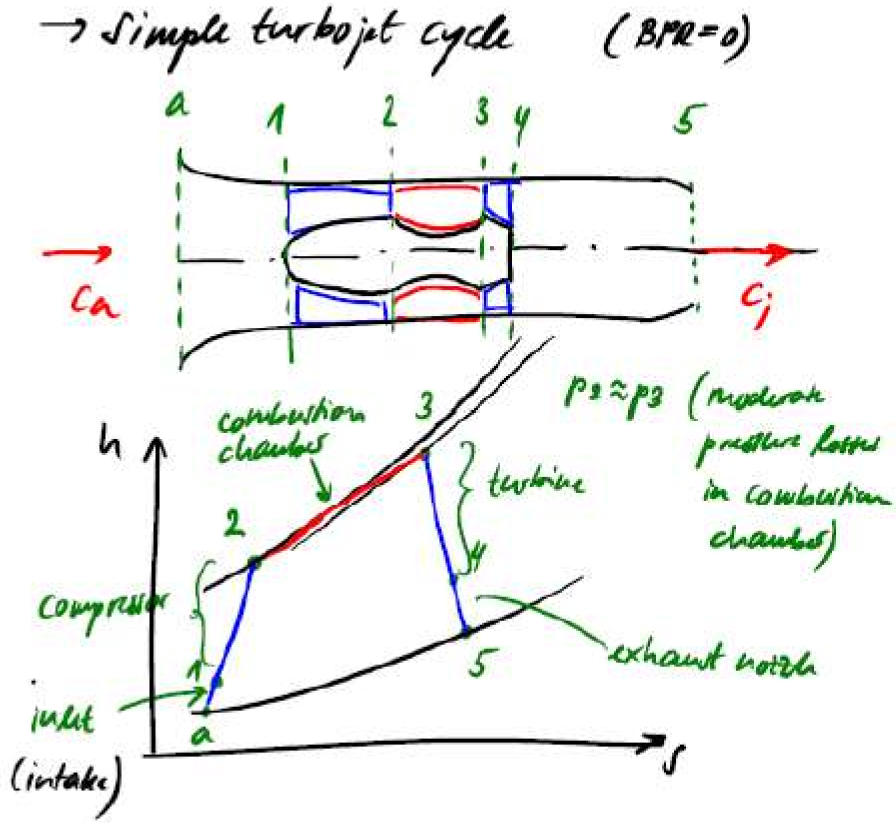
  …variable guide vanes

  ”Reciprocating” motion

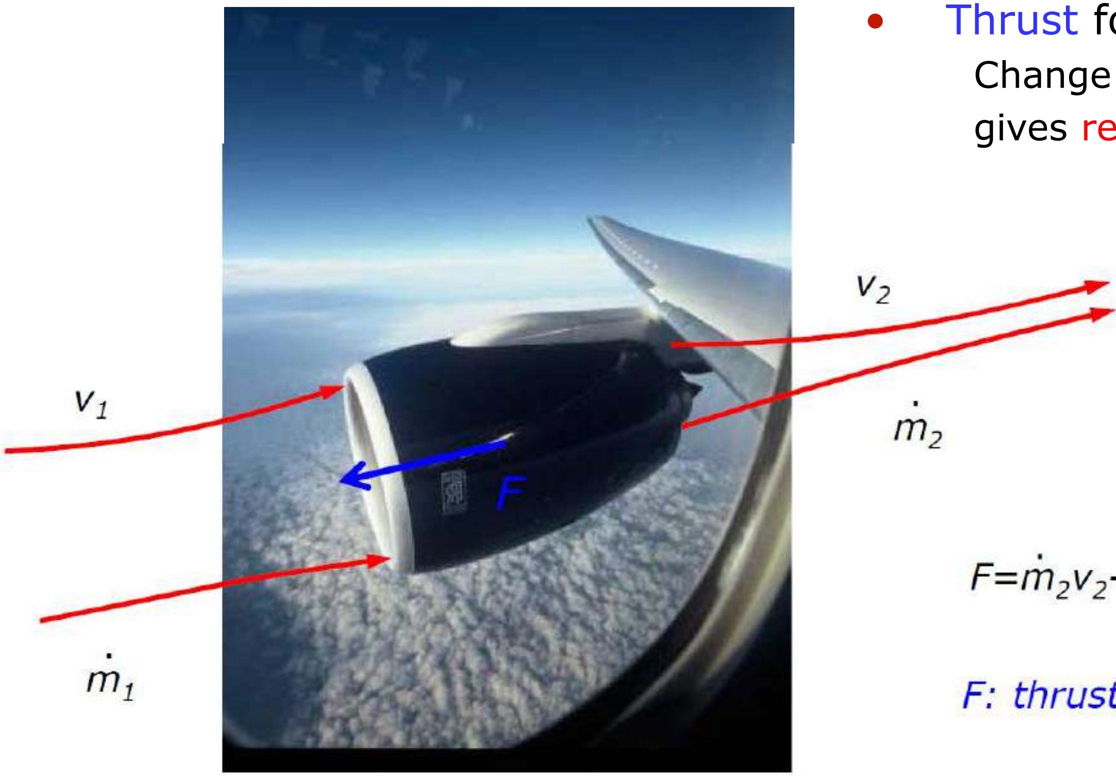
Working principle of Turbomachinery (propulsion)



Cycle thermodynamics



Airbreathing Propulsion



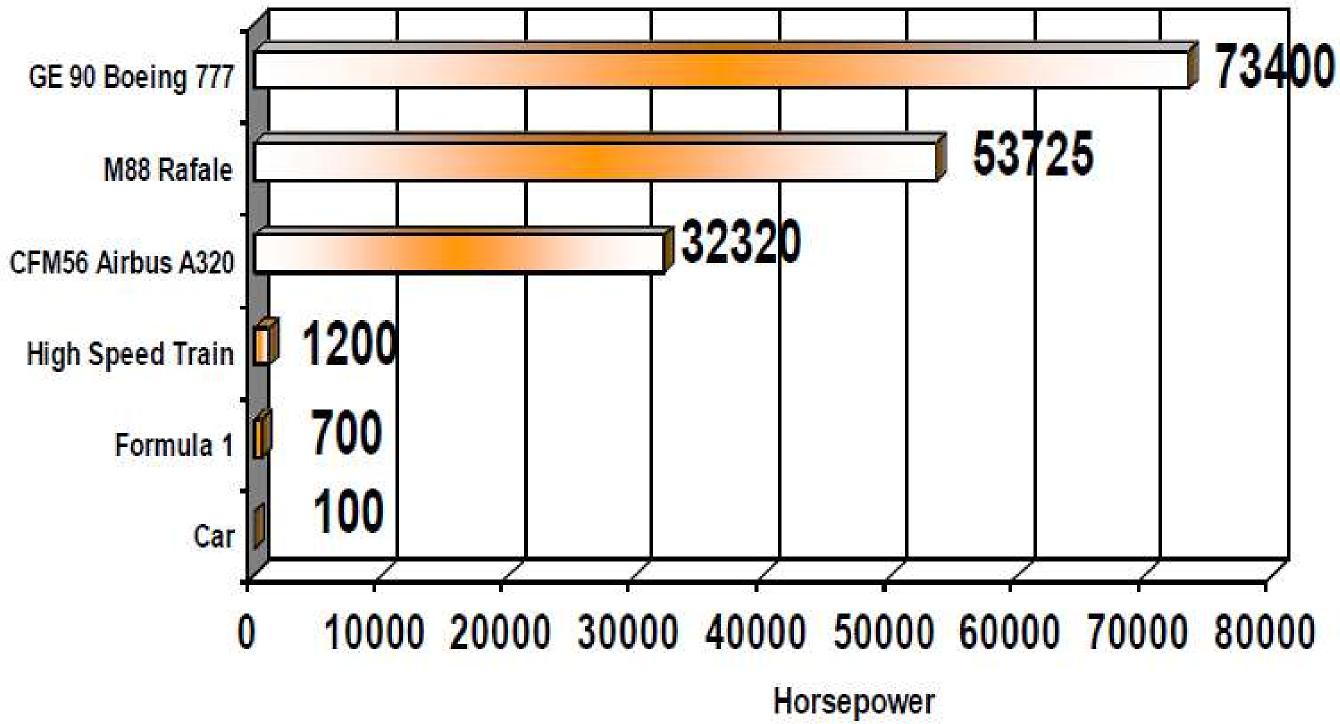
- Thrust force

  Change in momentum gives reaction force

$$F=\dot{m}_2 v_2-\dot{m}_1 v_1$$

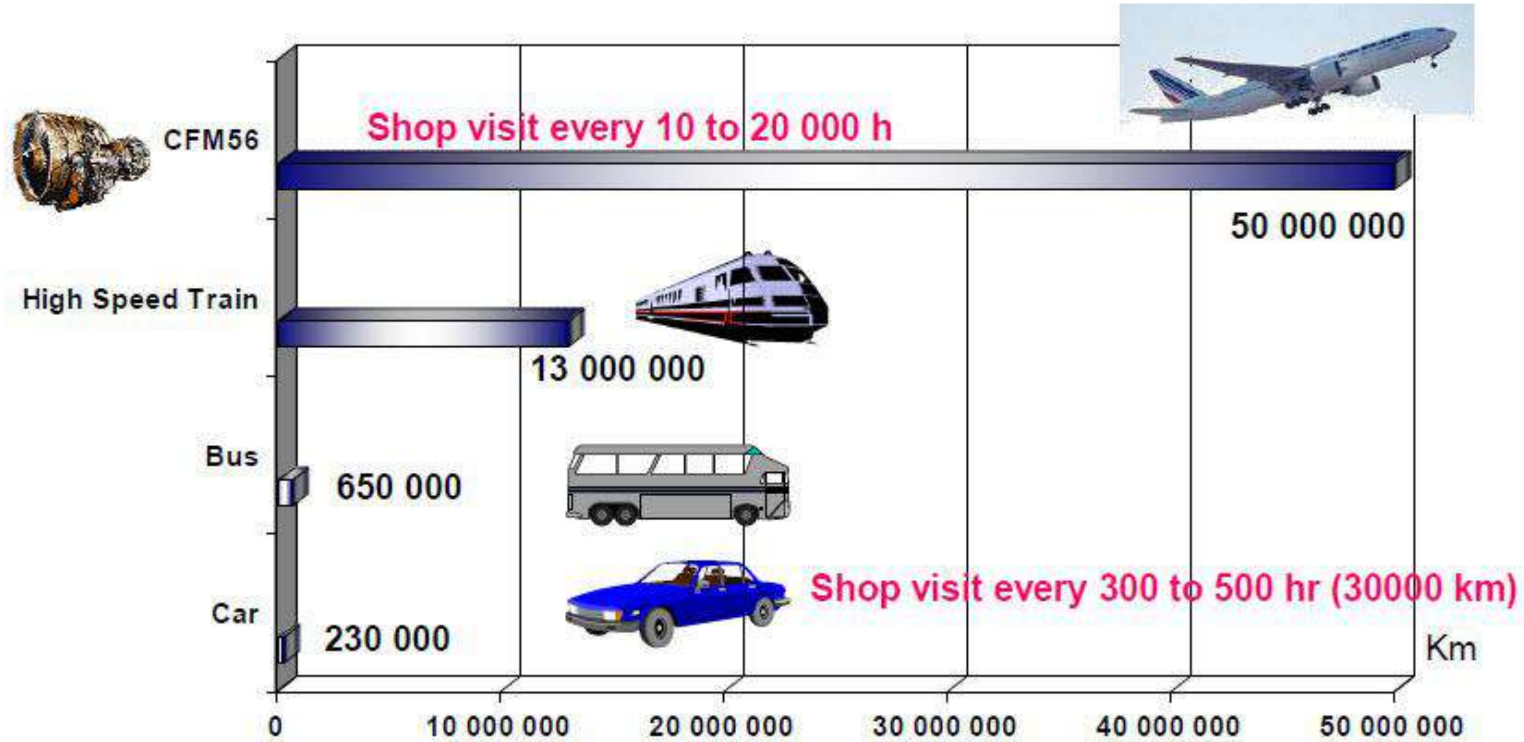
F: thrust force

Plenty of power

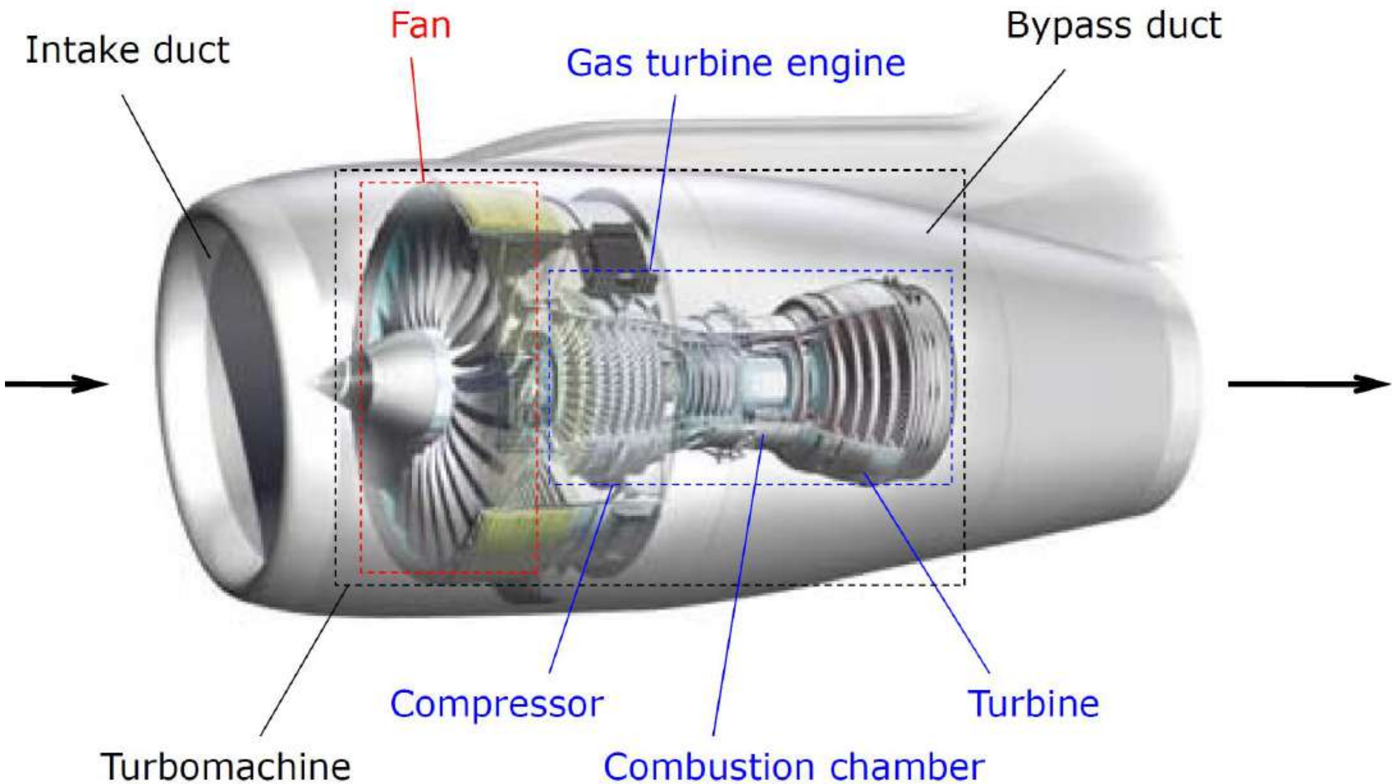


Lightweight power: engine weight for 100 hp

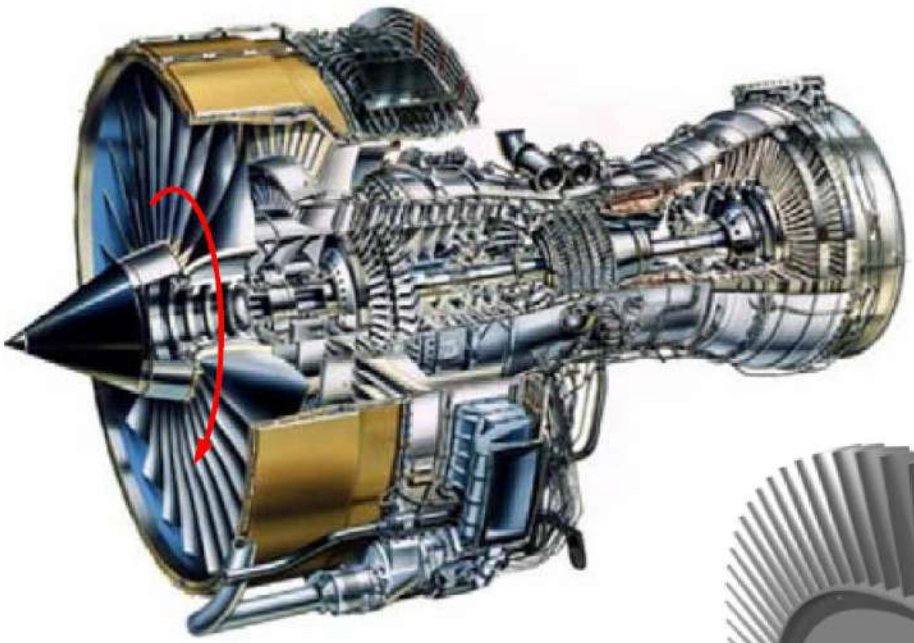
Durable power



What is Inside?



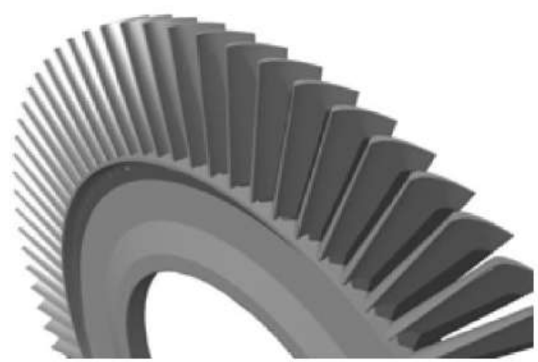
Turbomachine Environment



Blade rows

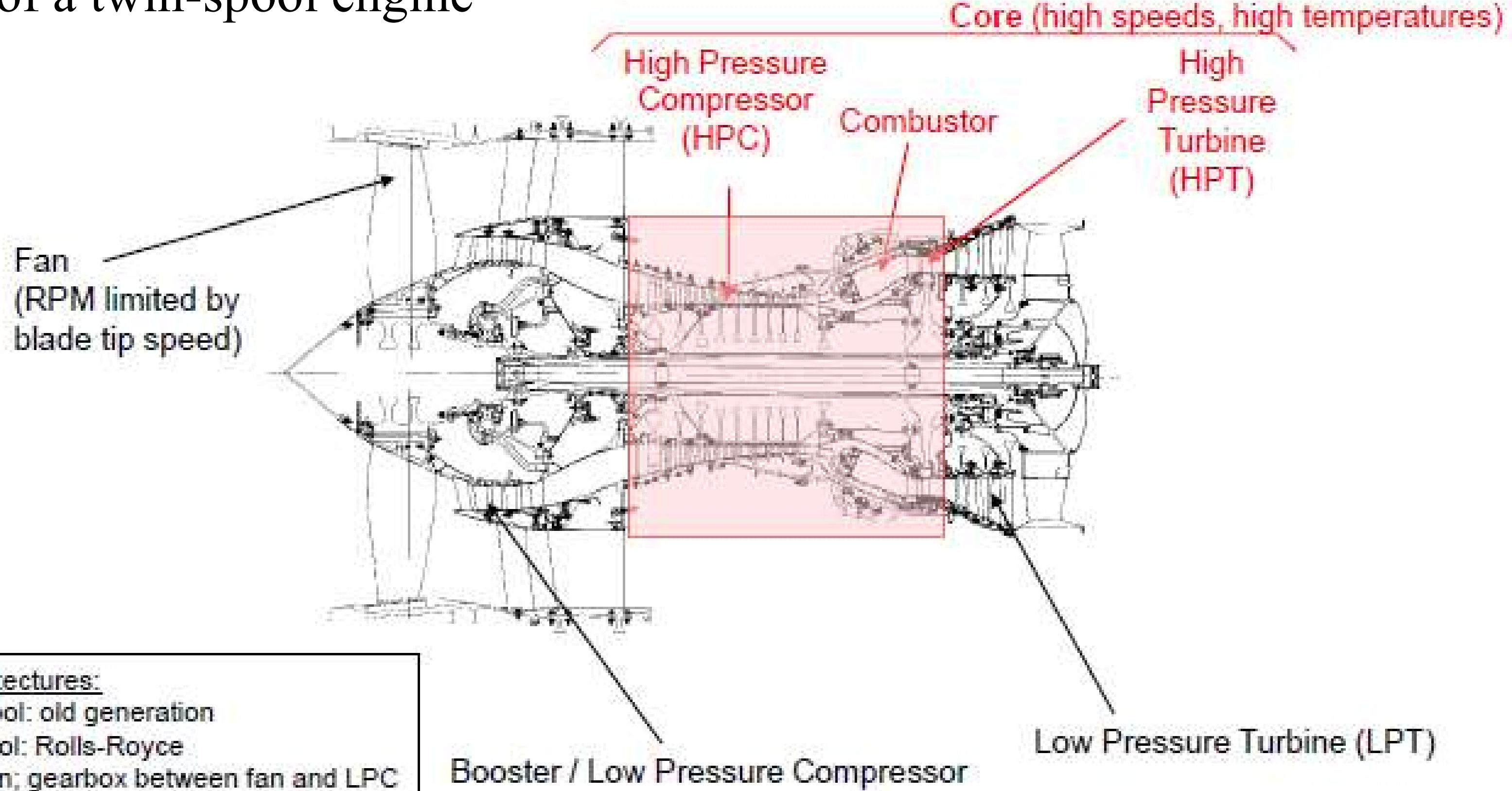
Stationary

Rotating



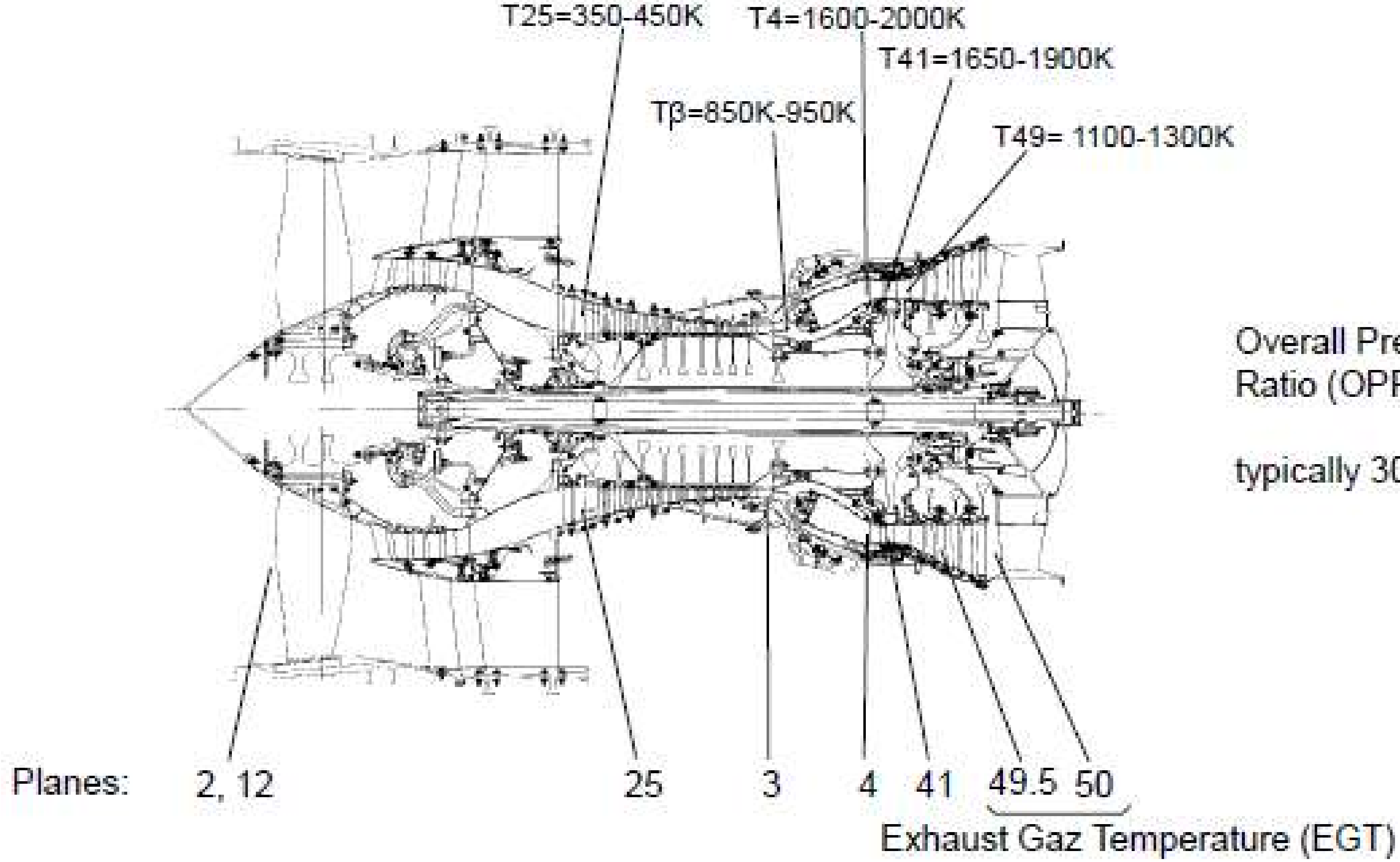
Typical engine architecture

Example of a twin-spool engine



Other architectures:
- Single spool: old generation
- Three spool: Rolls-Royce
- Geared fan; gearbox between fan and LPC

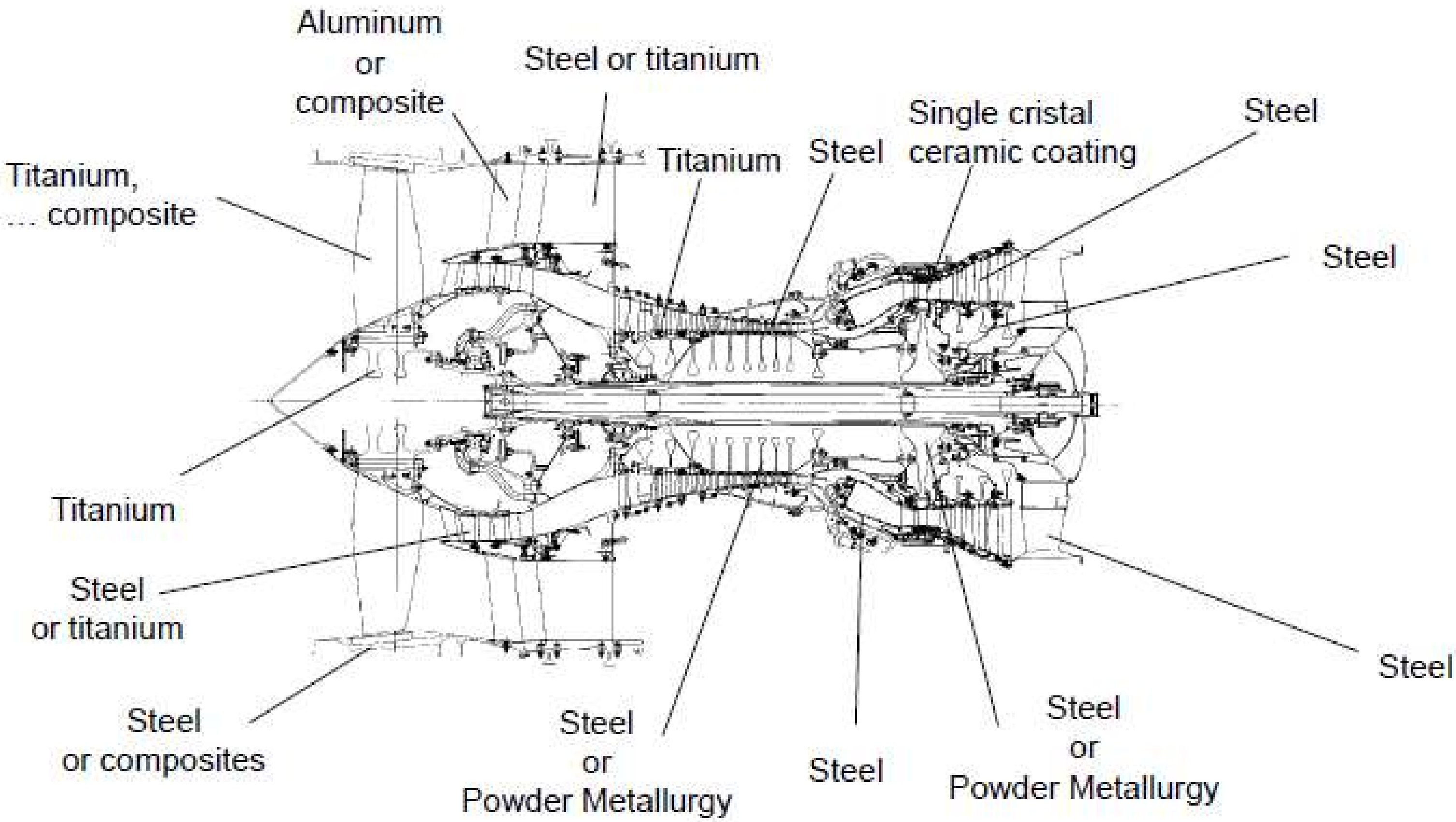
Typical temperatures



Overall Pressure Ratio (OPR)= P3/P2

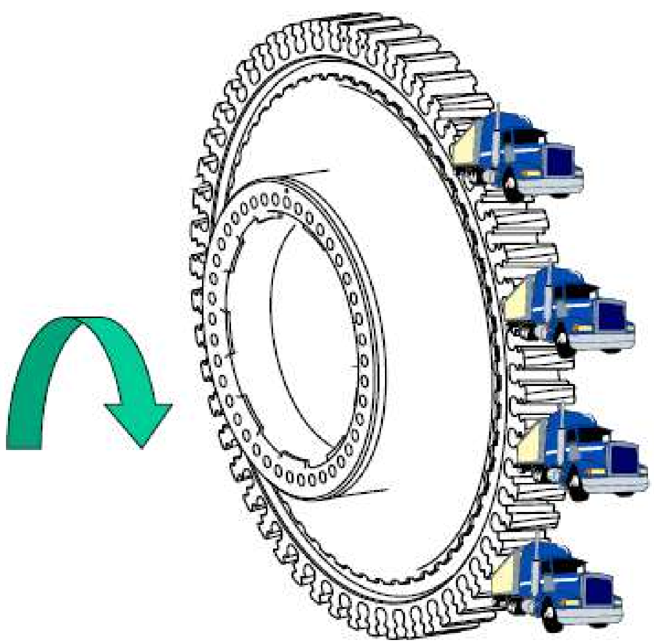
typically 30 to 50

Typical materials



Technology pushed to the limits

17000 RPM

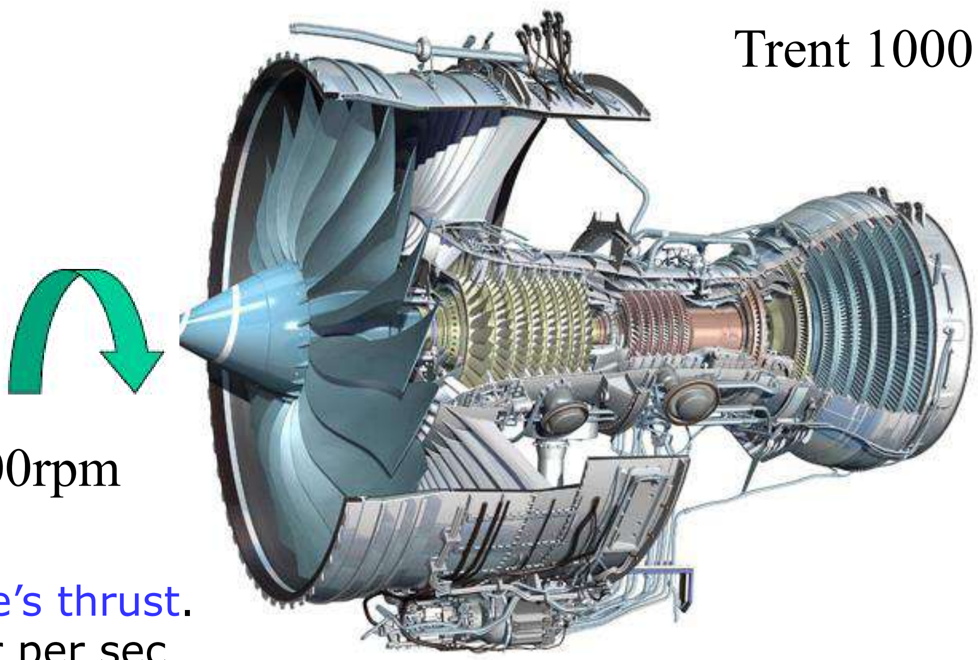


High Pressure Turbine:

- Each blade applies a 38 tons centrifugal force

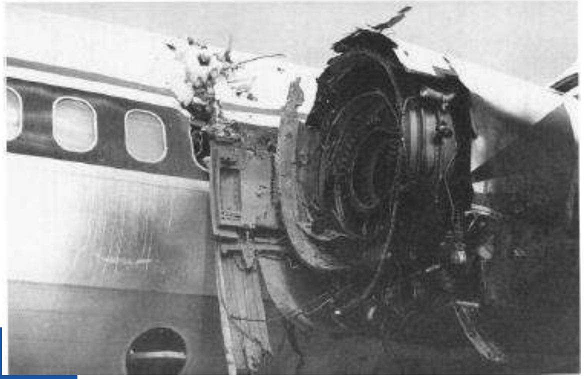
- Airflow temperature is 500° C above material fusion point

Technology pushed to the limits



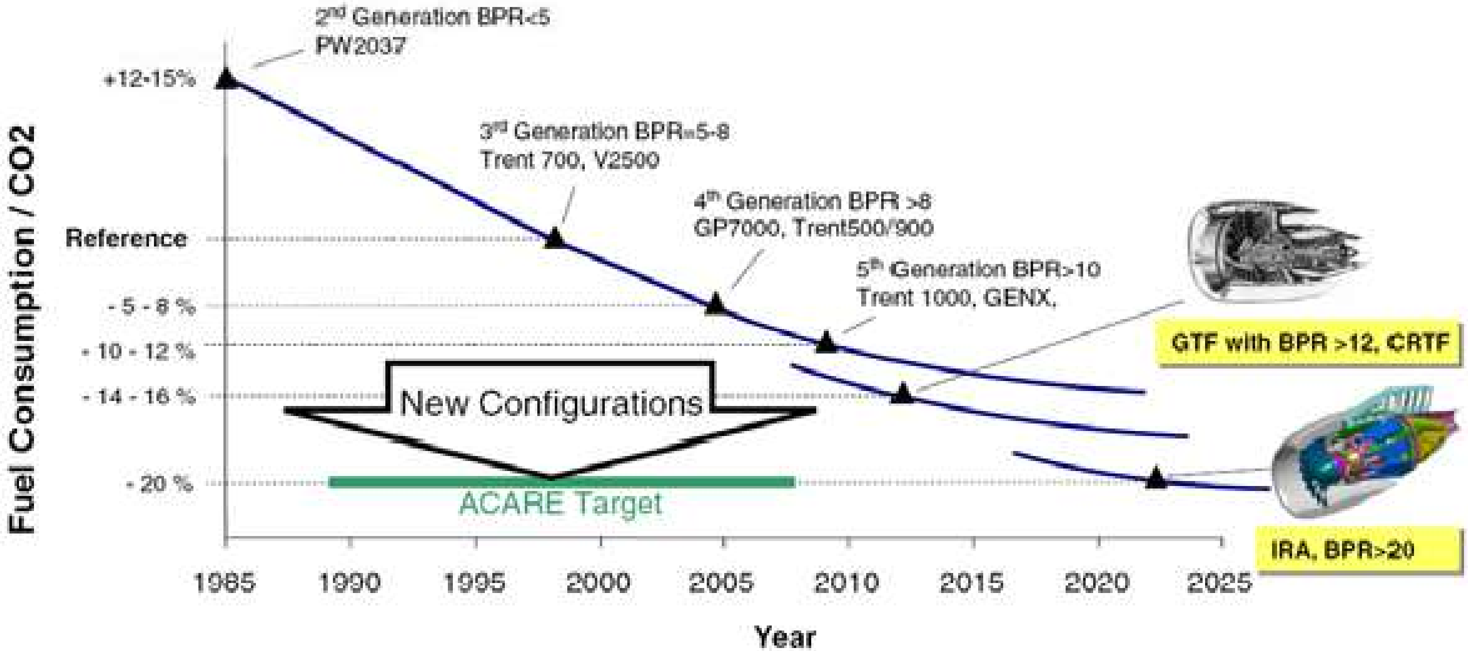
- Fan blades deliver 75% of the engine’s thrust.
- Fan blades shift about 1.2 tons of air per sec
- Loading on the blade is something like 90 ton centrifugal load at take off.
- That’s like hanging **13 double-decker busses** on each of the fan blades!

Can things go wrong?



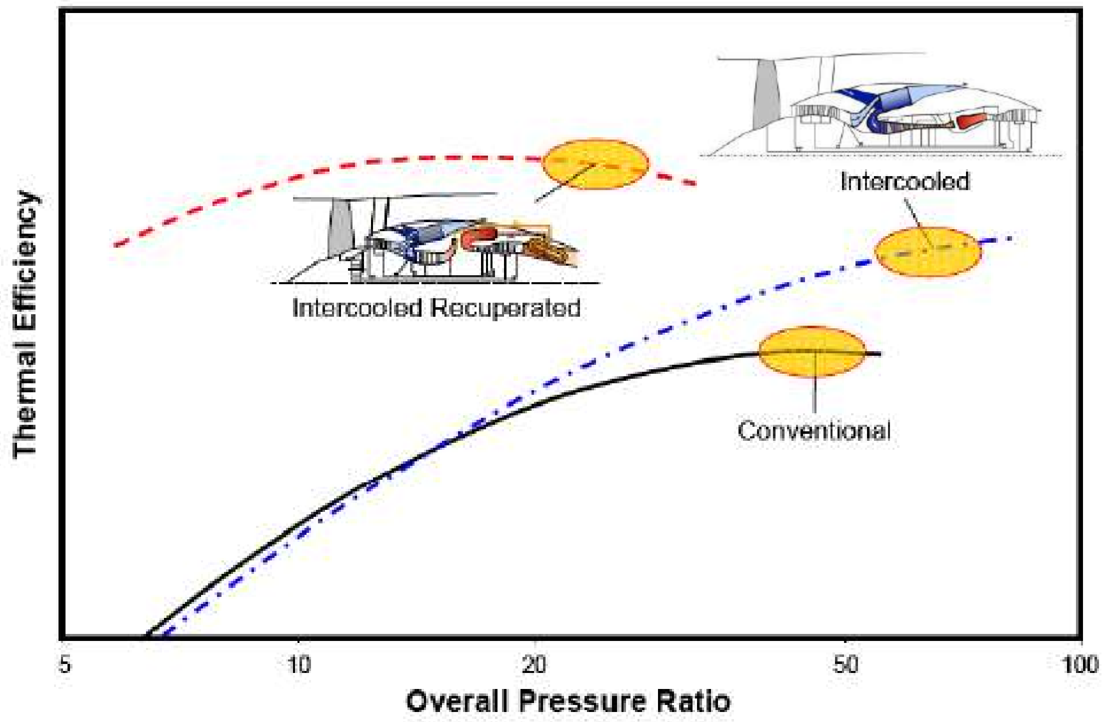
Current development Turbofan…

Trends SFC/CO2



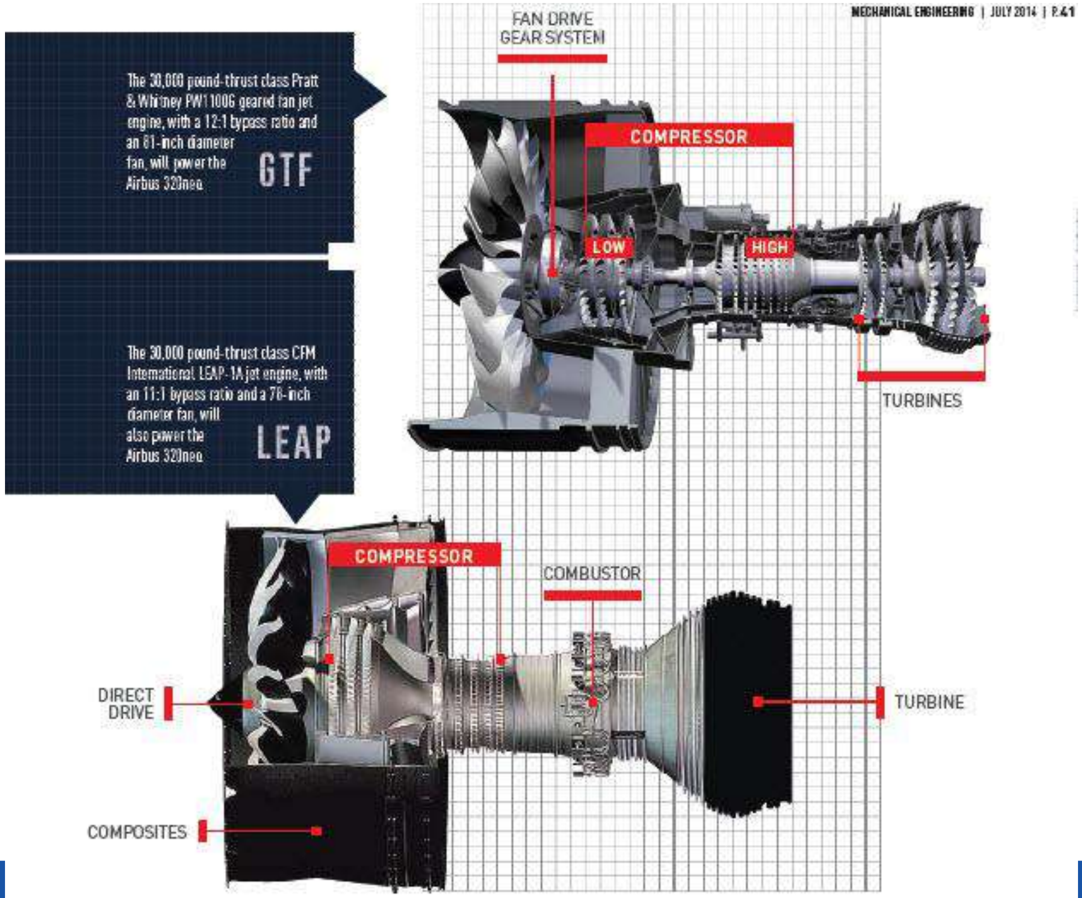
- **ACARE**: Advisory Council for Aeronautical Research in Europe
- Improved Design = Small, Steady Improvements
- Biggest 'Leaps' when new (revolutionary) technology arrives
  - Higher temperature-resistant materials
  - Efficient Component Design – reduction in secondary flow losses.

Trends

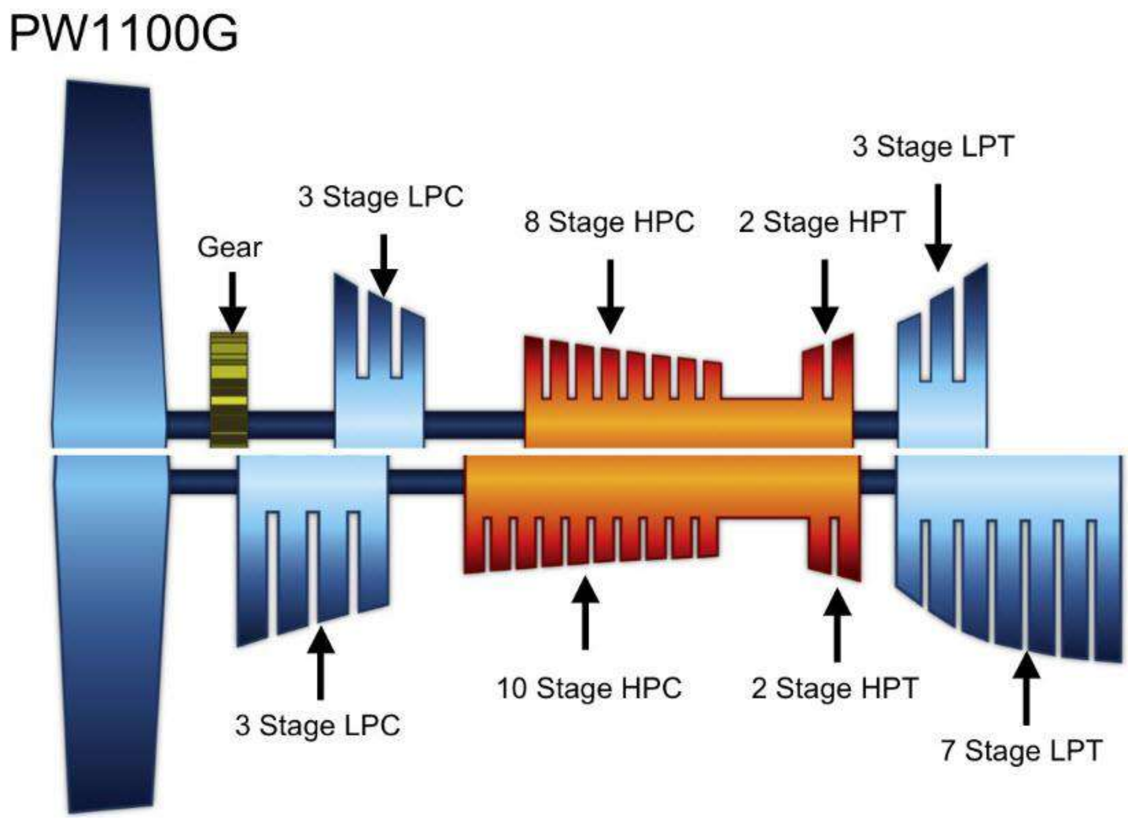


Intercooled
Intercooled Recuperated
Conventional
Thermal Efficiency
5
10
20
50
100
Overall Pressure Ratio

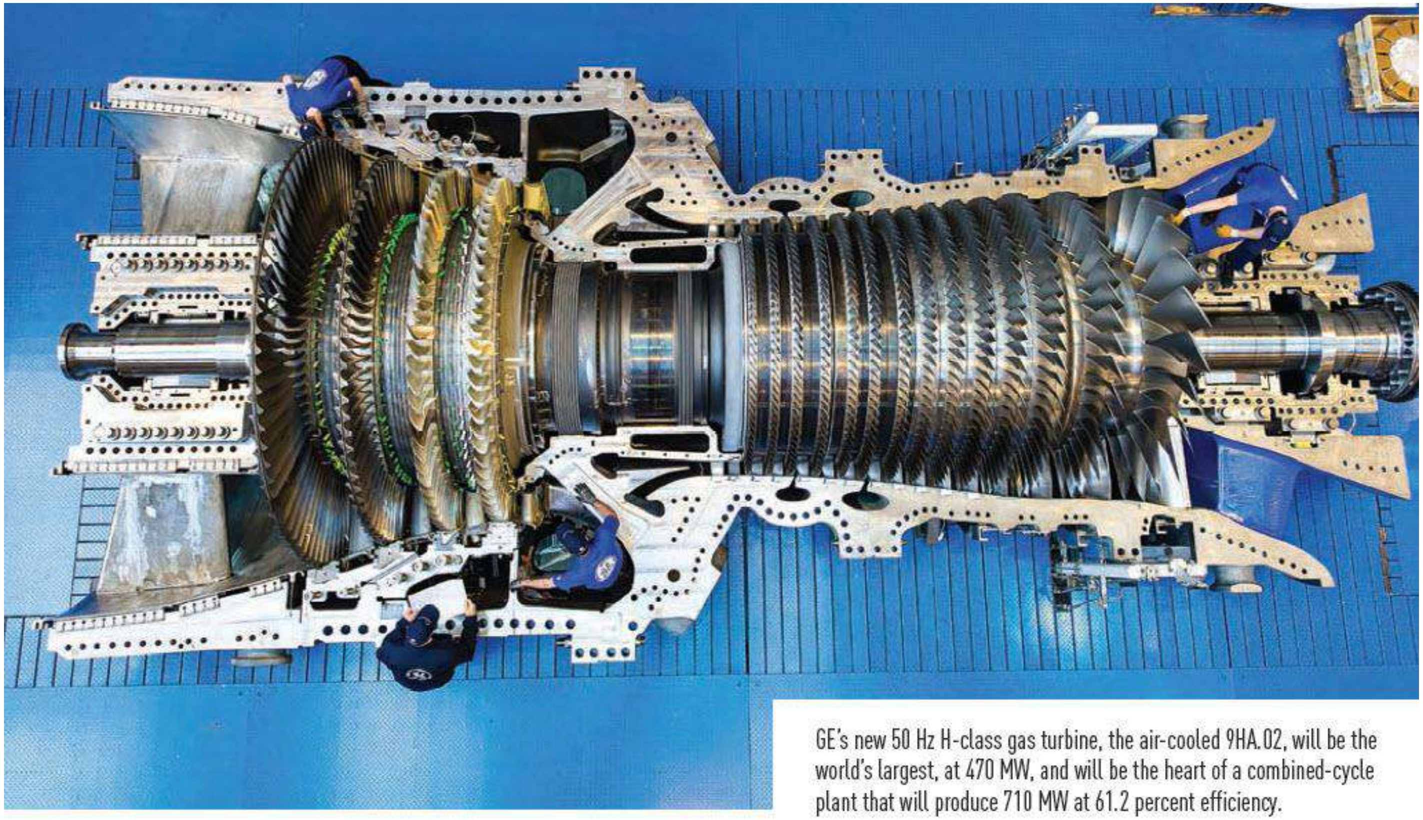
Current (new) turbofan engines



Current (new) turbofan engines



Current (new) gas turbines



GE's new 50 Hz H-class gas turbine, the air-cooled 9HA.02, will be the world's largest, at 470 MW, and will be the heart of a combined-cycle plant that will produce 710 MW at 61.2 percent efficiency.

X-TRA SLIDES

Fluid machines

- Rotodynamic machines

  Continuous fluid flow

  Rotating motion

  No closed volume

  Energy transfer between rotating part (rotor) and fluid by momentum

  → Angular momentum = swirl → swirl = turbo → turbomachines

- Volumetric machines

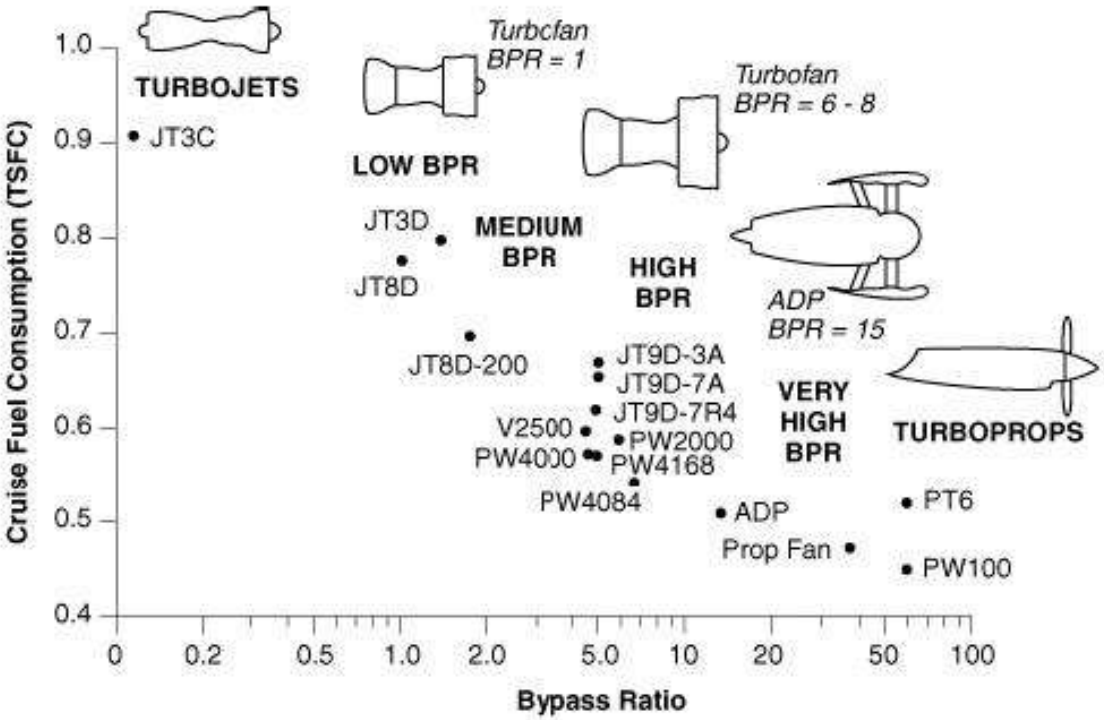
  Intermittent fluid flow

  Reciprocating or rotating motion

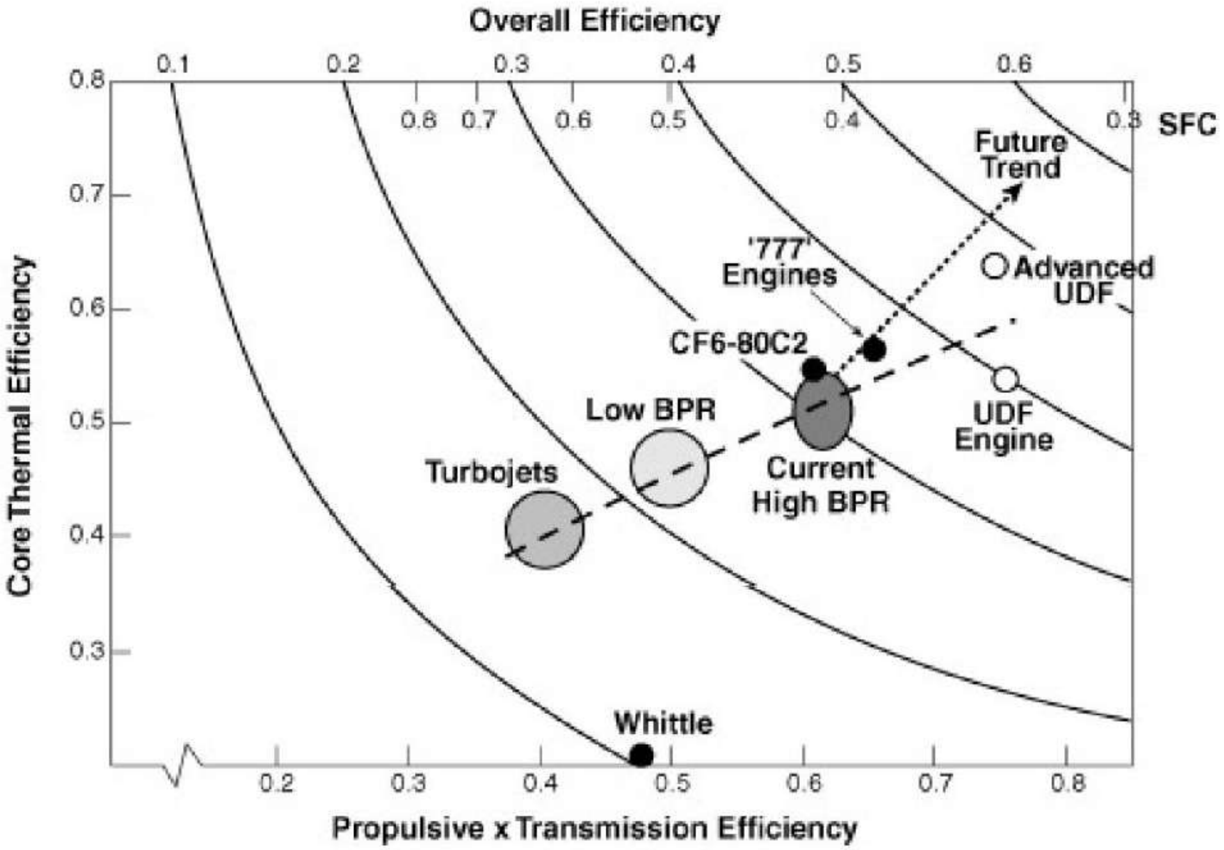
  Temporarily closed volume (valves, ports)

  Energy transfer between oscillatory part (e.g. piston) and fluid by volumetric displacement (→ pressure)

Propulsion Concepts

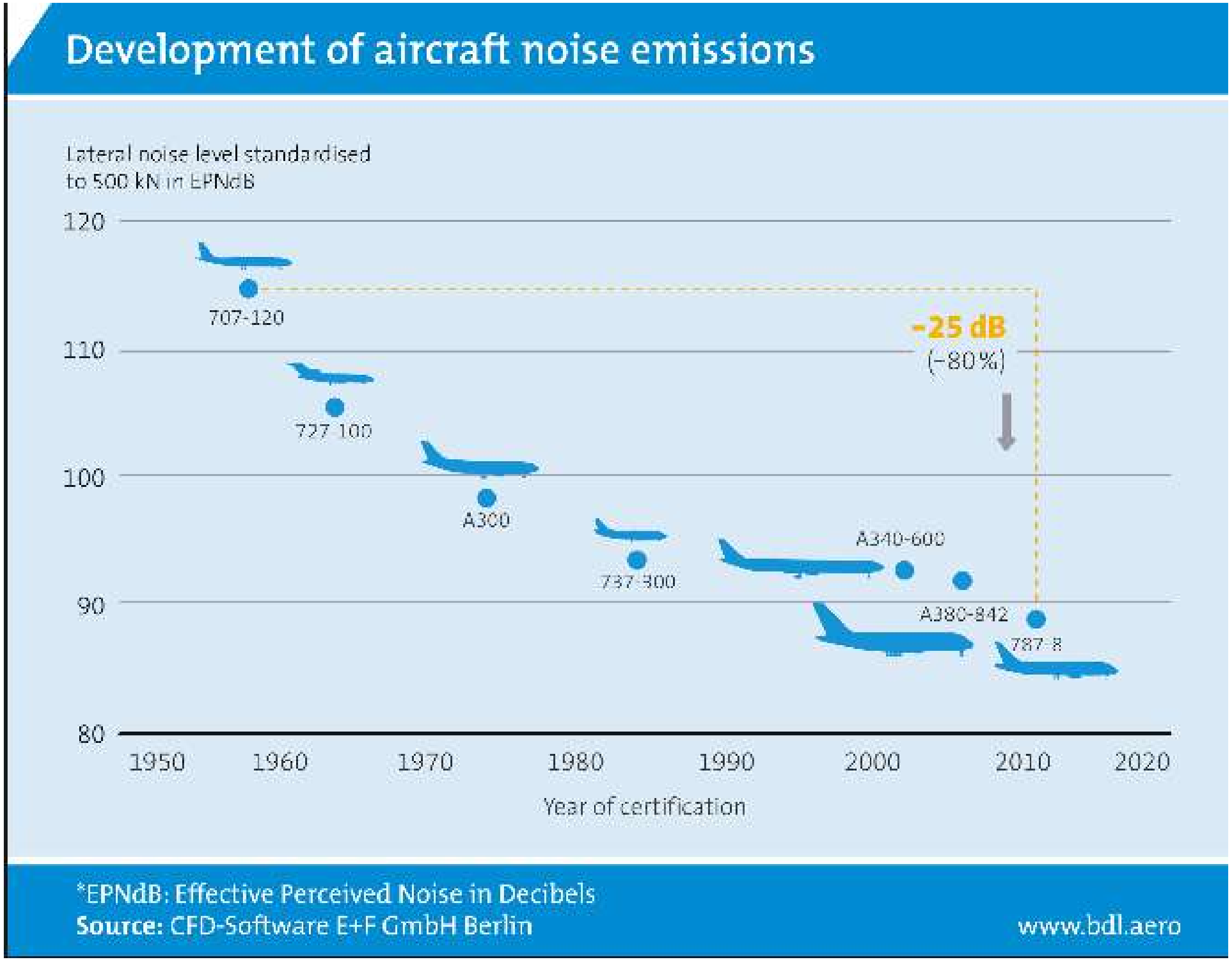


Trends



Overall Efficiency
0.1
0.2
0.3
0.4
0.5
0.6
0.8
0.7
0.6
0.5
0.4
0.3
SFC
Future Trend
'777' Engines
Advanced UDF
CF6-80C2
Low BPR
UDF Engine
Turbojets
Current High BPR
Whittle
Core Thermal Efficiency
Propulsive x Transmission Efficiency

Noise


Development of aircraft noise emissions
Lateral noise level standardised
to 500 kN in EPNdB
120
110
100
90
80
707-120
727-100
A300
737-300
A340-600
A380-842
787-8
-25 dB
(-80%)
1950
1960
1970
1980
1990
2000
2010
2020
Year of certification
*EPNdB: Effective Perceived Noise in Decibels
Source: CFD-Software E+F GmbH Berlin
www.bdl.aero