Compressor Development Reflections and Challenges

Robin Elder

(PCA Engineers Limited)

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Philosophers

Wikipedia gives 352 Greek philosophers starting from

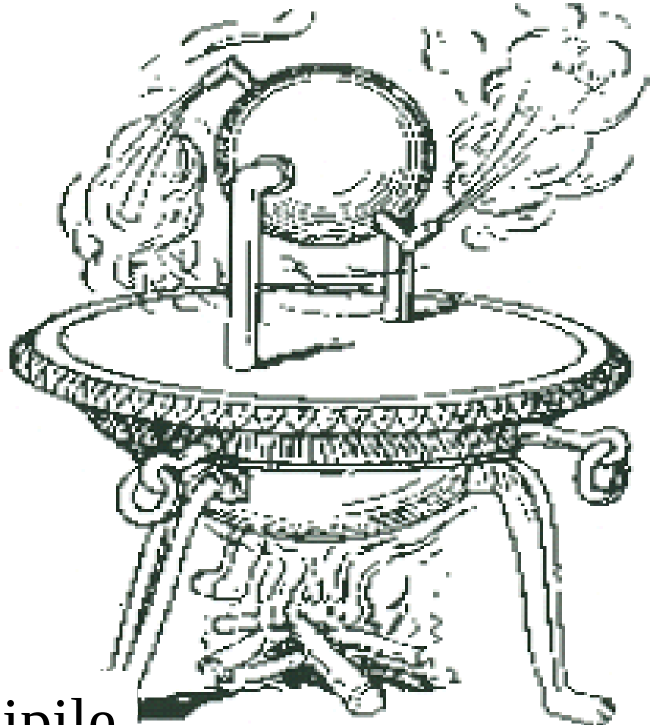
Acrion of the Pythagorean School to

Zeno (of Tarsus) of the Stoic School

Many with household names to this day.

For comparison, there are about half that number of named British philosophers almost none of whom have household names.

Hero’s Turbine



Aerolipile

c 10 AD

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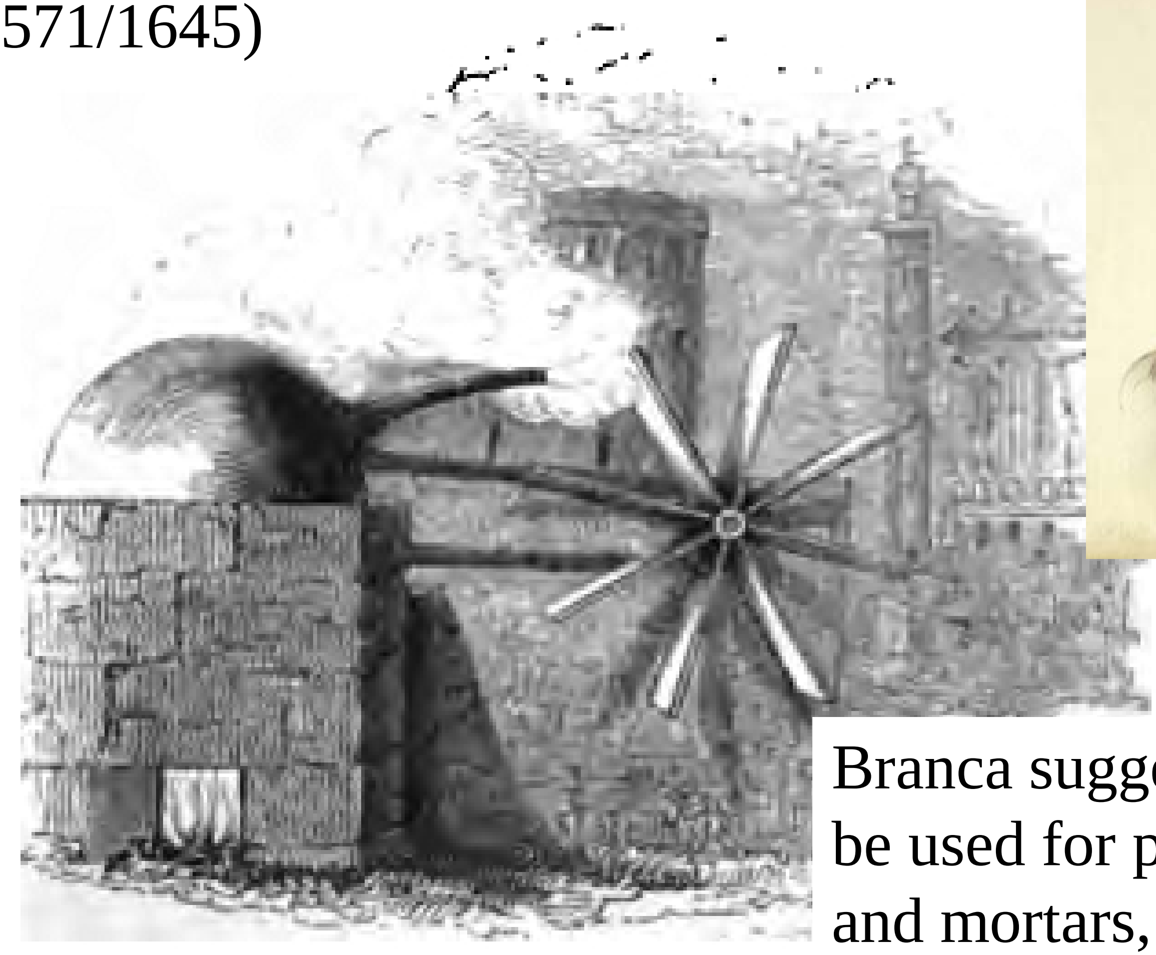
Branca's turbine

(1571/1645)



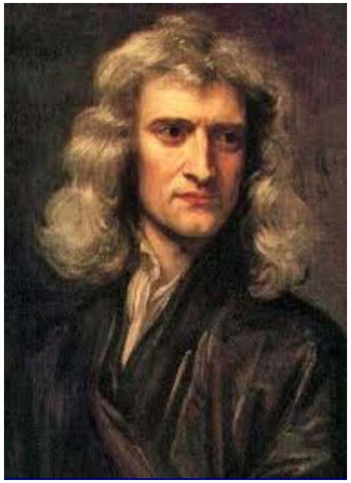
Branca suggested that it might be used for powering pestles and mortars, grinding machines, raising water, and sawing wood

Leonhard Euler (1707/1783)

Swiss but moving between Russia and Prussia gave us the fundamental turbomachinery equation governing the transfer of energy between a flow and rotating mechanism.

Just a small part of his contribution to science and engineering.

Isaac Newton
1643/1727



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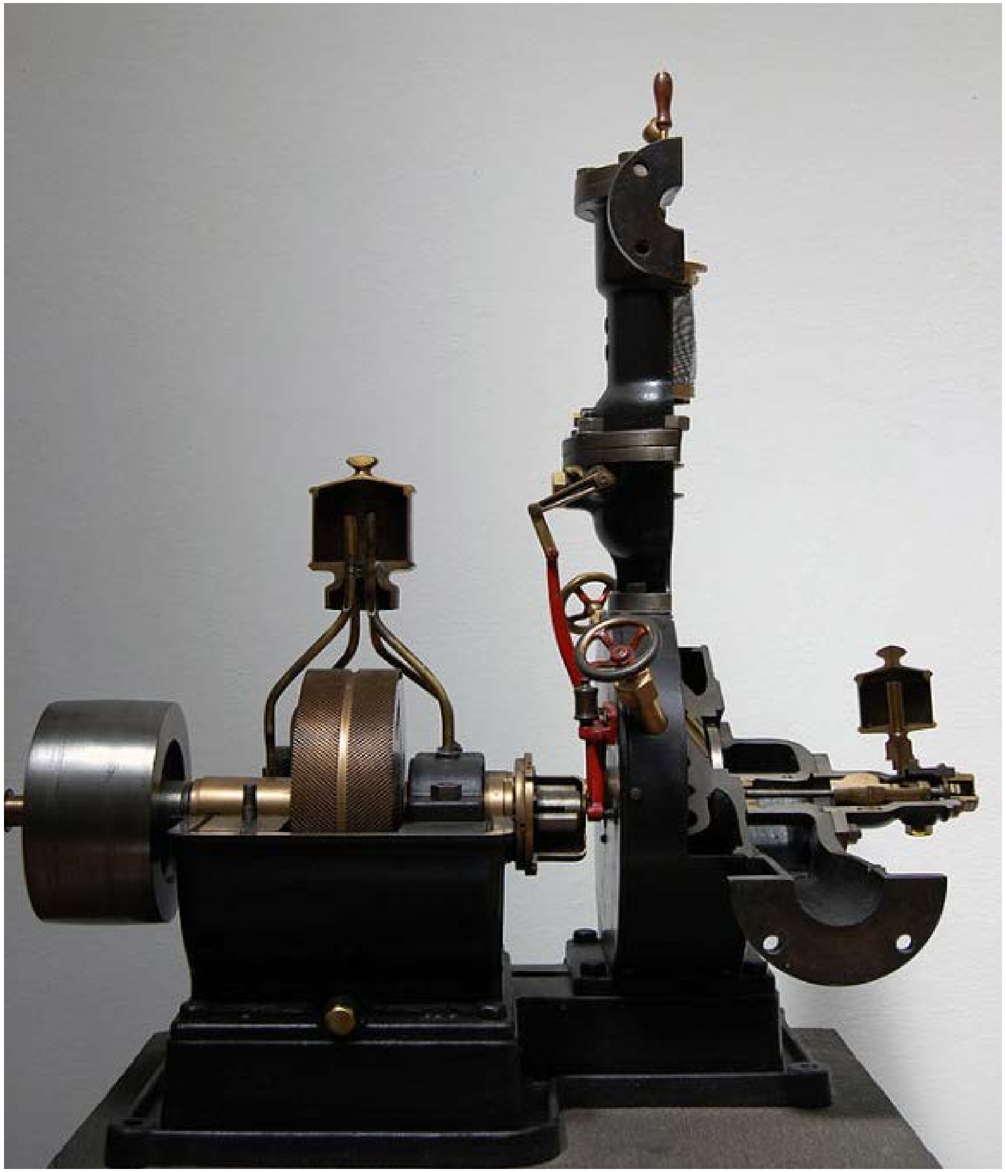
Gustaf de Laval
Impulse turbine

1835/1913



Charles Parsons (Rede Lecture 1911)

"It seemed to me that moderate surface velocities and speeds of rotation were essential if the turbine motor was to receive general acceptance as a prime mover. I therefore decided to split up the fall in pressure of the steam into small fractional expansions over a large number of turbines in series, so that the velocity of the steam nowhere should be great...I was also anxious to avoid the well-known cutting action on metal of steam at high velocity."

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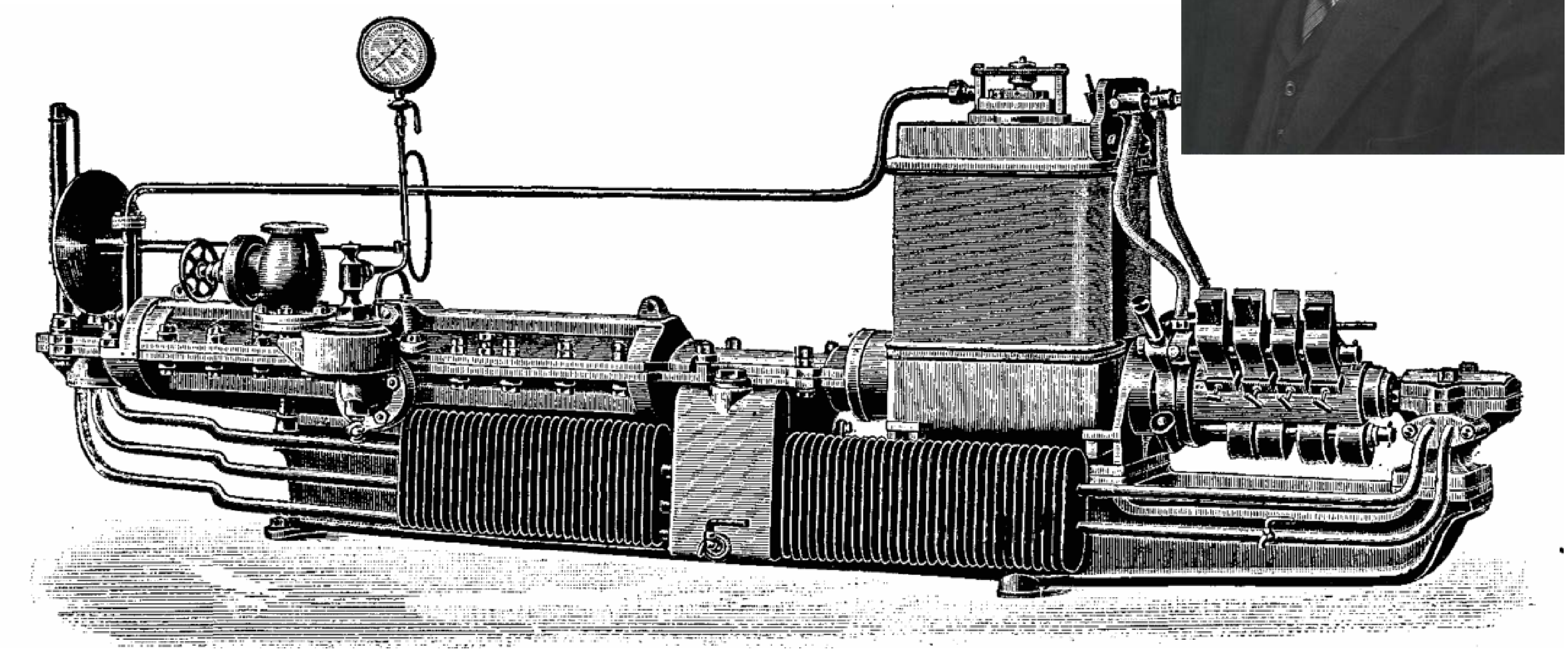
Parson's 1854/1931



First compound steam turbine,1887

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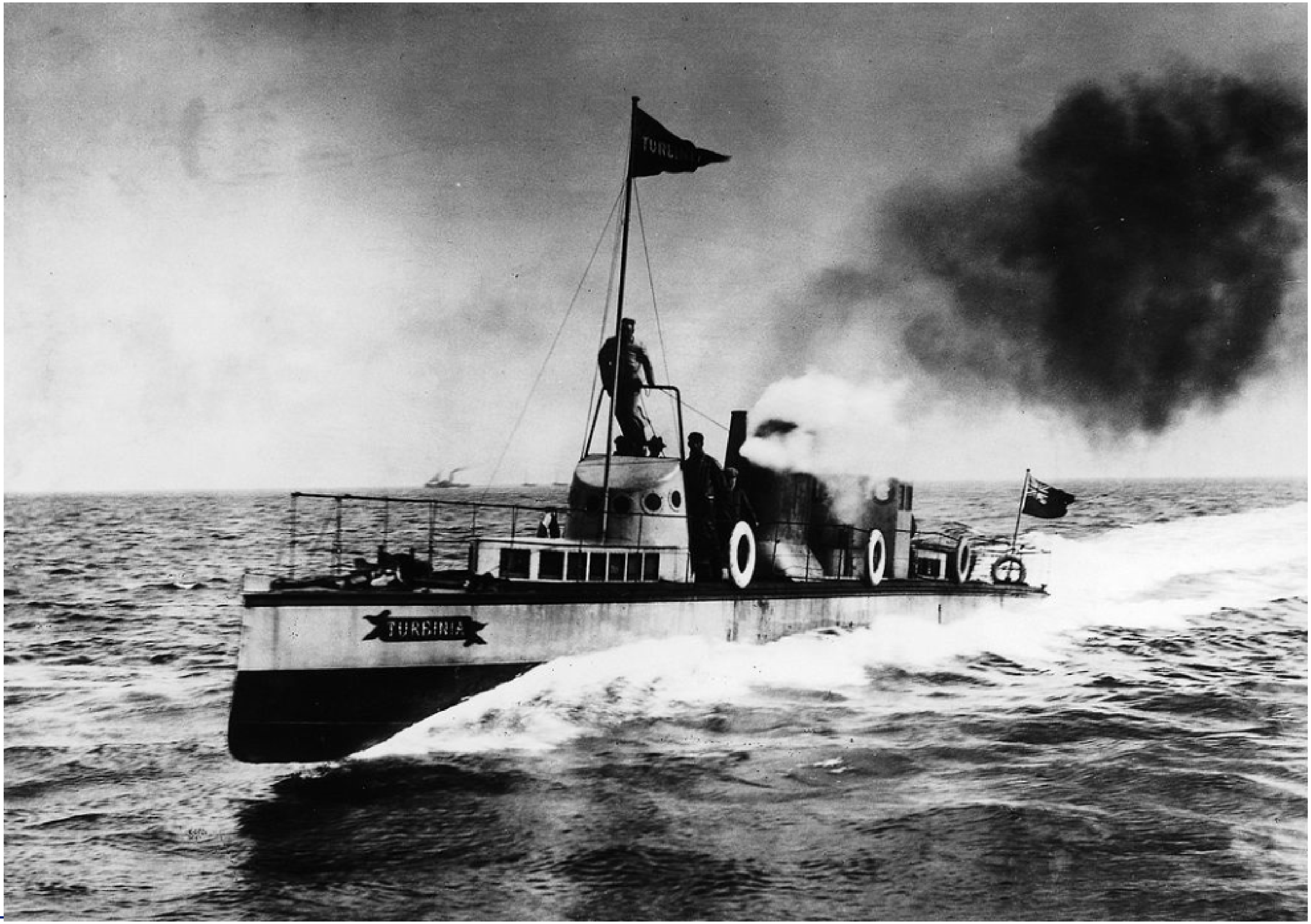
Naval applications (the Turbinia 1894)



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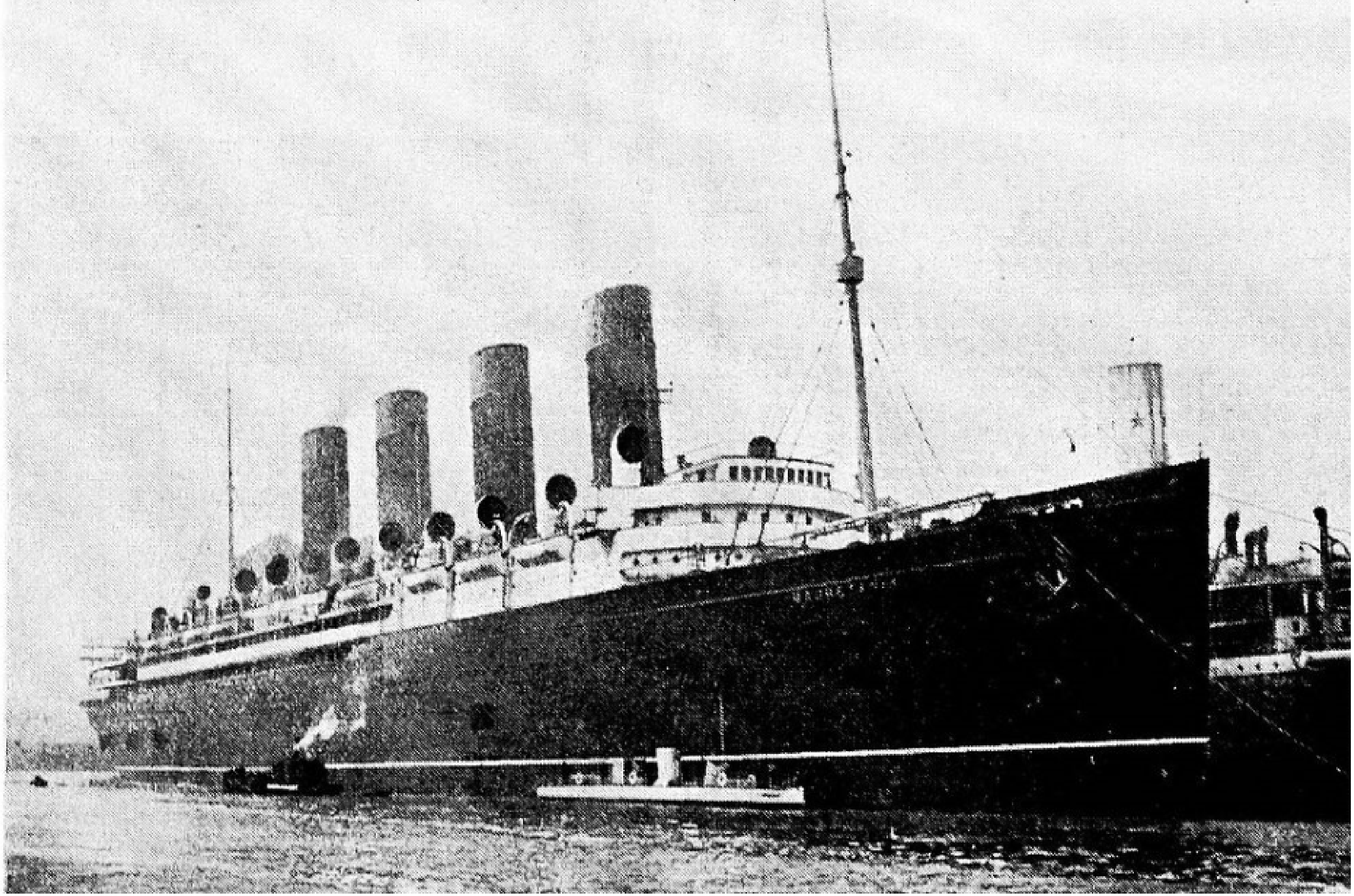
Mauritannia 1904 (68-90,000 SHP)



They grew and grew.

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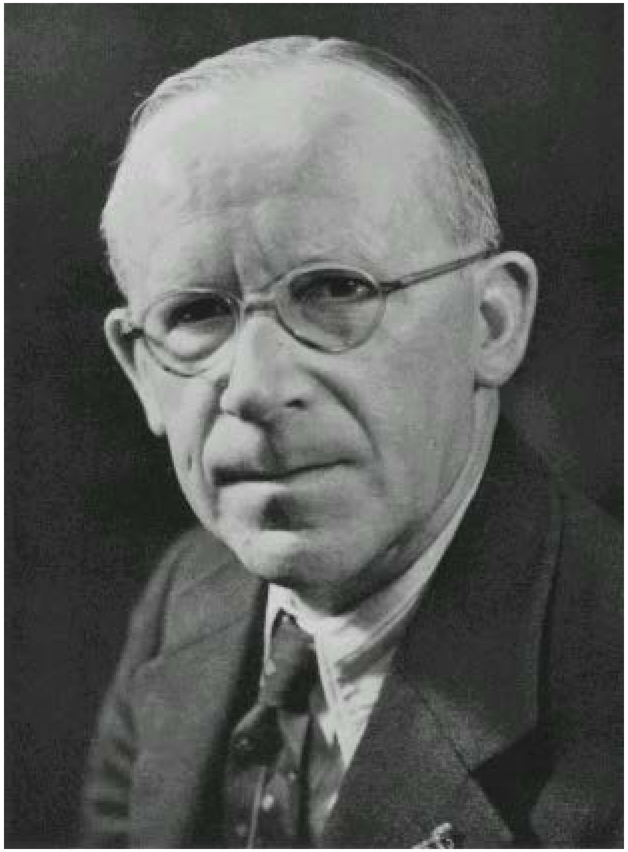
Axial compressors (the beginning)

- Parson (1884) patented a compressor concept based upon a ‘reversed turbine’.

- Griffith’s noted that existing turbine compressors were ‘flying stalled’ and introduced concepts leading to consideration of incidence and blade profile subsequently researched by such people as Cox and Howell to give us cascade theory and practice which is still in full use.



Alan Arnold Griffith FRS.

1893/1963

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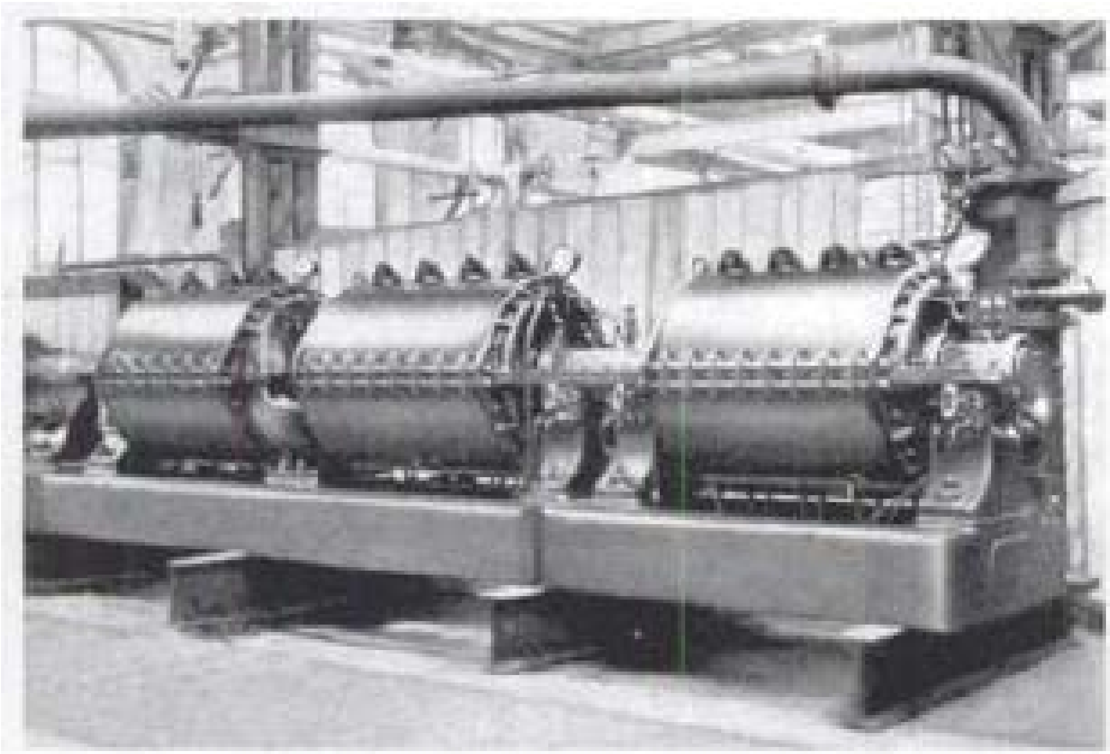
Centrifugal compressor



1906 multistage centrifugal compressor built by Brown Boveri according to patents of Rateau. It provided the air for the worlds first operable gas turbine. 1 m^3/s with pressure ratio of 4.5.

Auguste Rateau
1863/1930

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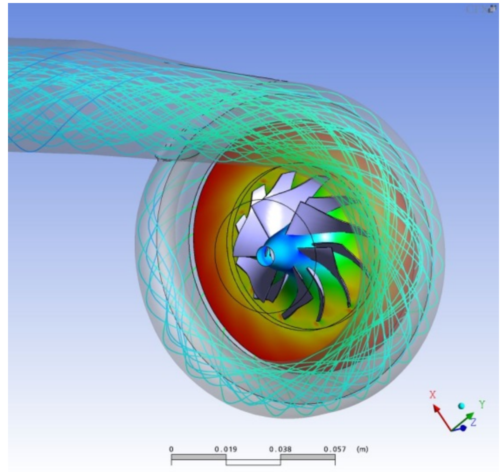
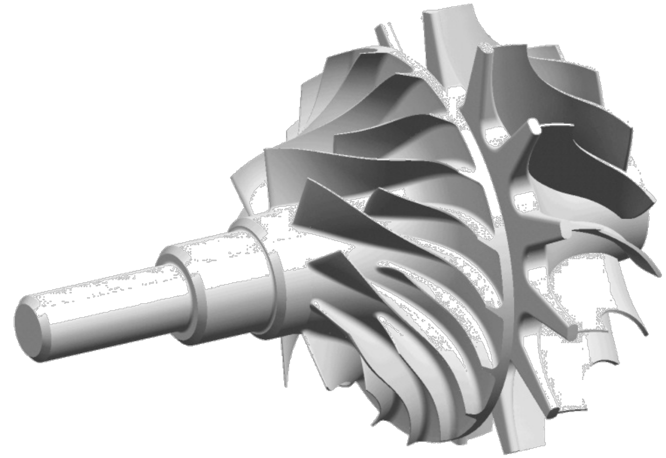
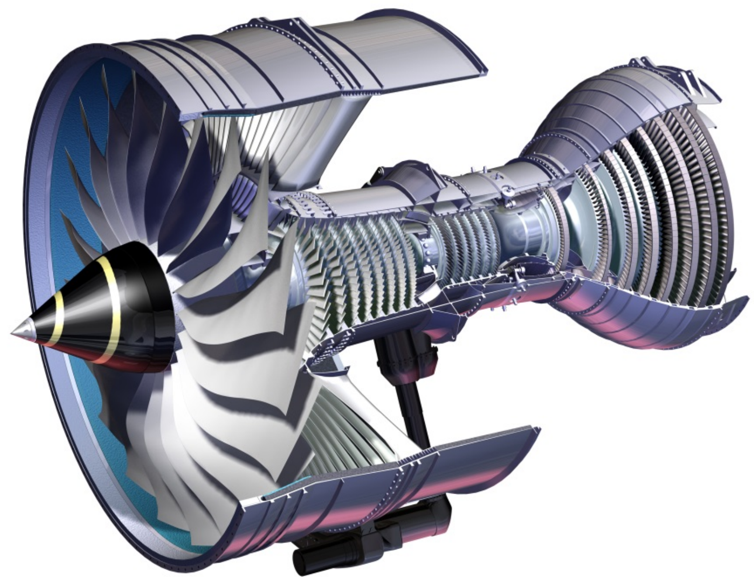




The swept fan of the Trent 1000 contains only 20 blades

Picture: Trent 1000 06105011

Rolls-Royce



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Turbomachinery means speed.

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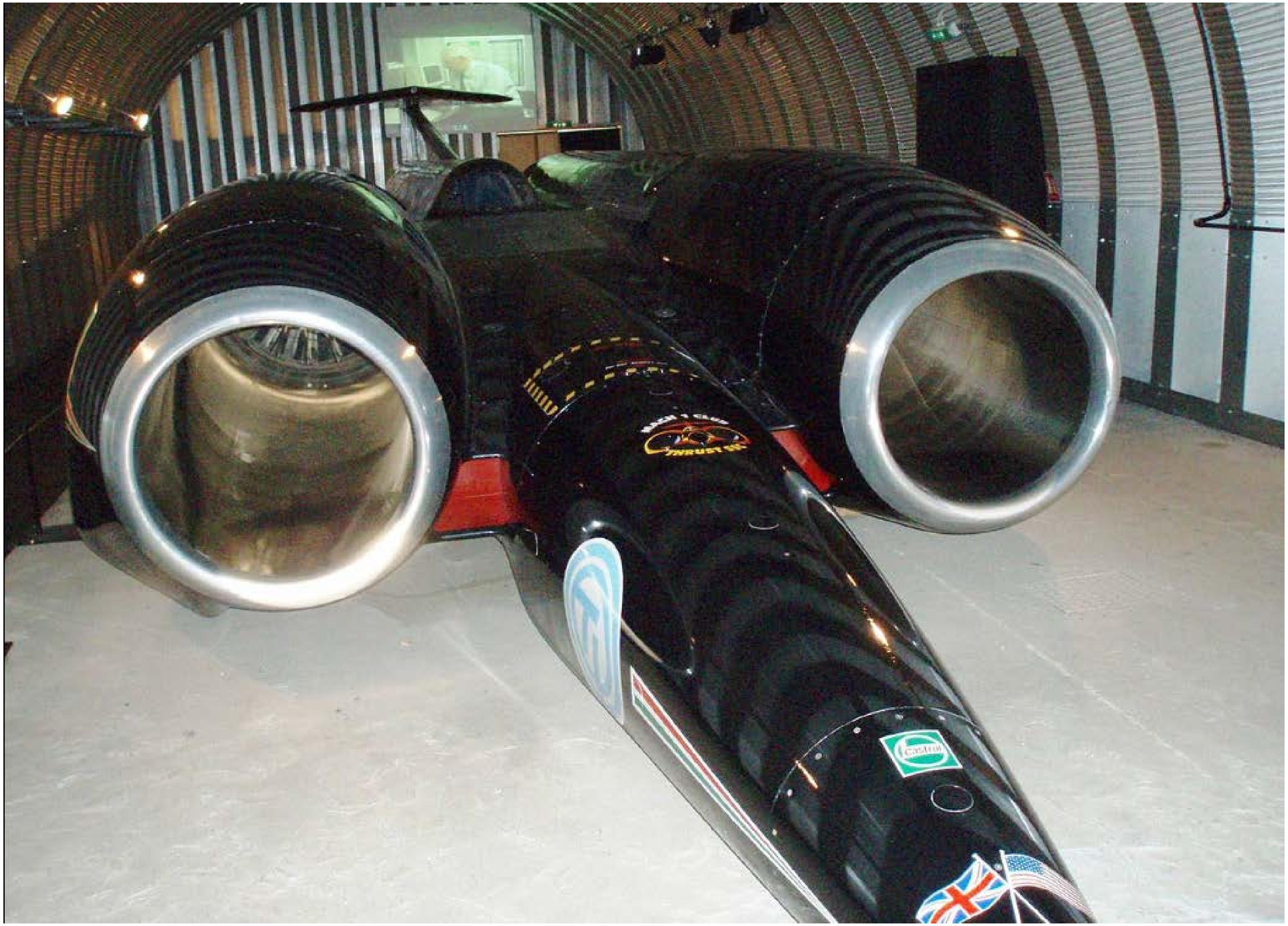
Thrust SSC



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1227 km/h

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Lockheed SR-71 Blackbird @ 3,299.6 km/h

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JCB Dieselmax @ 560 km/h (two stage turbos)

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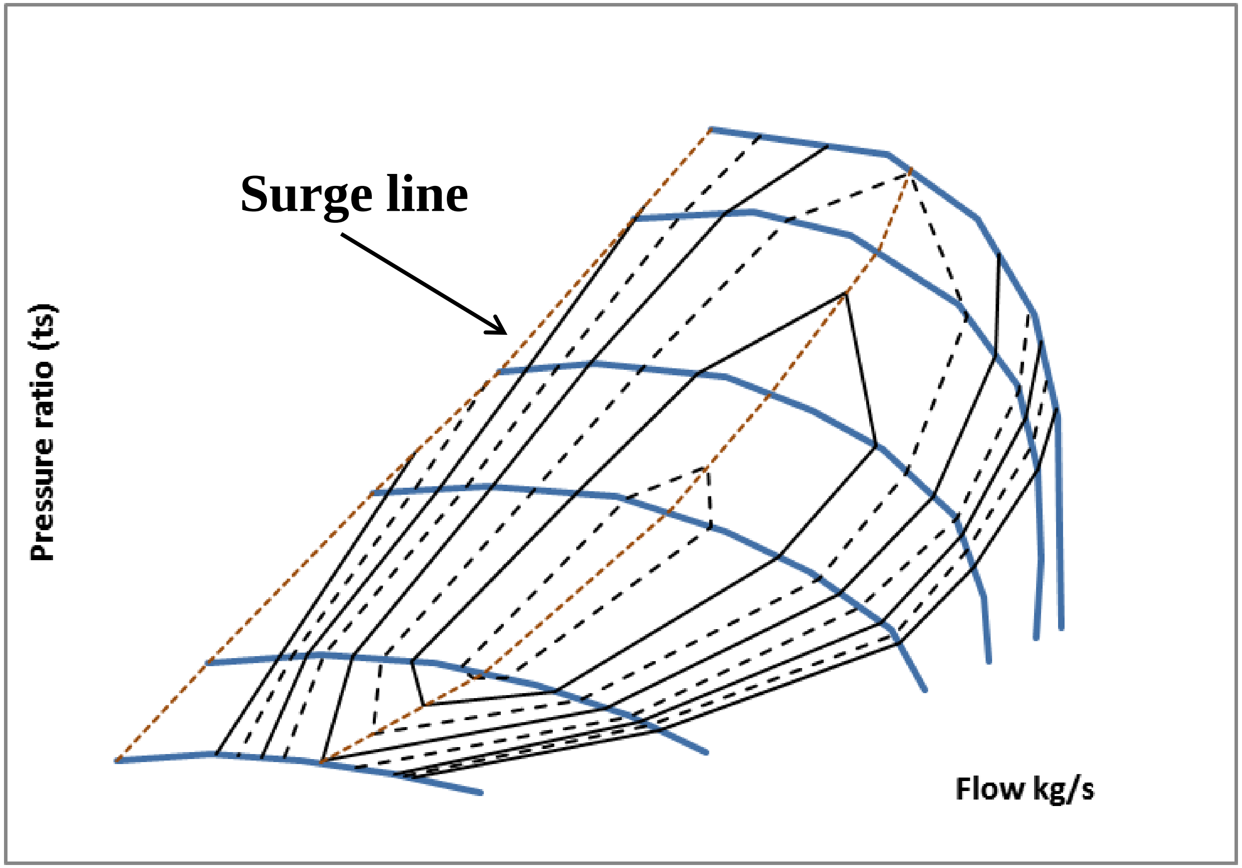
Issues

- Pressure ratio
- Efficiency
- Stability



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Surge

Surge

Surge

Surge

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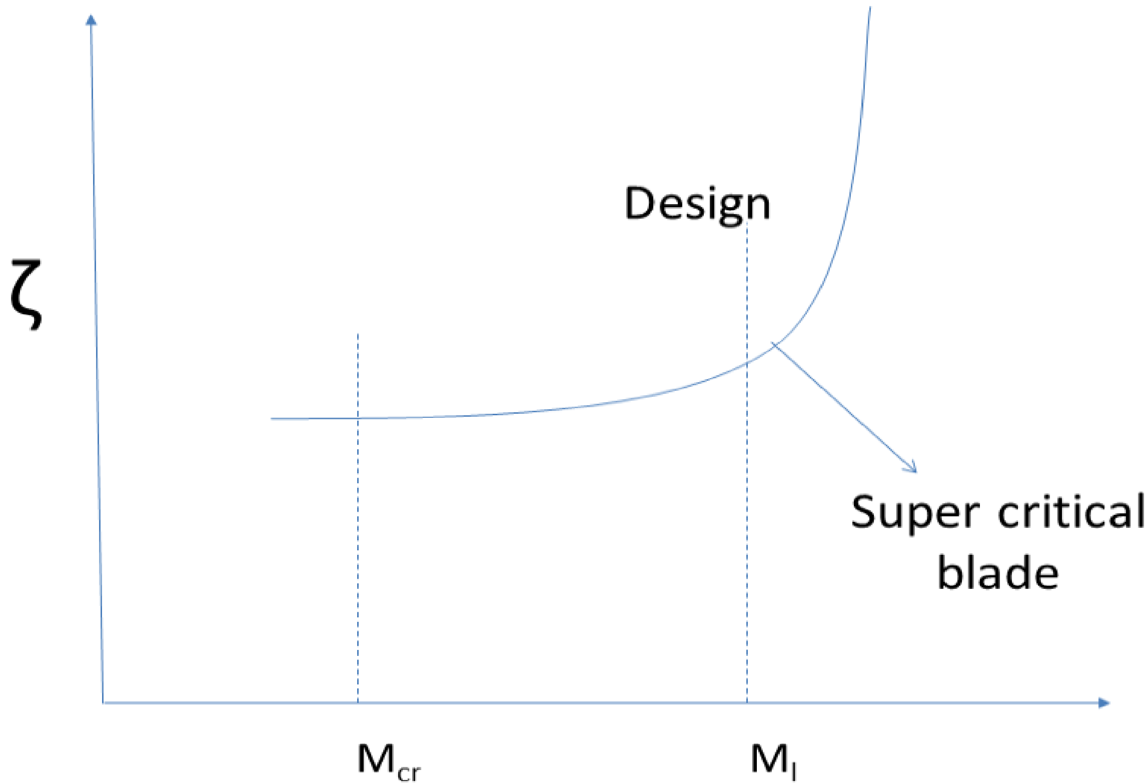
High speed blades

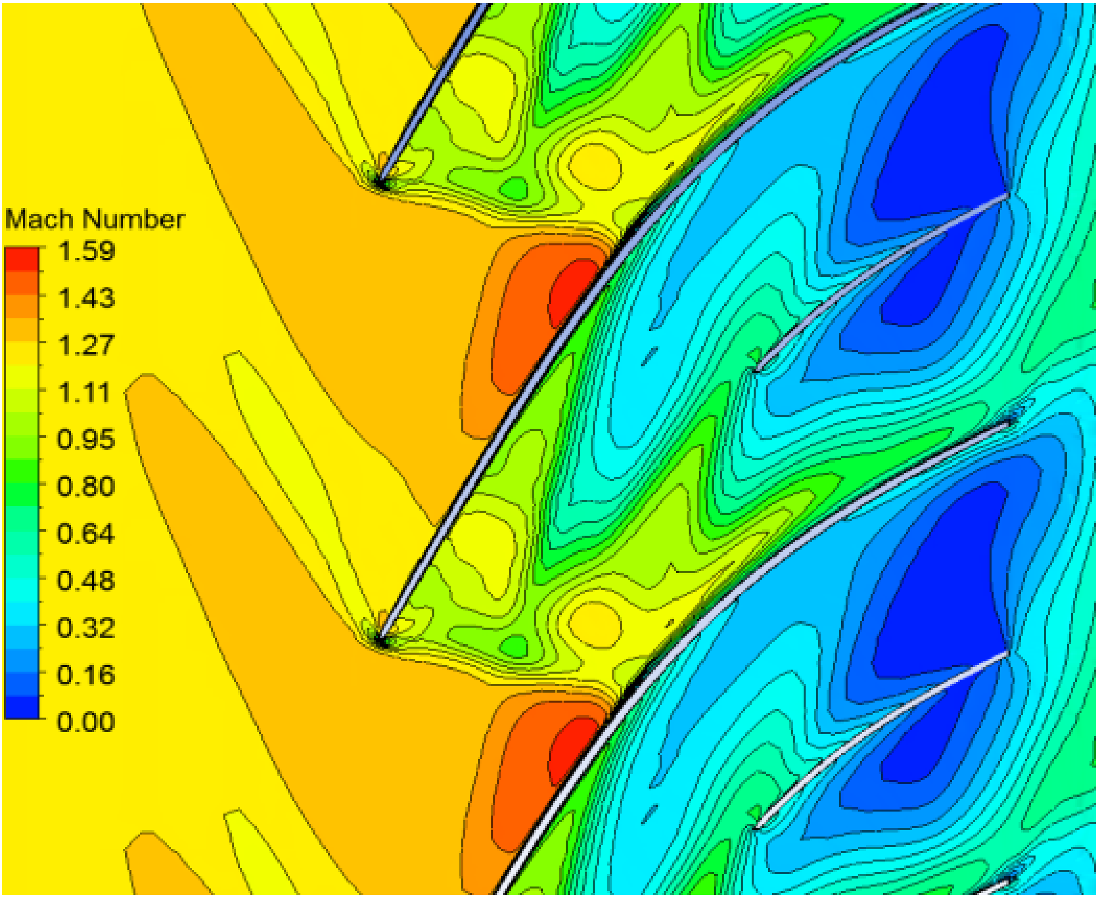
Work input depends on blade speed.

Location and strength of passage shock.
Losses from boundary growth and shock-boundary-layer interaction.
Aerofoil shape.



High speed blades

Control of the shock structure



Hazby et al

Aero fans

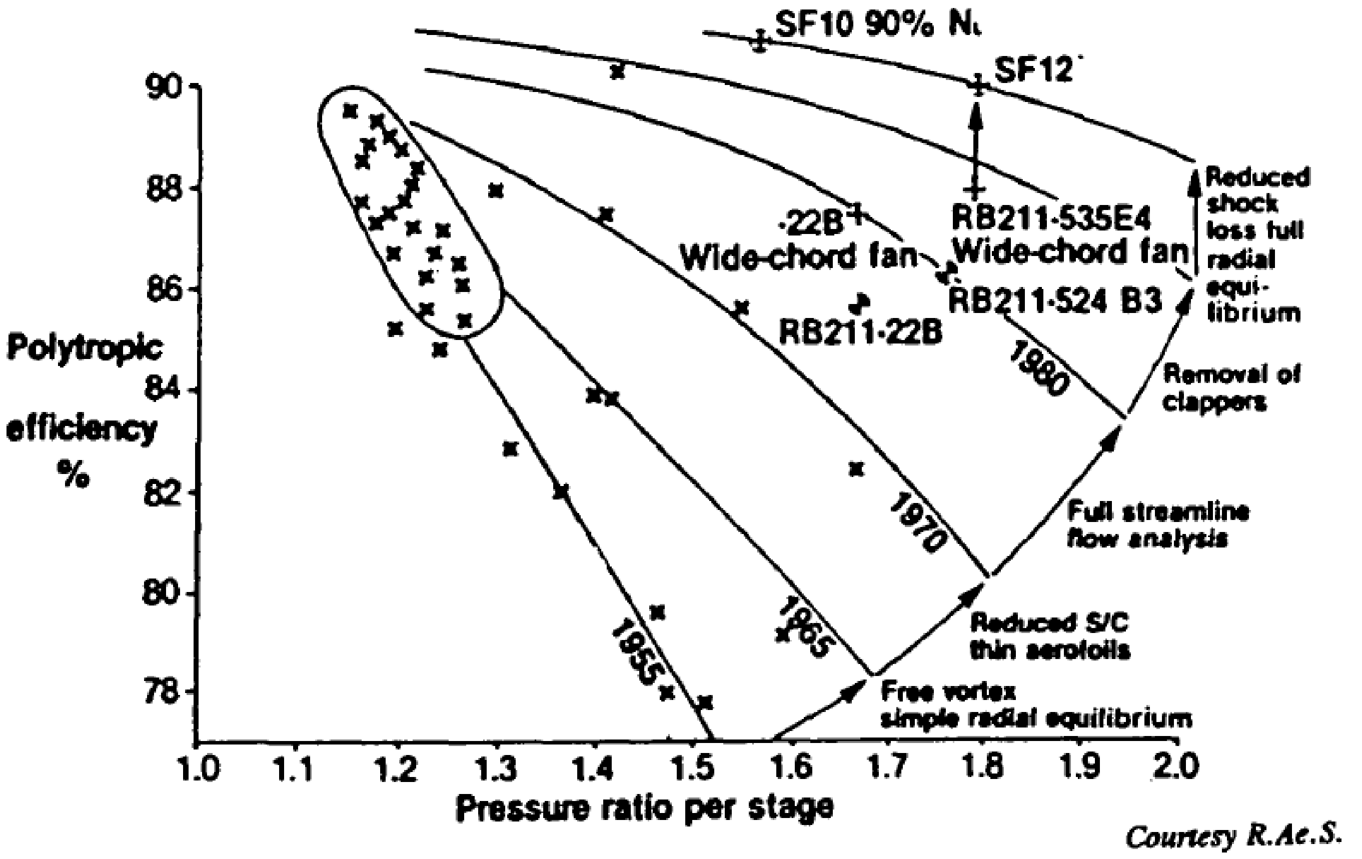
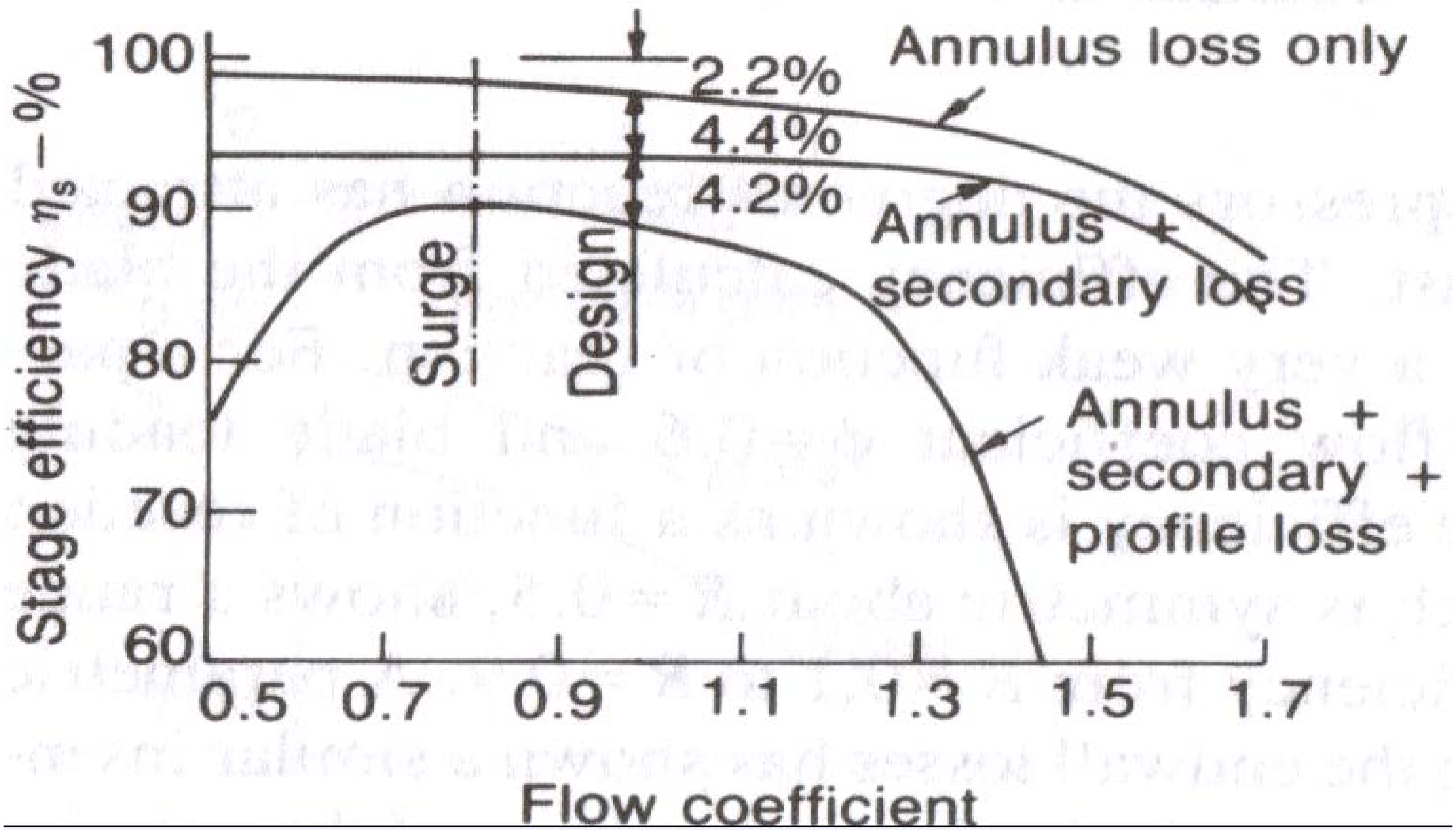


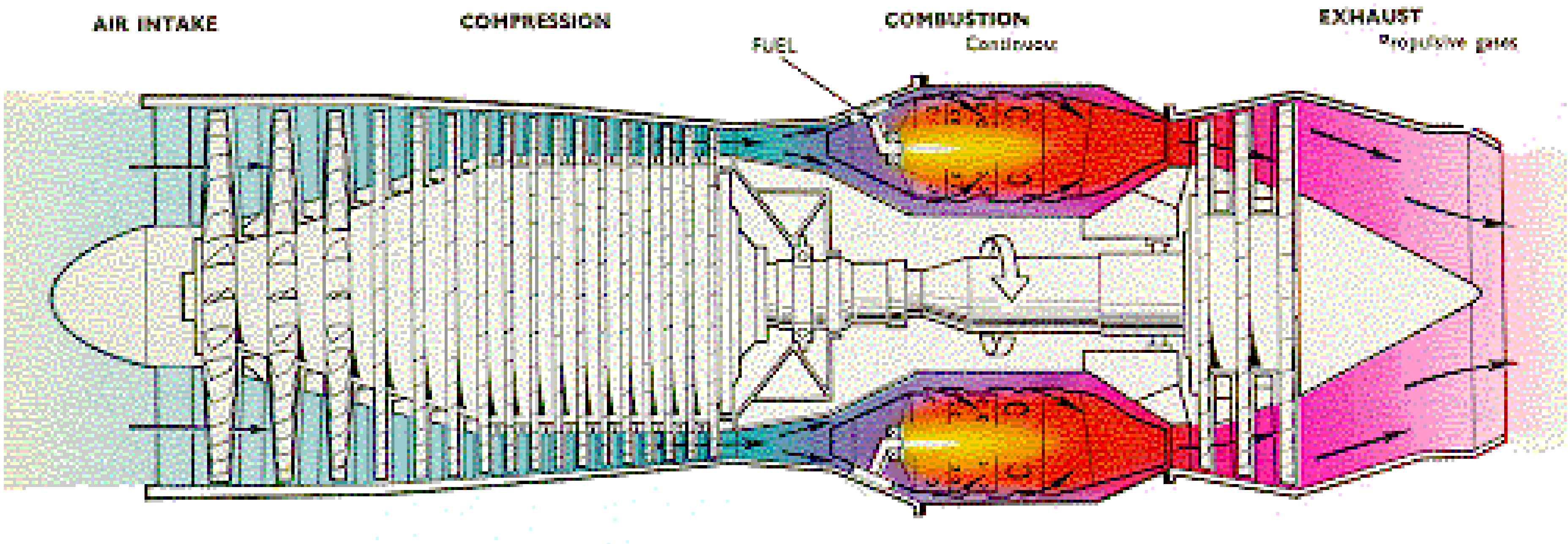
Fig.8 Rolls-Royce single stage fan progress (1984)

Dunham

Loss reduction



Losses in rear stages



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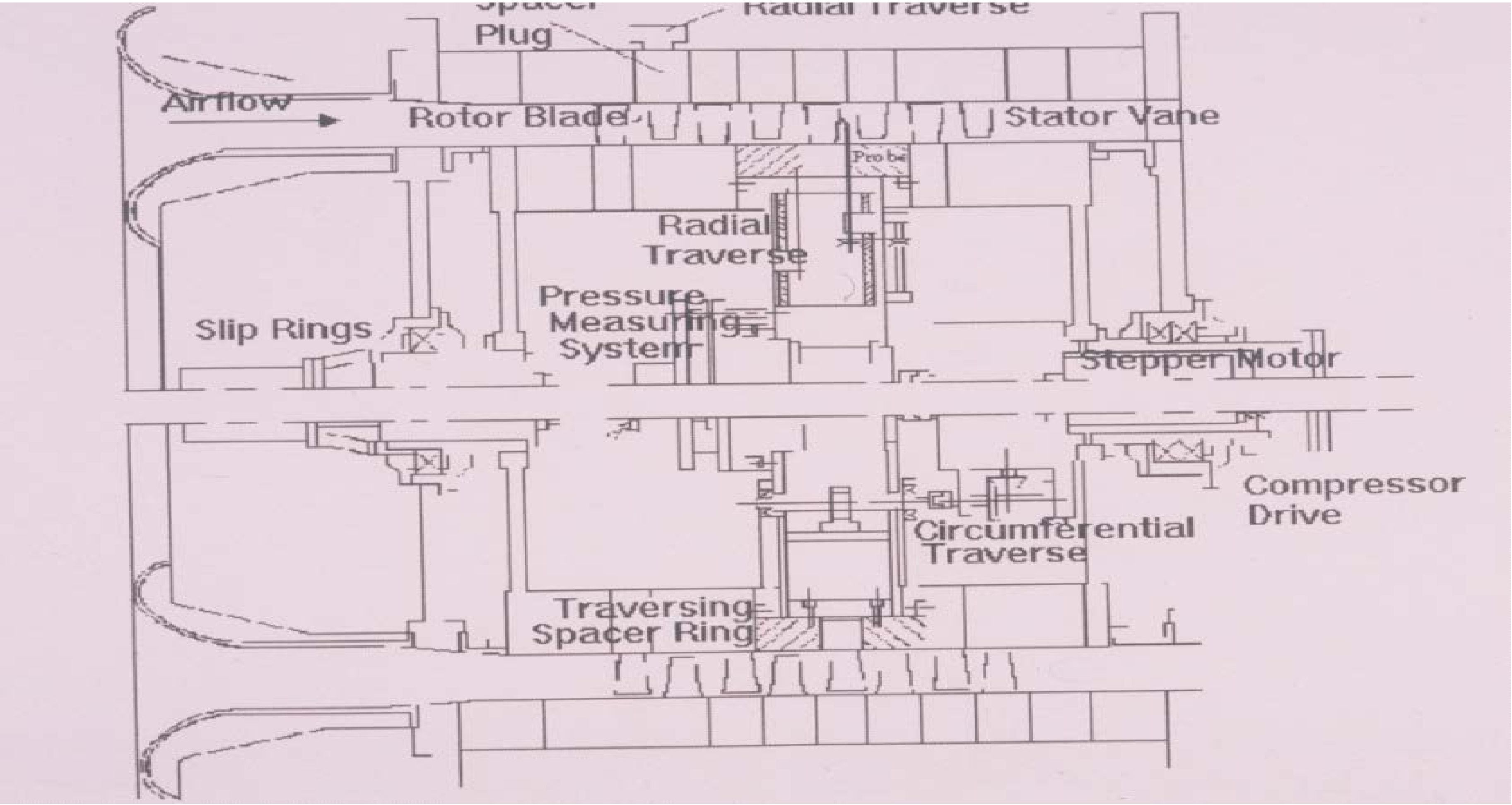
Rear stages present a particular problem



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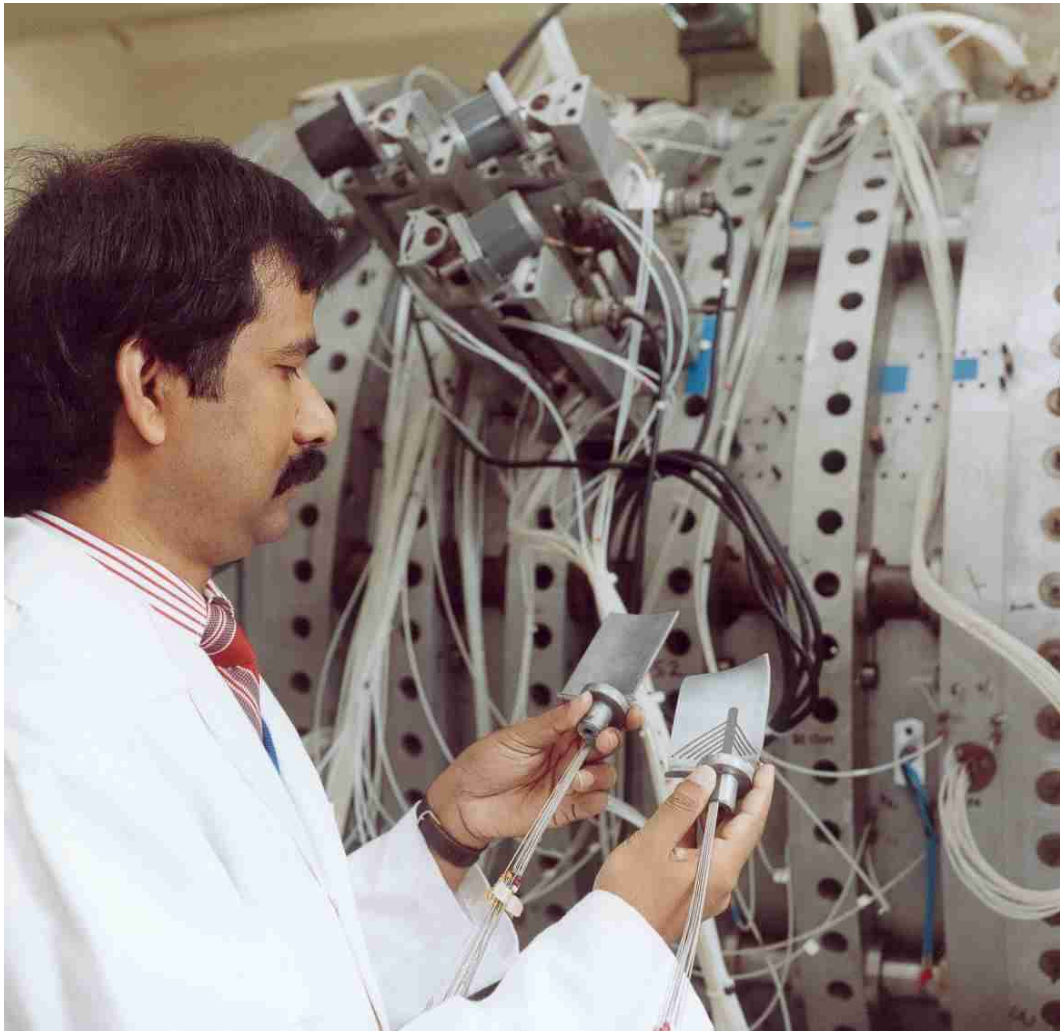
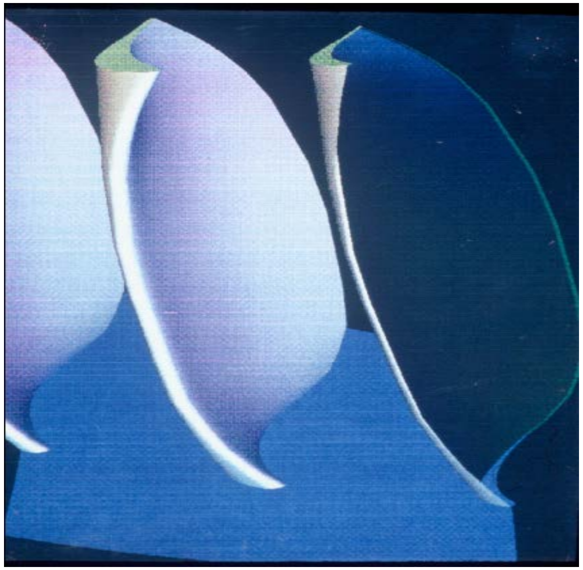
Application to 3D blade sesign.





RB211-535E4 HPC

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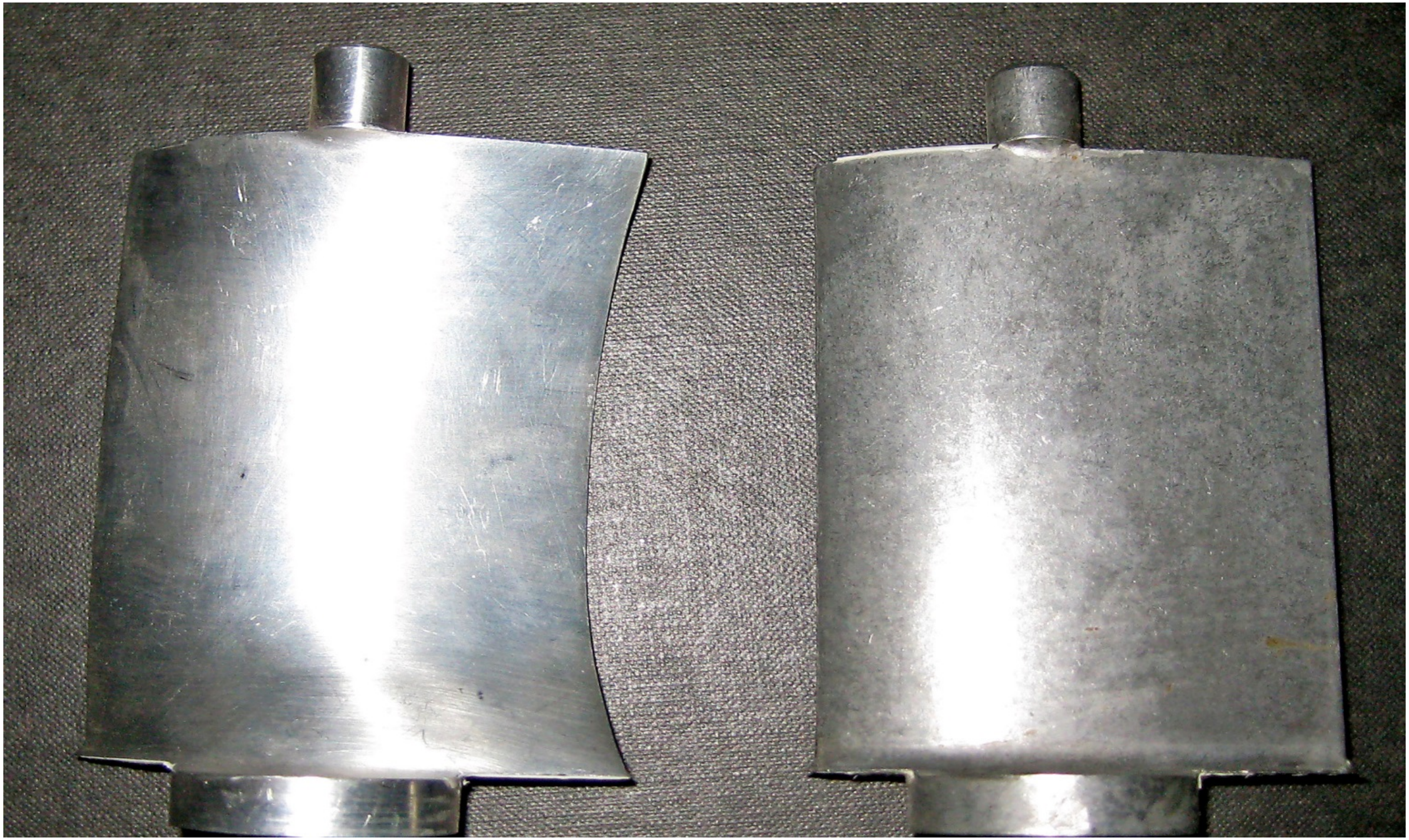
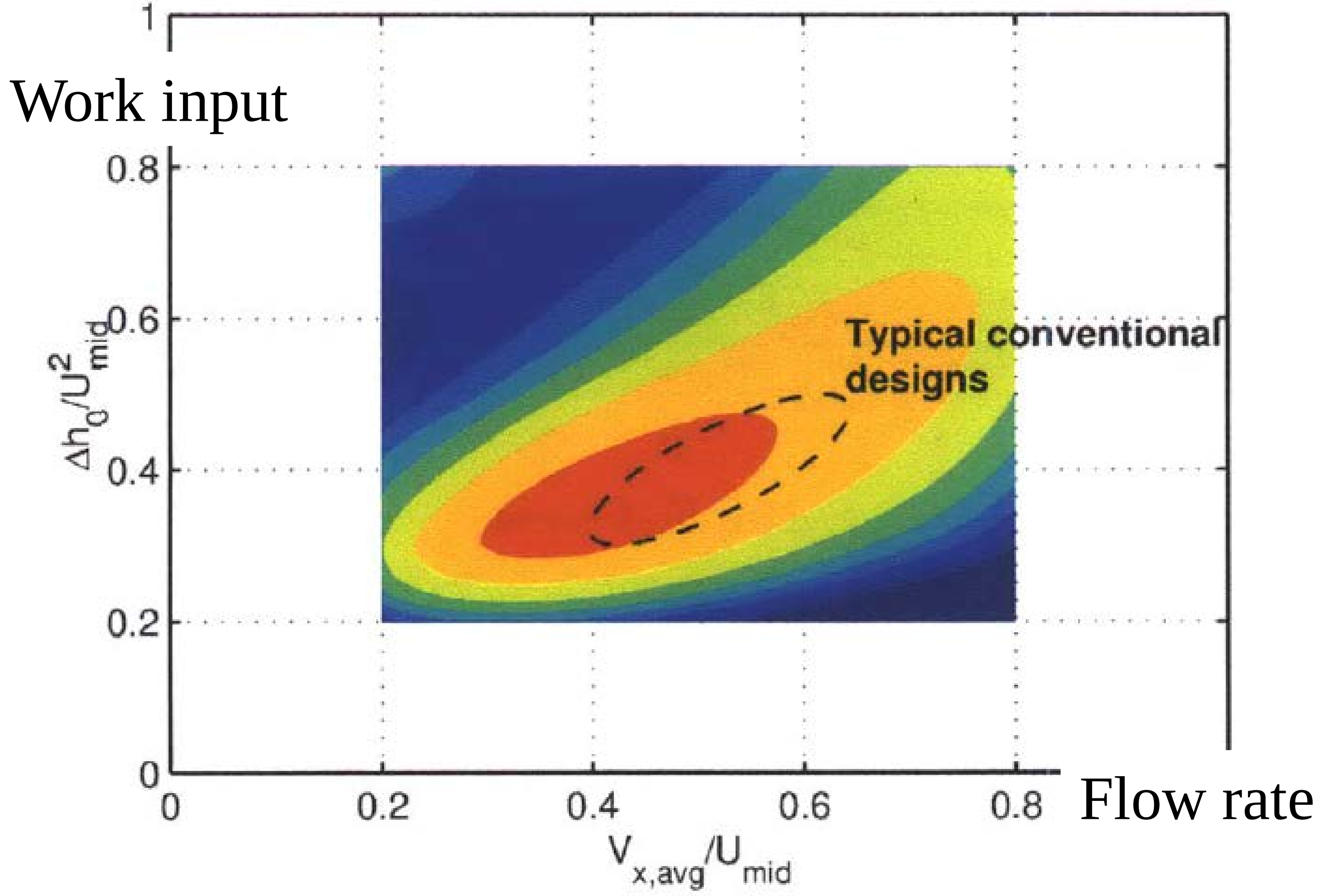
Profile development



Efficiency

Managing the loss processes.



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Hall

Stage loadings

Engine		No Stages	Pressure Ratio
Beryl	1940s	9/10	3.5
Avon	1950s	12	6.5
Spey	1960s	16	15
RB211	1970s	13	25
Trent	1990s	14	52

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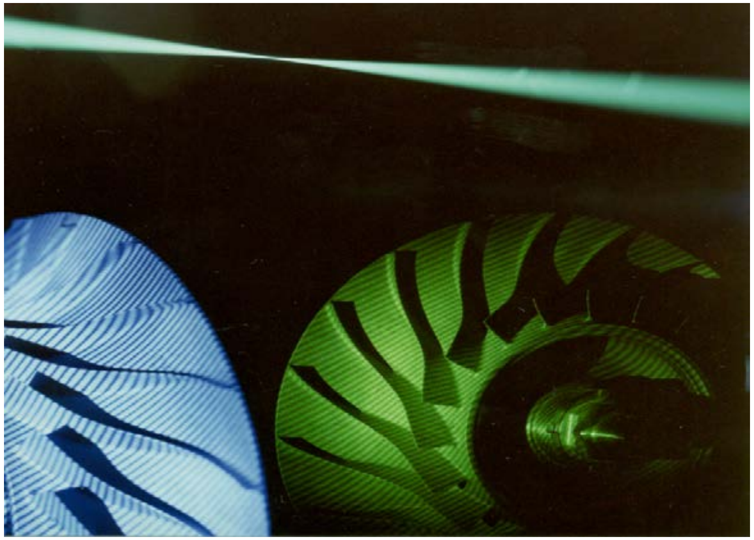
Improvements gained

- Through experiments



- Computation (particularly CFD)

  Very clever people pushing forward the ability to simulate the N-S equations and exploiting advances in computational methods.

CFD problem

- Invicid Euler equations were being solved fairly routines by around 1960 with the greatest issue probably being computational power.
- Complex viscous terms in the Navier-Stokes equations have presented quite a different challenge.
- With a concerted effort over the last fifty years and contributions from many researchers including Professor Goulas, very significant practical progress has been achieved.
- Still plenty to do.

Richardson, in 1922 wrote about viscosity

Big whirls have little whirls,
which feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity.

Addendum
Viscosity and turbulence create the complexity of fluid flows.

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Horace Lamb (Hydrodynamics)

"I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic."

Werner Heisenburg (Physicist)

"When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first."

Addendum: Some things are made in heaven and others elsewhere.

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daVinci

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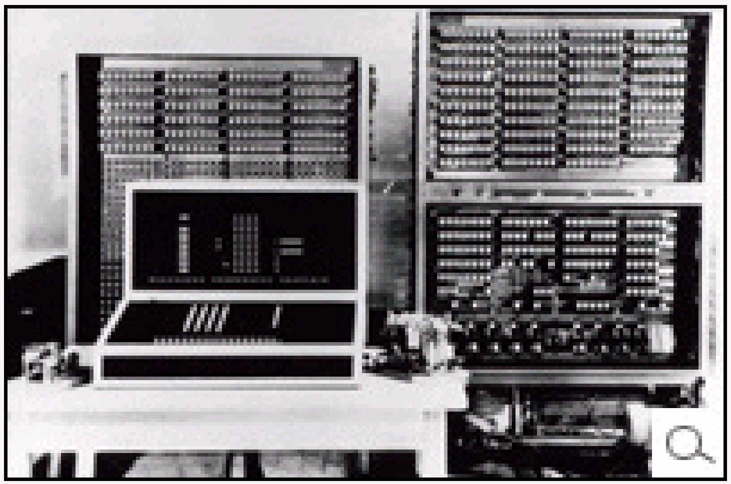
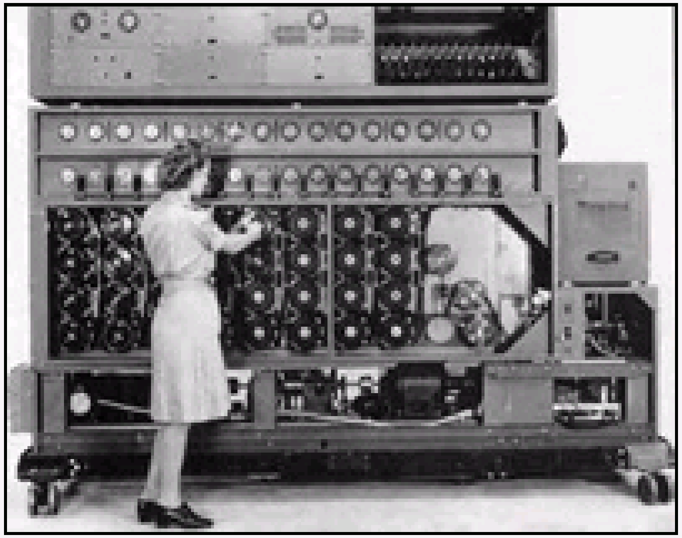
Computers

1941

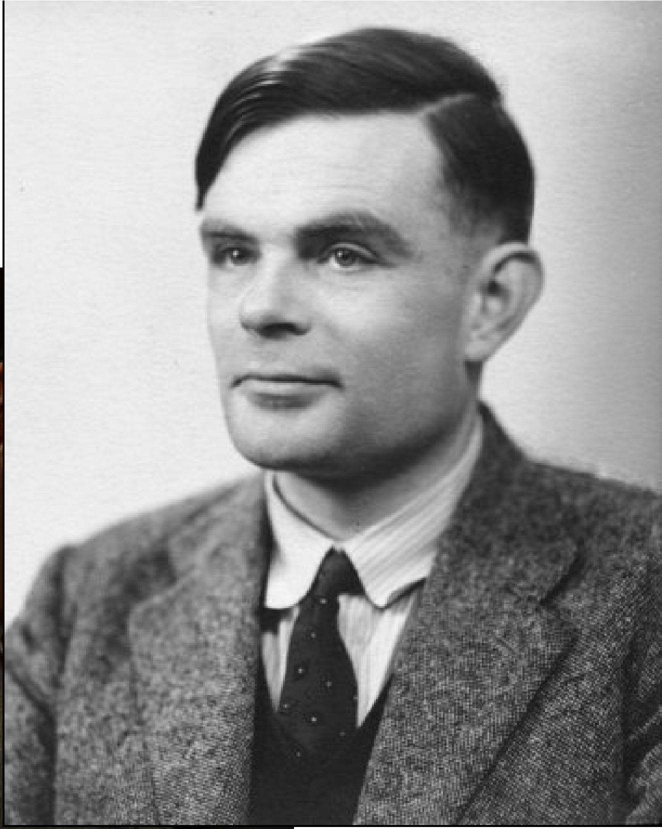


The Zuse Z3 Computer

1941



The Bombe at Work



Keira Knightley, Matthew Beard, Matthew Goode, Benedict Cumberbatch, and Allen Leech star in The Imitation Game

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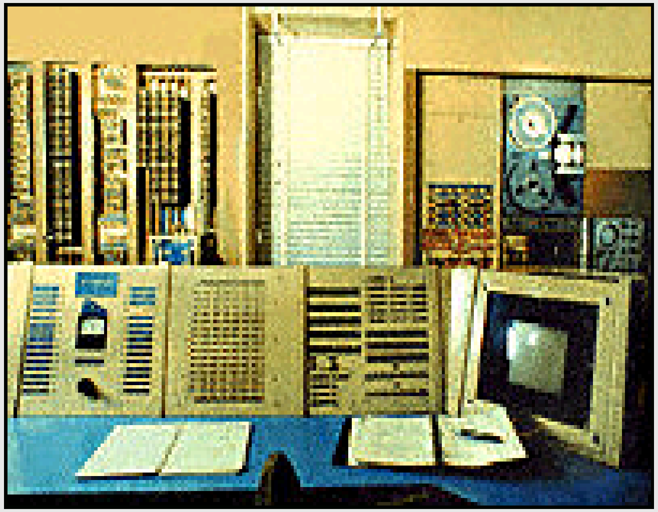
1956

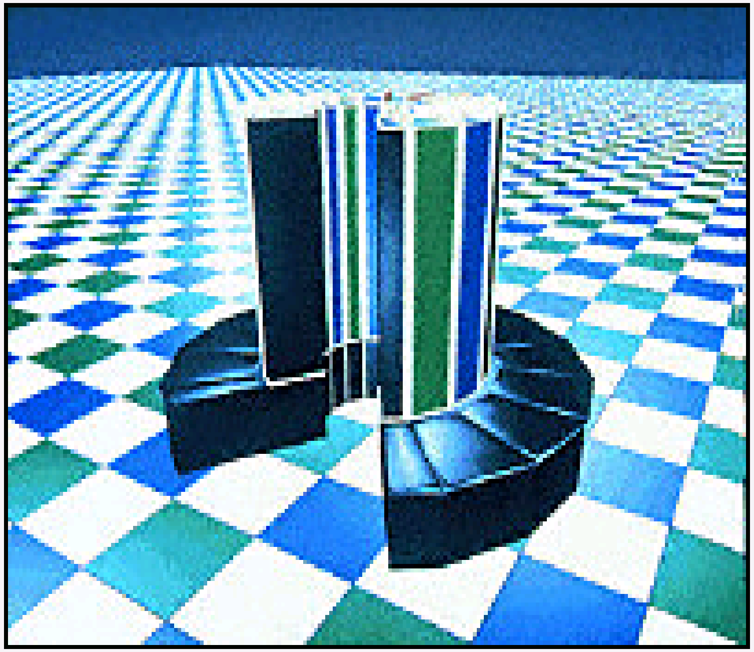


MIT TX0

1960

DEC PDP-1

1976

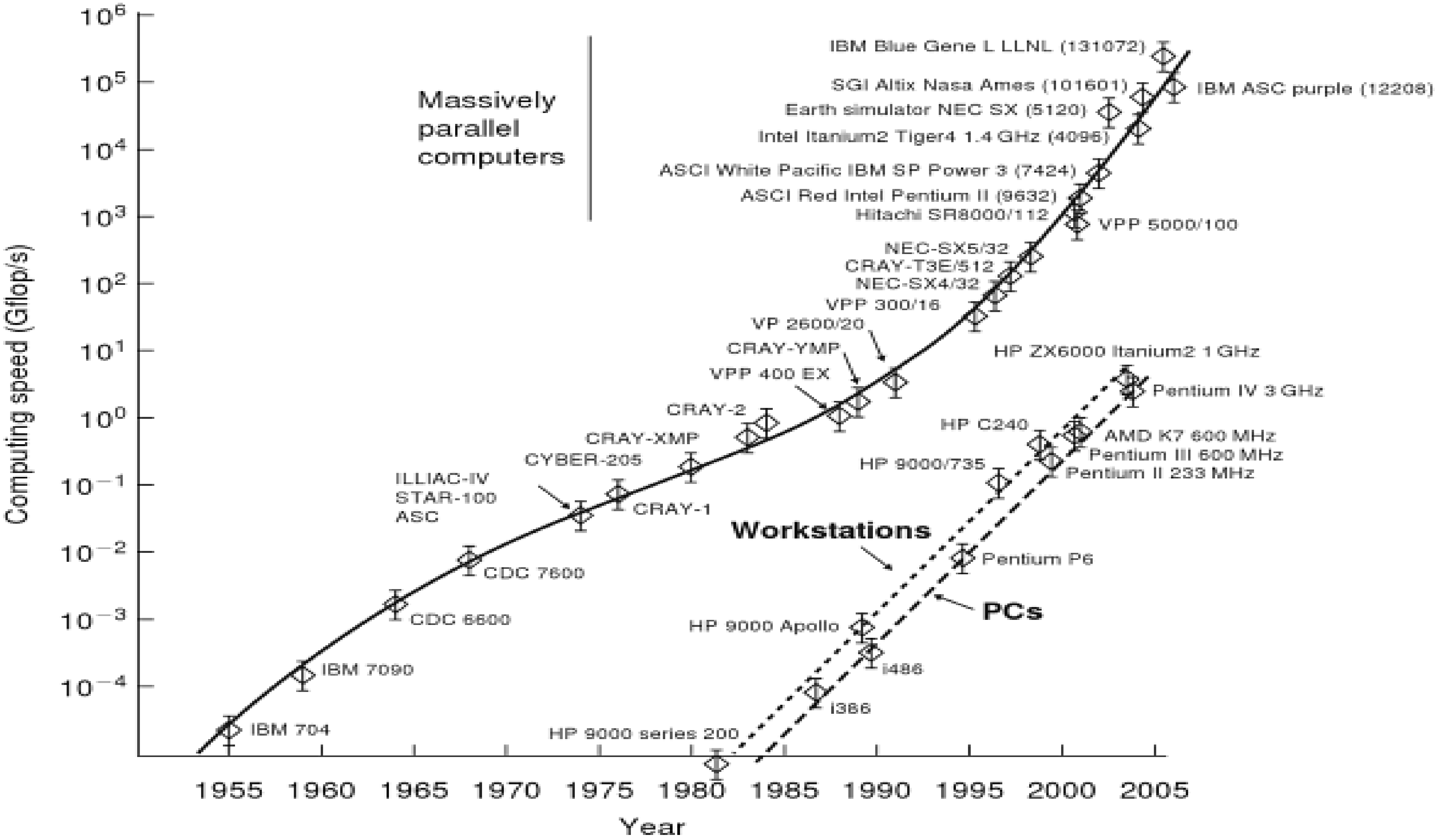


Cray I

1977

Commodore PET

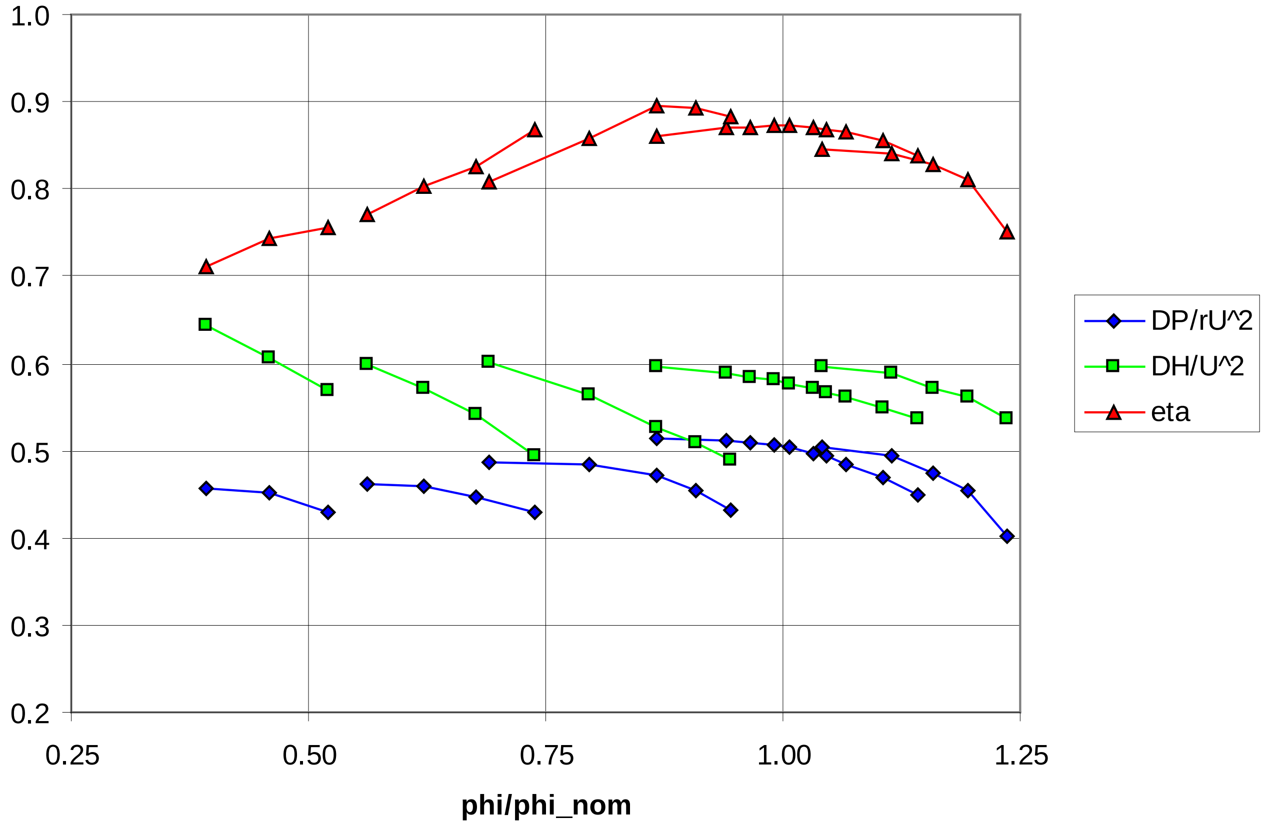
Developments



Hirch

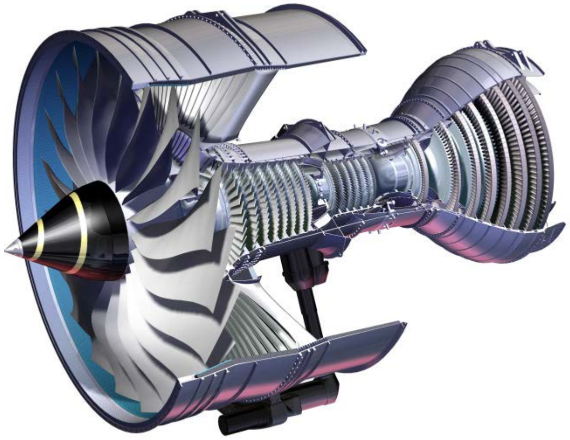
Routine application of CFD

- 27 runs at various IGV settings (-60° to +10°)



Steps in the turbo design process

- Preliminary (1D design)
  - Defines the geometrical envelope within the larger picture
  - Determines the performance potential
  - Errors very expensive to recover later
- Throughflow (2D design)
  - Semi-empirical approach
  - Many calculations, needs to be rapid and robust
  - Results integrated into overall system model
- Detailed design
  - Absolute accuracy important
  - An advancing front of capability
  - Trade with ‘usability’ in the design process
  - CFD is critical



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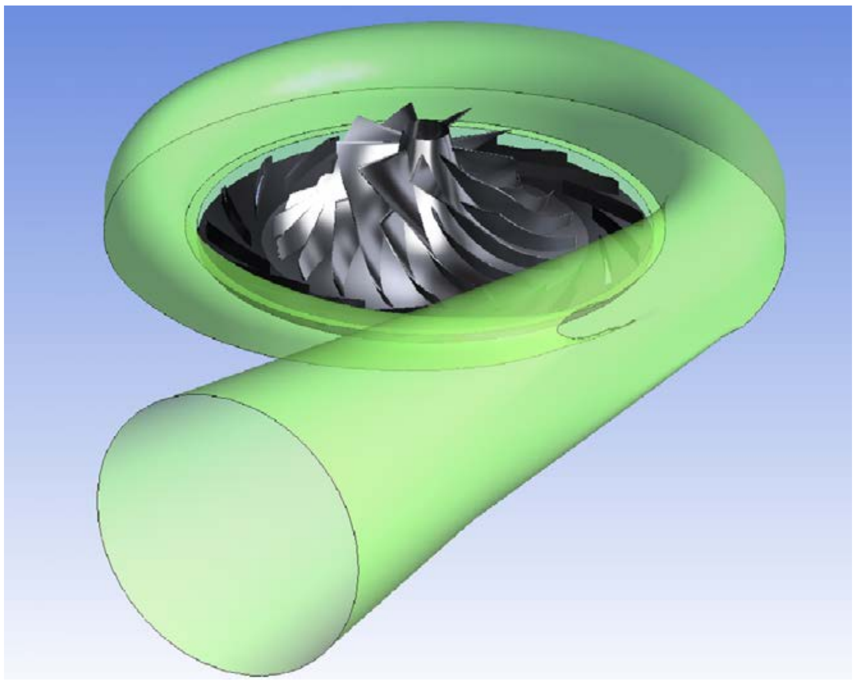
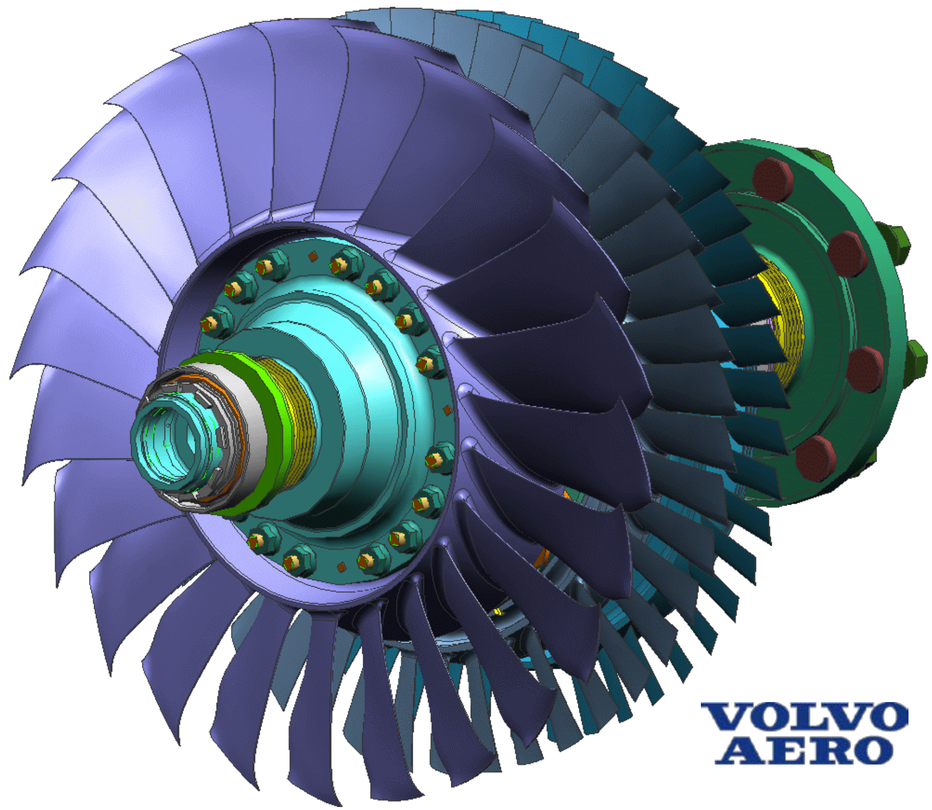
Typical compressor applications

- Industrial gas compressor and aero-engine booster





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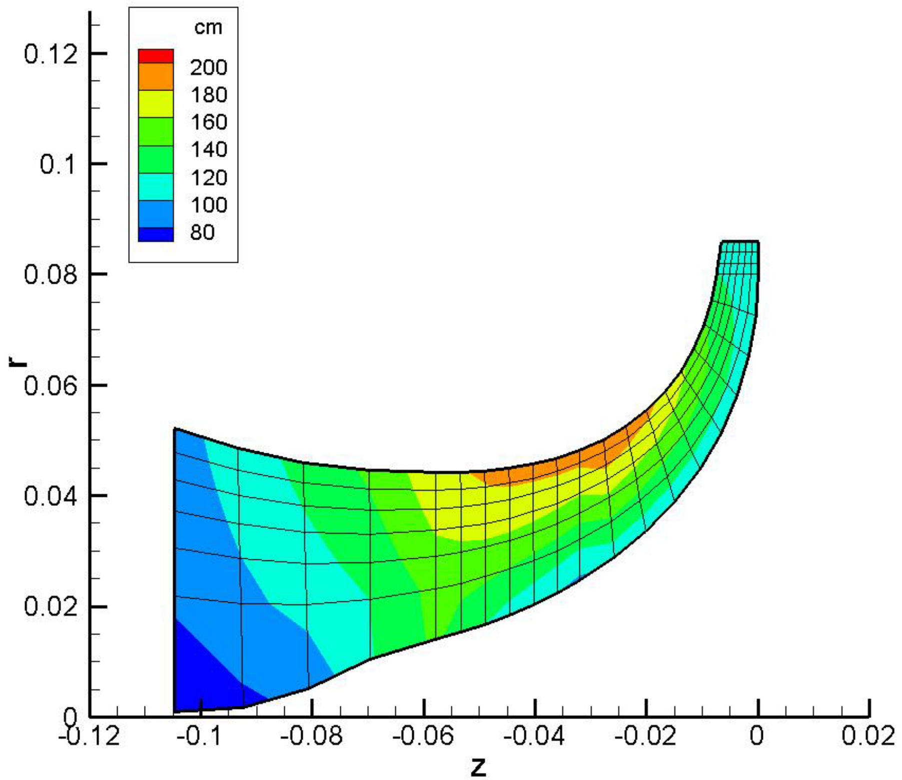
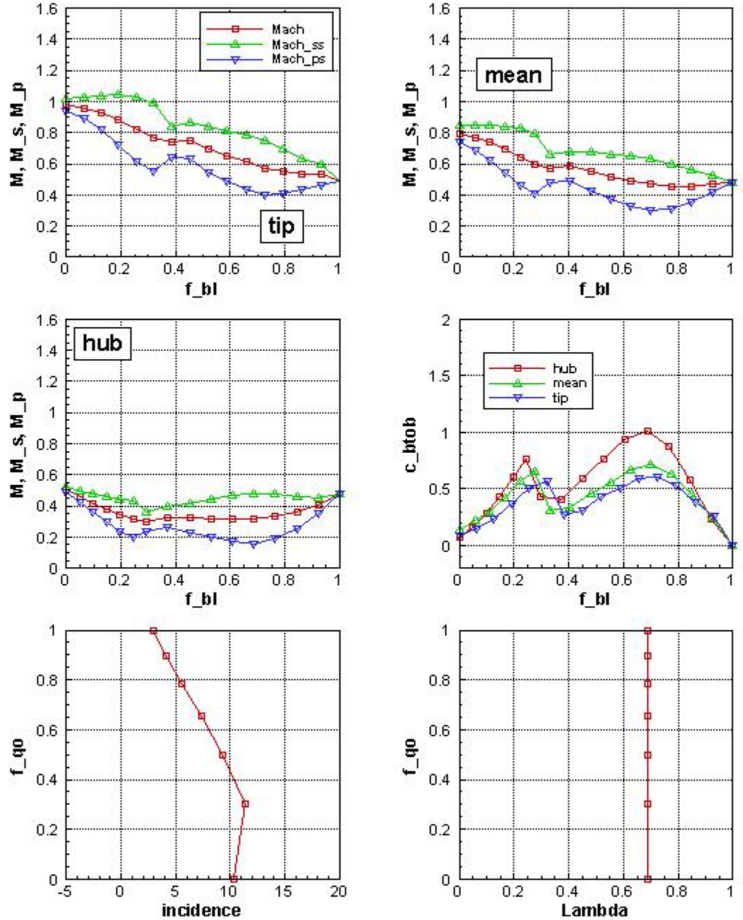
Example of throughflow: Vista TF

- 4:1 compressor impeller





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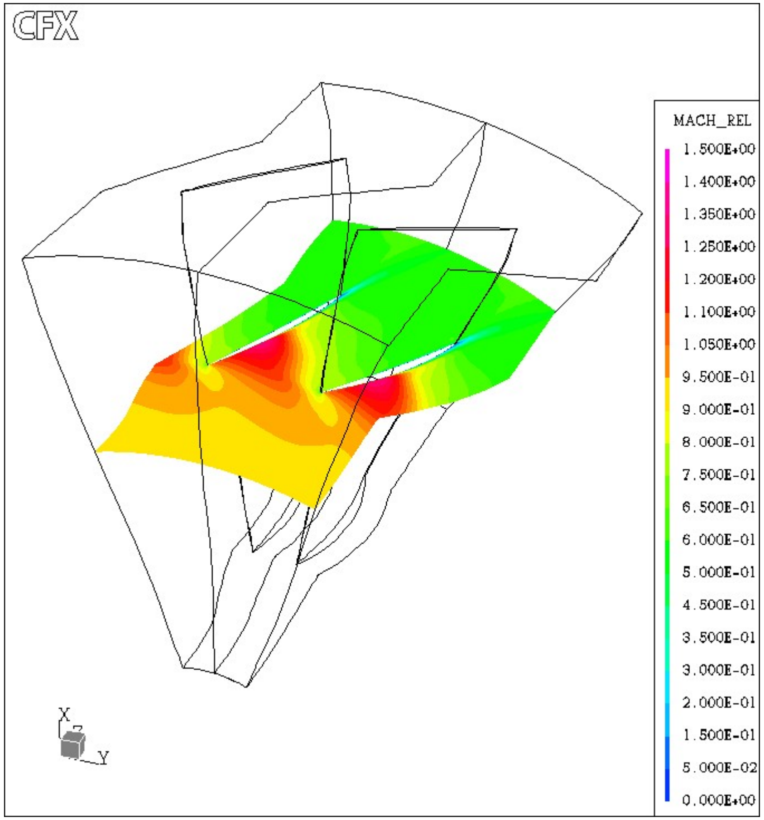
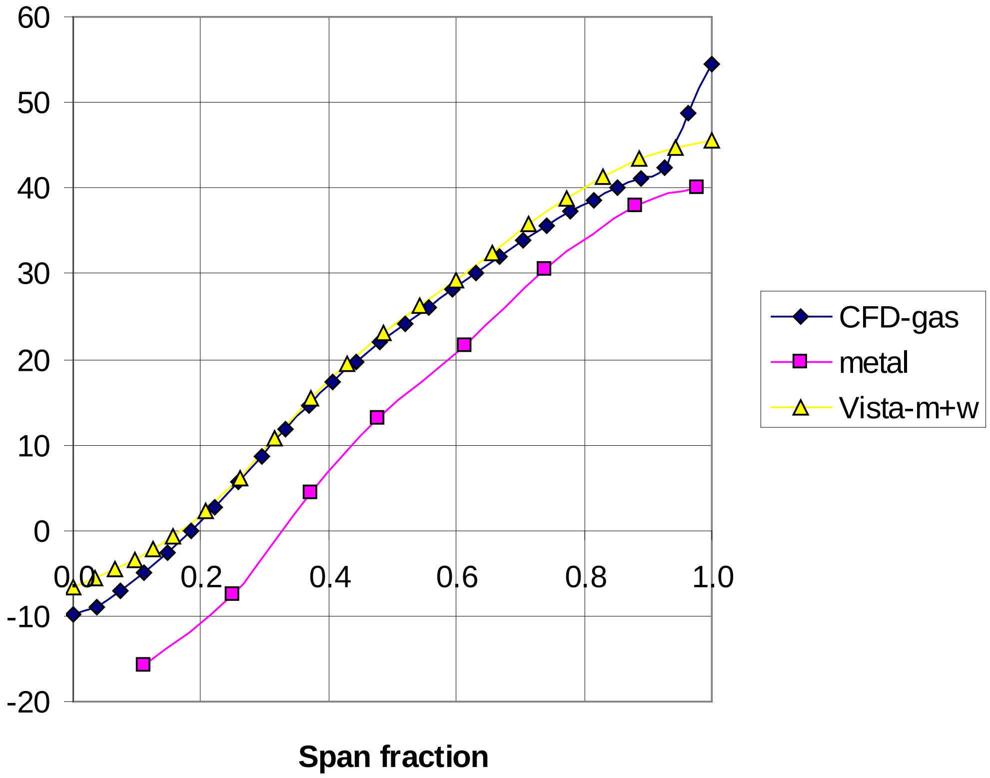
Throughflow and CFD

- Transonic fan





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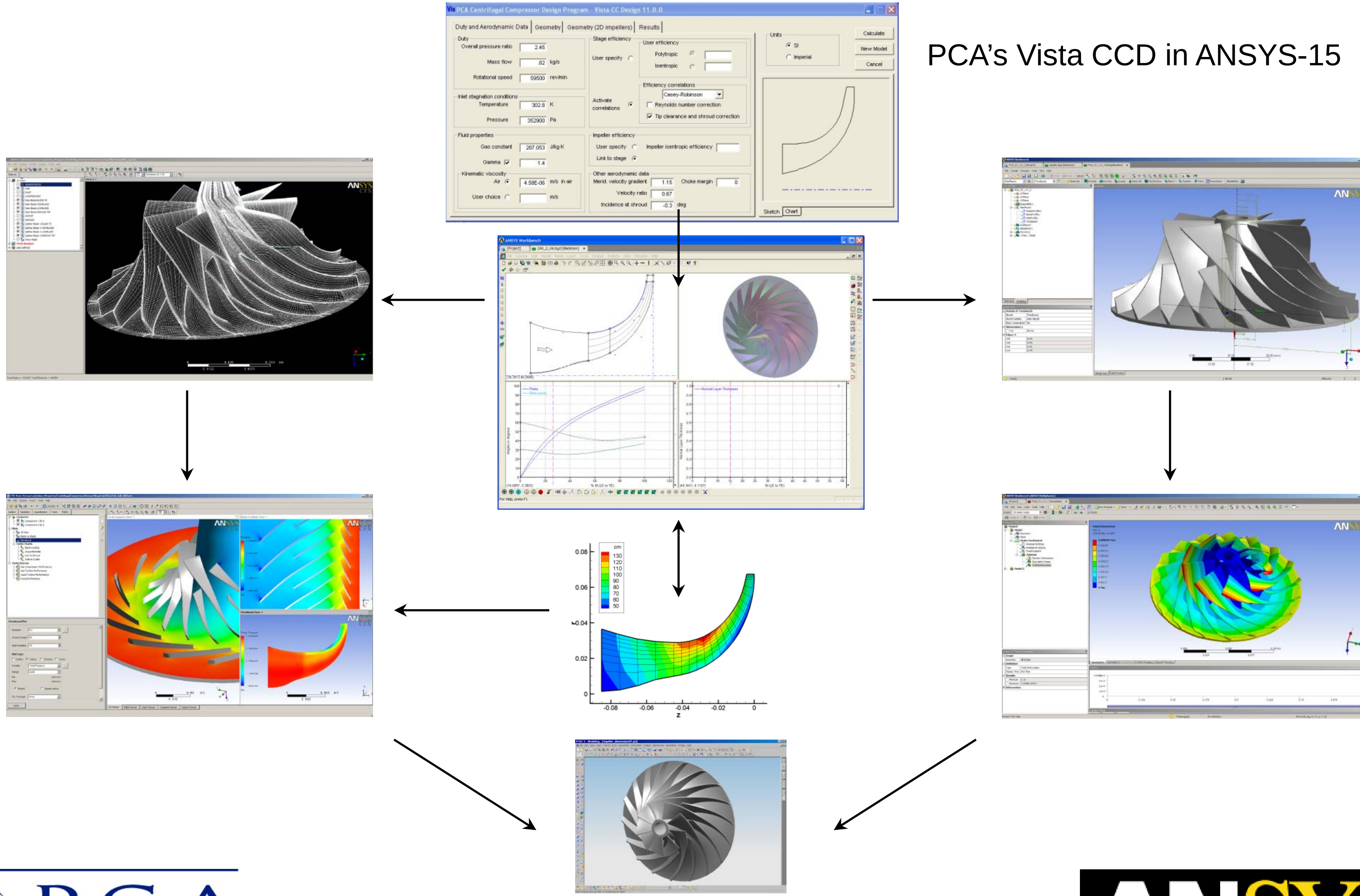
Integrated design system



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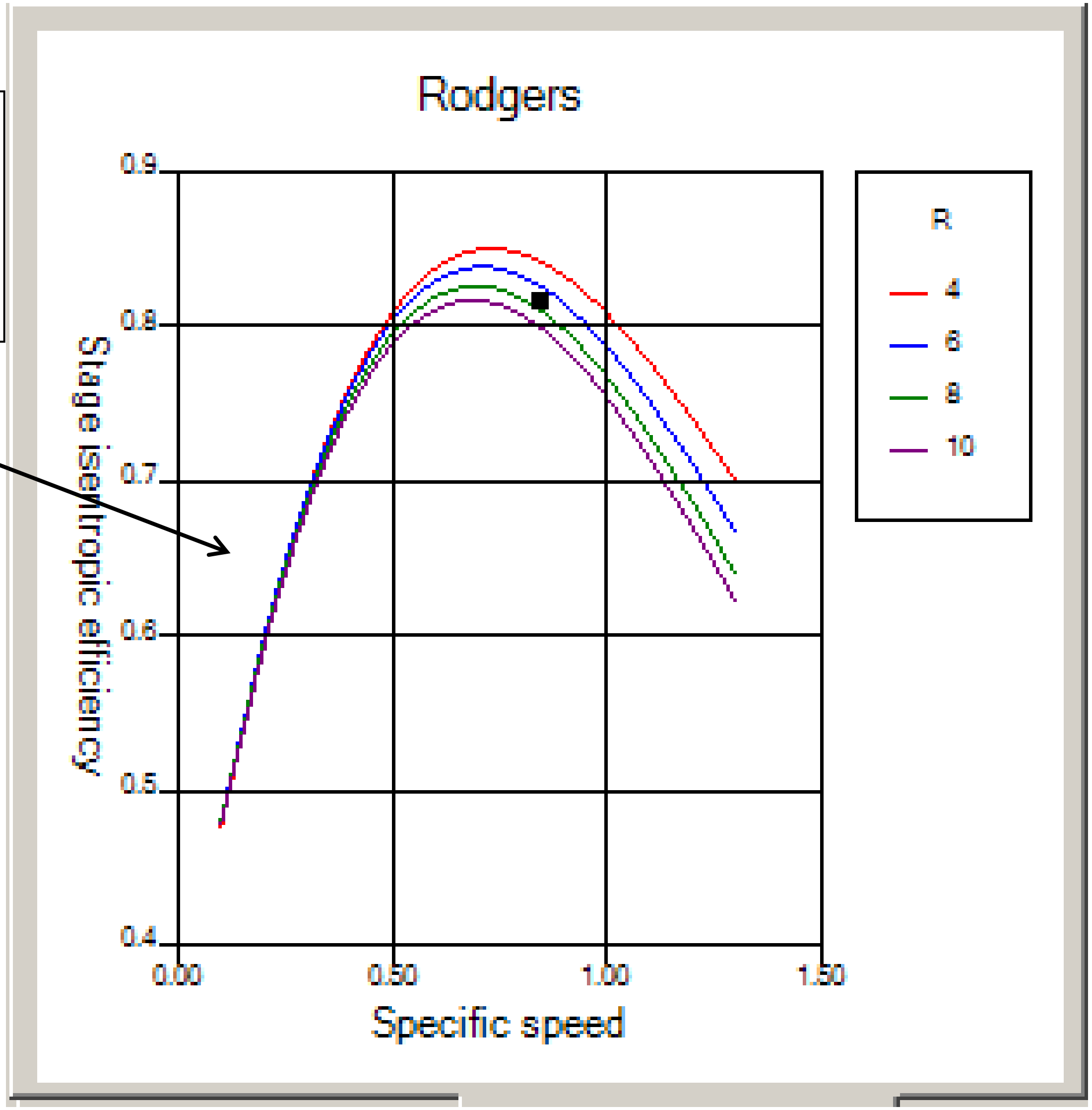
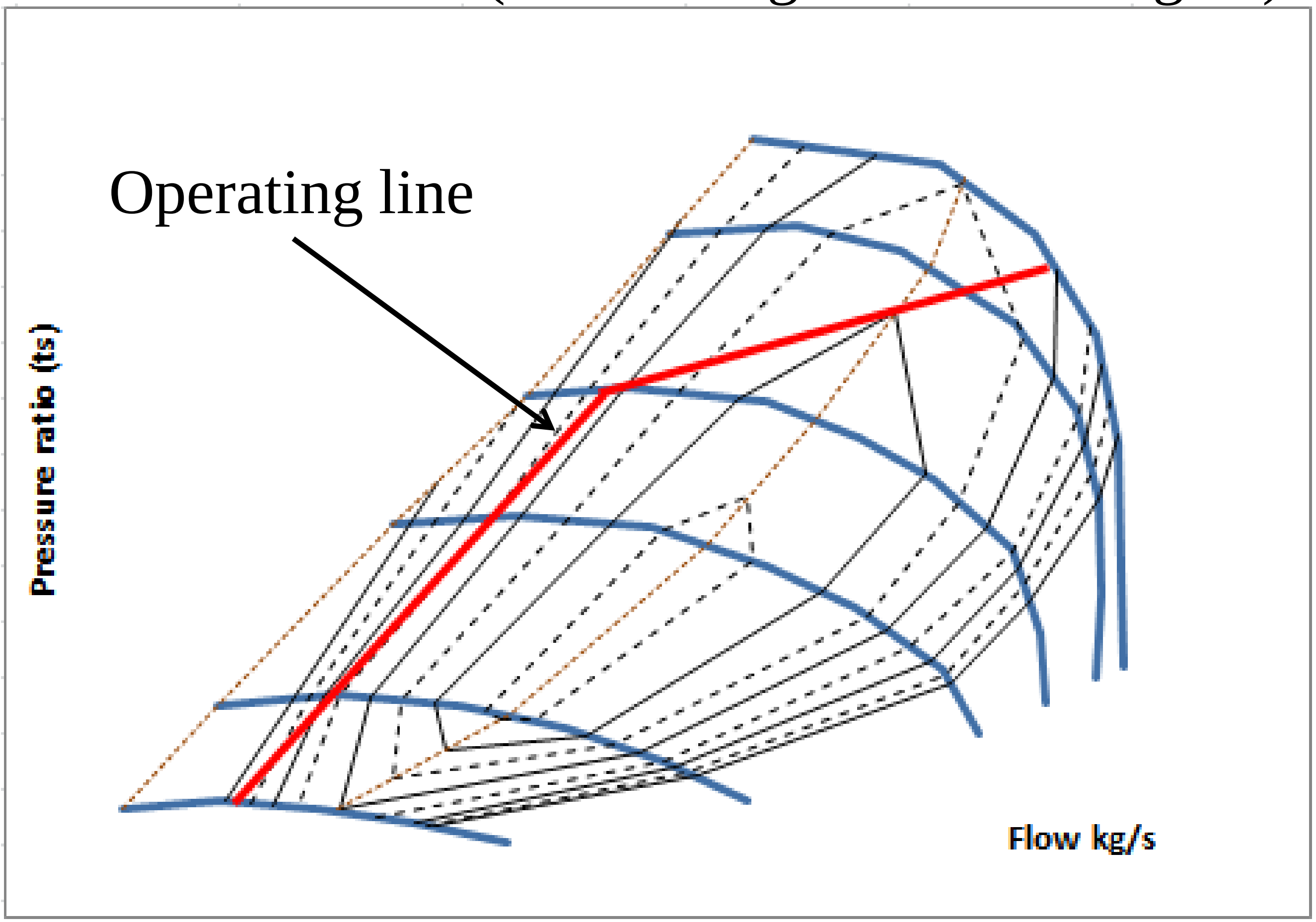
Challenges

Limited speed
High head (pressure ratio)
Low volume



Matching machine to duty

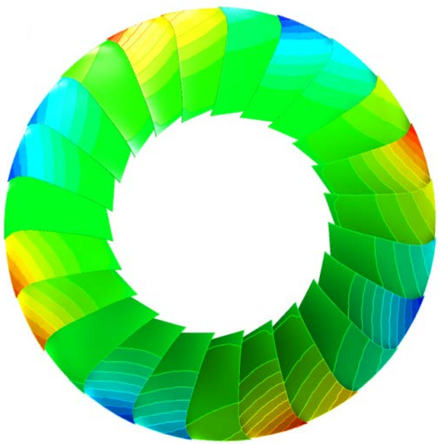
(Turbocharger to diesel engine)



Analysis capability: FSI

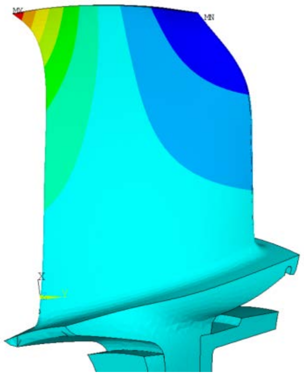
- Flutter analysis of an axial compressor

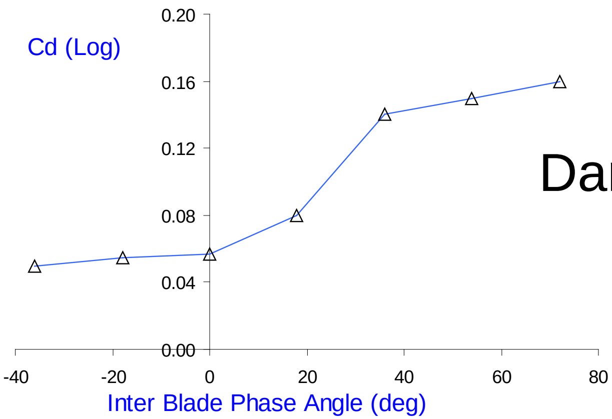
1st Flap



Nodal displacement pattern

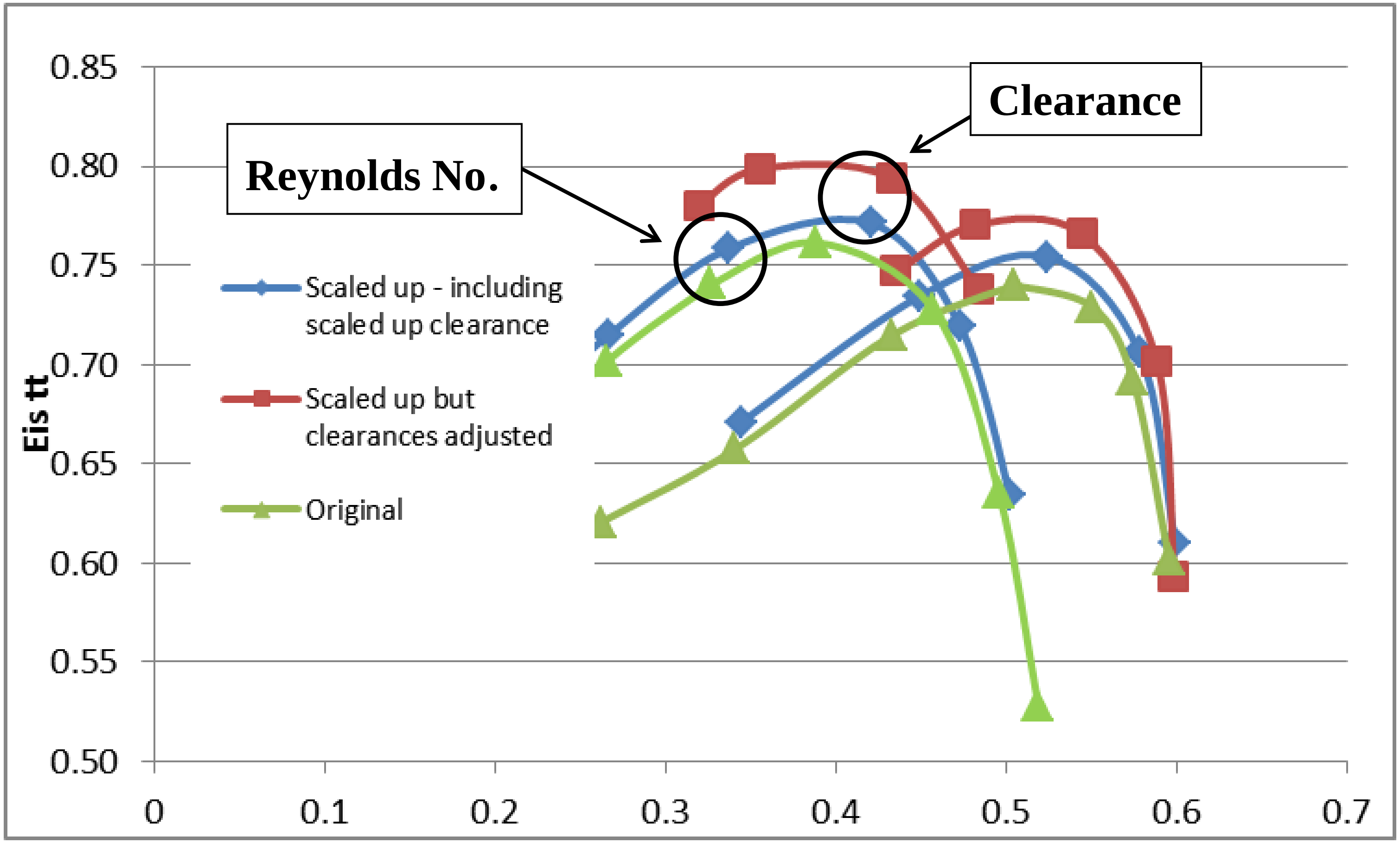
1st Torsion





Damping coefficient

Clearance don't scale with size.



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True 3D design

Hazby et al

Optimisation

- A holy grail,
  - ‘optimisation will eventually automate design’
- Difficulties
  - Must be able to define quantitatively what is considered to be a good design, ‘fitness’ functions
  - System needs to be able to recognise compromises
  - Efficiency and surge margin, mechanical integrity all need to be considered.
  - When combined with 3D CFD, huge computational effort is implied

Year end?

Event	Compressed time scale
Big bang	Jan 1st
Origin of Milky Way	May 1st
Our solar system	Sept 9th
Formation of Earth	Sept 14th
Jurassic period	Dec 27th
First Humans	Dec 31st 10:30pm
Agriculture	Dec 31st 11:59:20pm
Bronze age, Trojan wars, compass	Dec 31st 11:59:53pm
Iron age	Dec 31st 11:59:54pm
Euclidean geometry, Archimedes, Christ	Dec 31st 11:59:56pm
Renaissance, experimental methods	Dec 31st 11:59:59pm
Wide developments including a better understanding of fluids (turbomachinery), flight, computers, telecommunications and many others disciplines	Last second of the year.