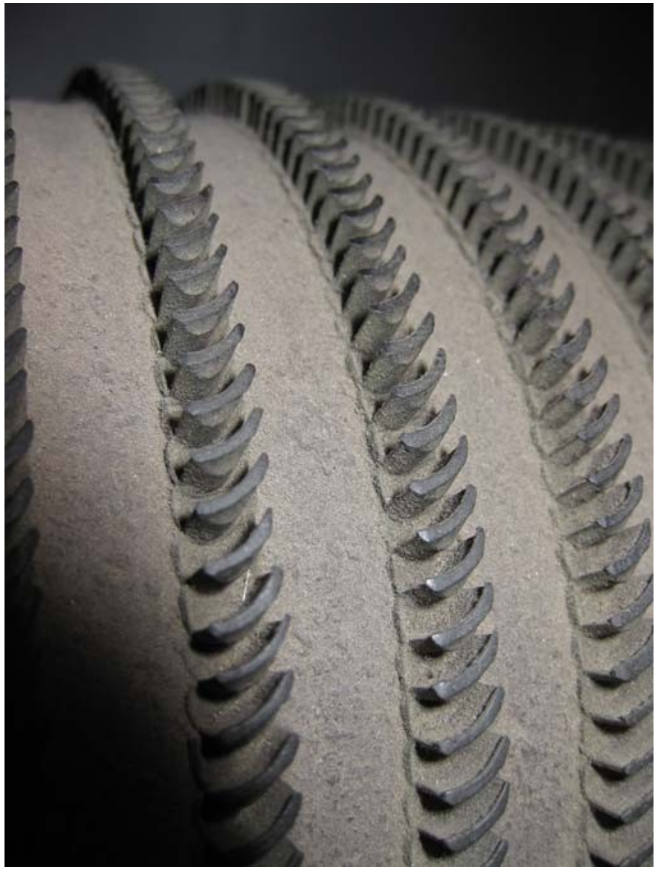
THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)



Parsons 1895

Siemens (2010)

Parsons 1895

100kW Steam turbine

- Pitch/chord a bit too low.
- Tip thinning on suction side.
- Trailing edge FAR too thick.
- Surface roughness poor.

1897: 1570 kW (Turbinia)

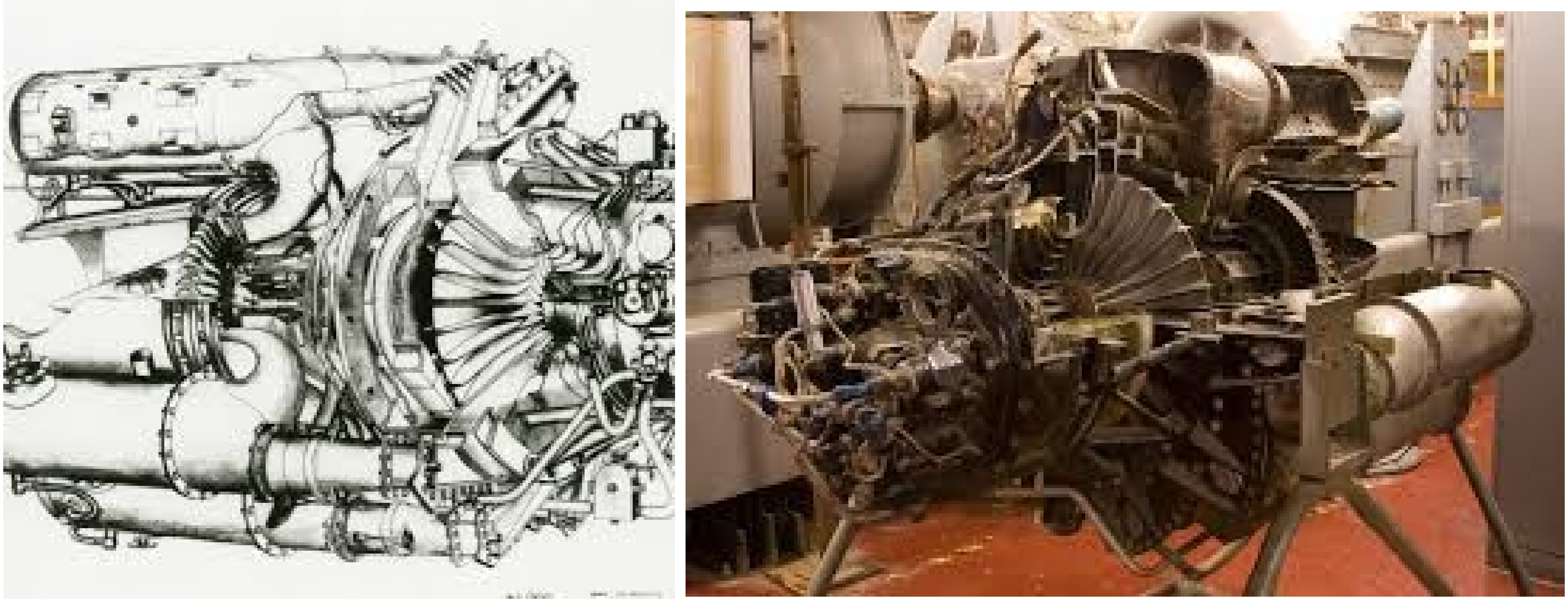
THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

Siemens (2010)

By 1920 40 MW turbines were in operation.

Now:
- up to 1 GW on a single shaft
- large aspect ratio blades
- twisted blade
- thin trailing edges

THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

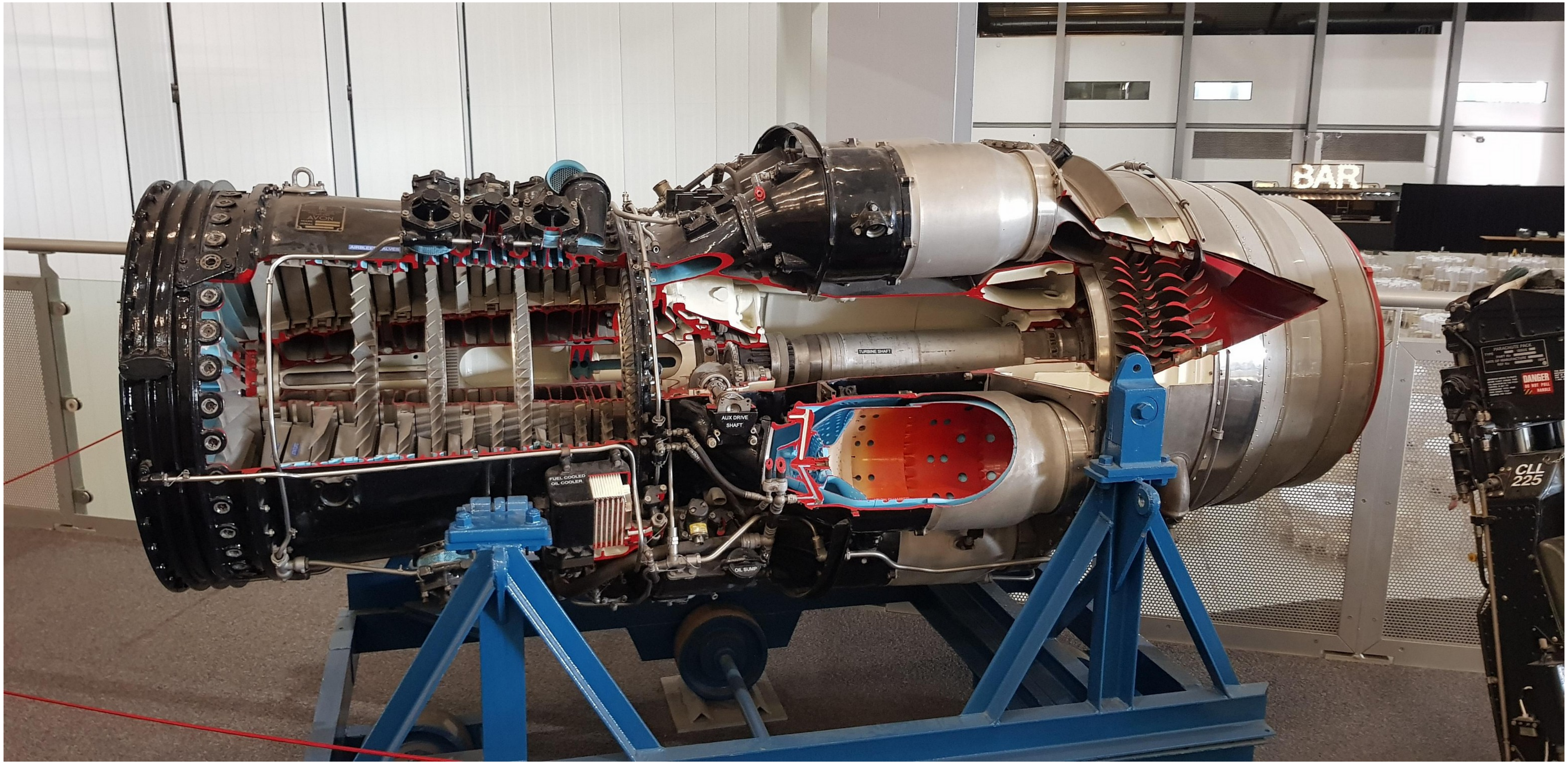


Sir Frank Whittle 1932

THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

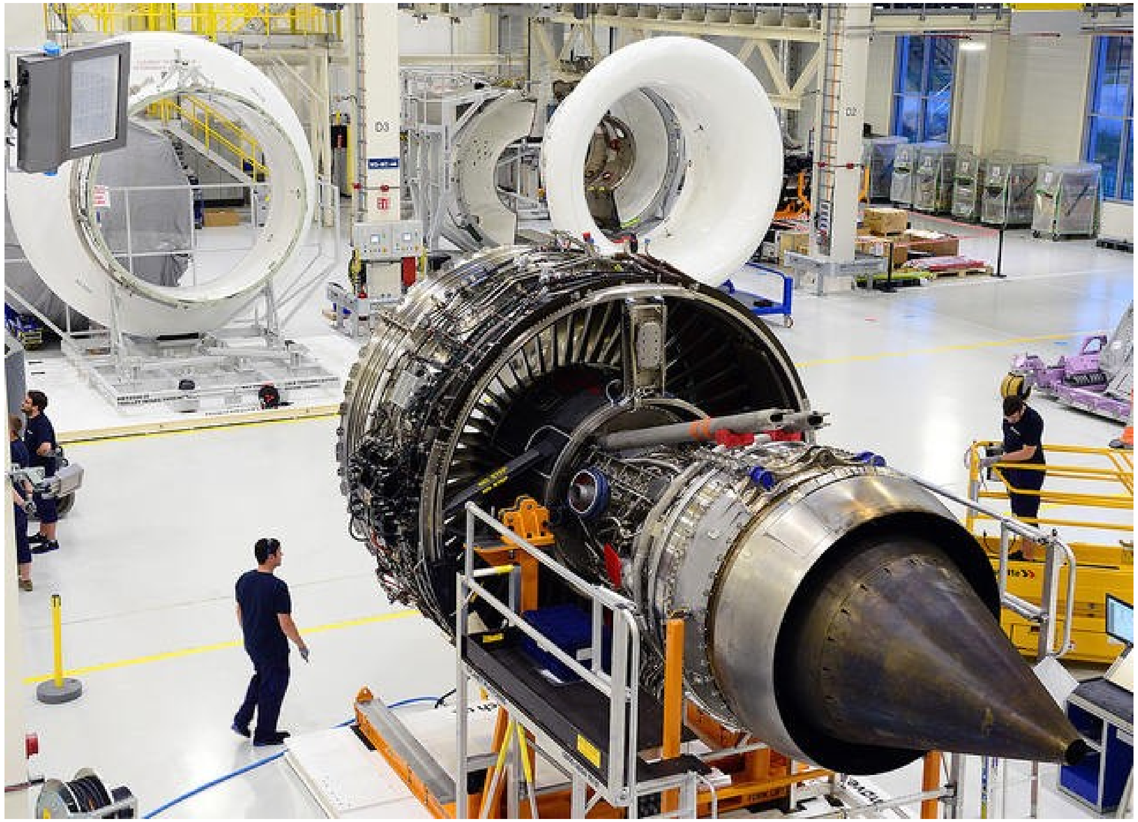
- Centrifugal compressor (1 stage)
- 10 reverse flow chambers
- axial turbine (1stage)
- 5.5 kN thrust
- 17,750 rpm
- 254 kg
- 21 N/kg

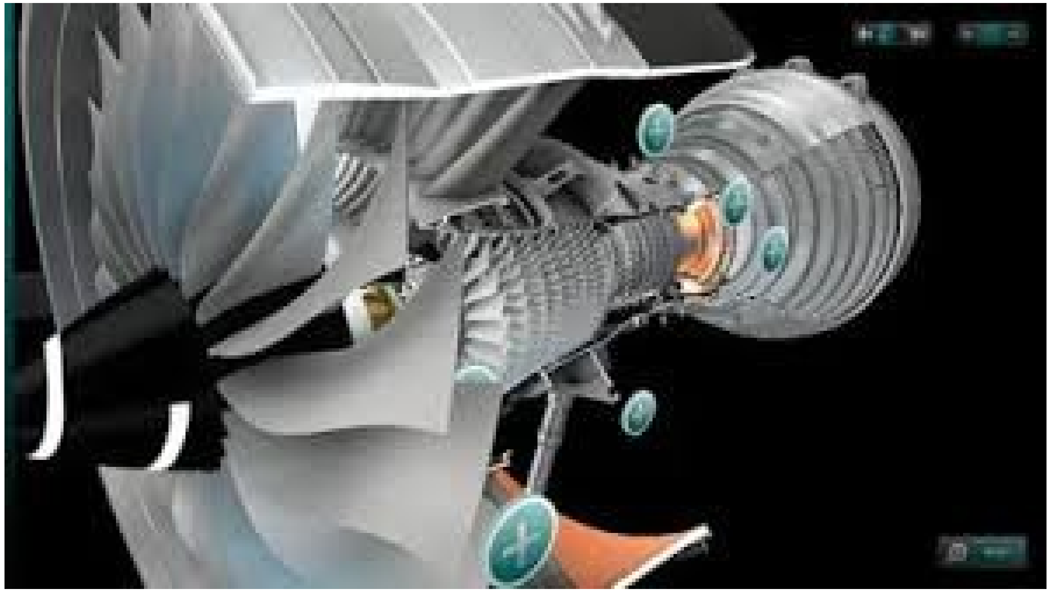
THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)



15 stage axial compressor (PR=7.45), cannular combustor, 2 stage turbine
1310 kg, 73 kN thrust, .9m x 3.2m, 56 N/kg

THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)





3 shaft engine, 1+8+6 stage compressor (50 PR), 1+2+5 stage turbine
2700-8200-12600 rpm, 7200 kg, 420 kN, 3m x 6m
1436 kg/s, 58 N/kg,

THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

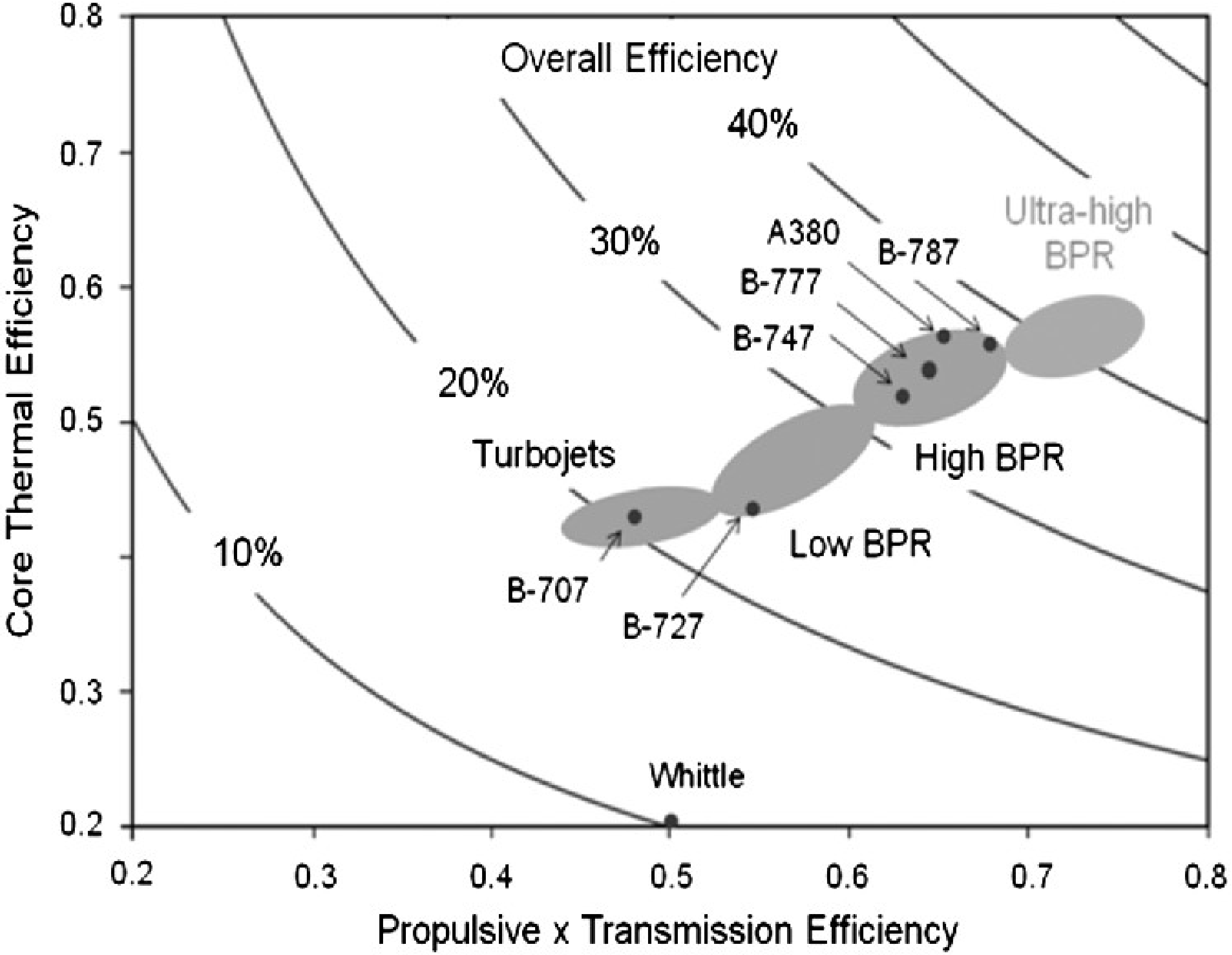
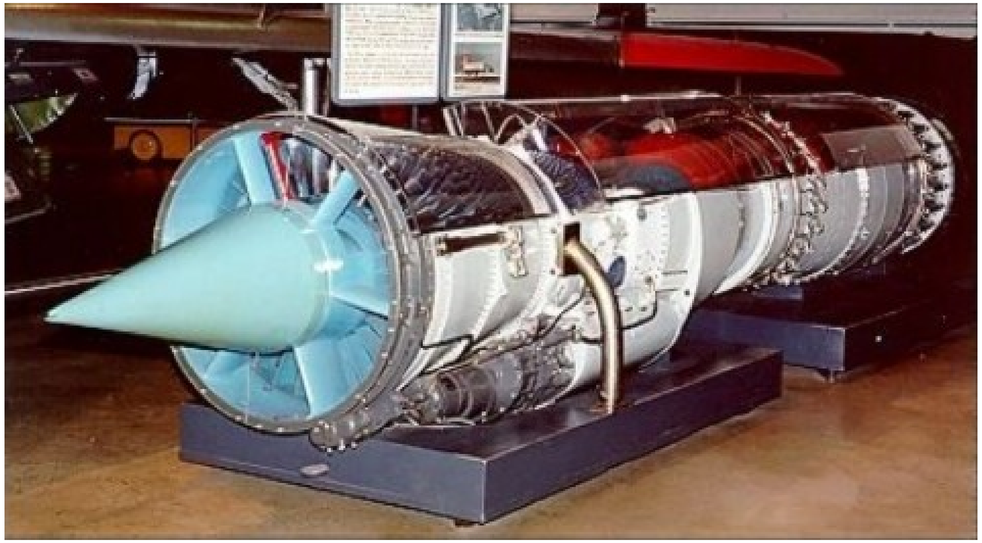


Fig. 2 Core thermal and propulsive efficiencies for commercial aircraft engines.

THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

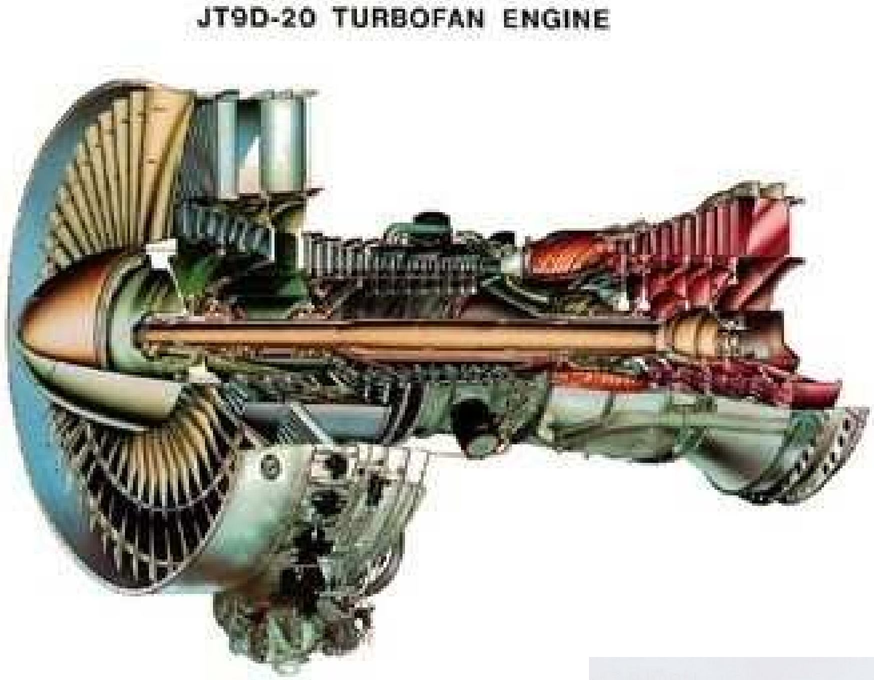
B707 → PW J57



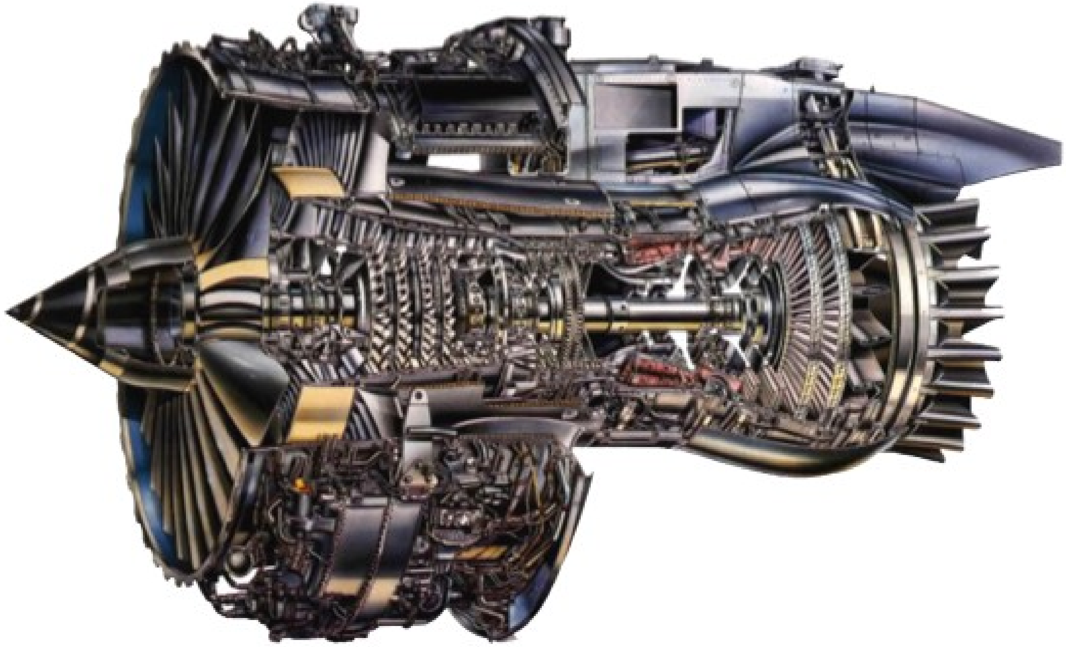
B727 → Allison AR963

THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

B747 → PW JT9D



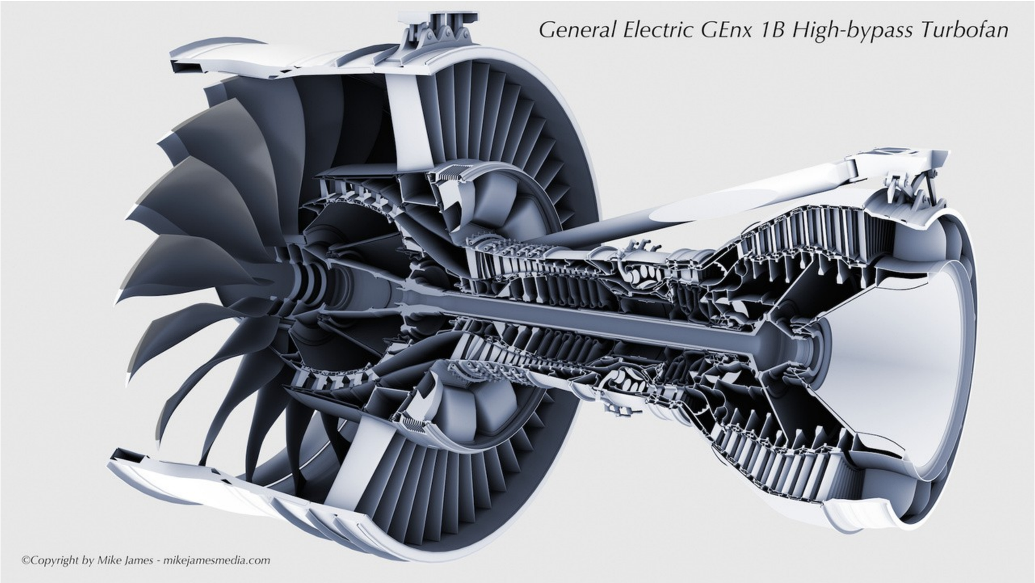
B747 → RR RB211

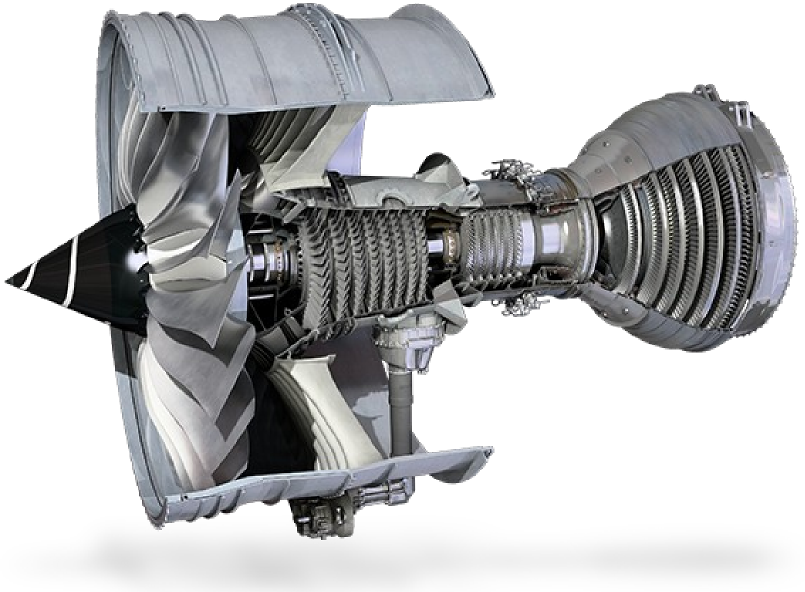


THE EVOLUTION OF TURBOMACHINERY DESIGN (METHODS)

B787/A380 → GEnx

B787/A380 → RR T1000

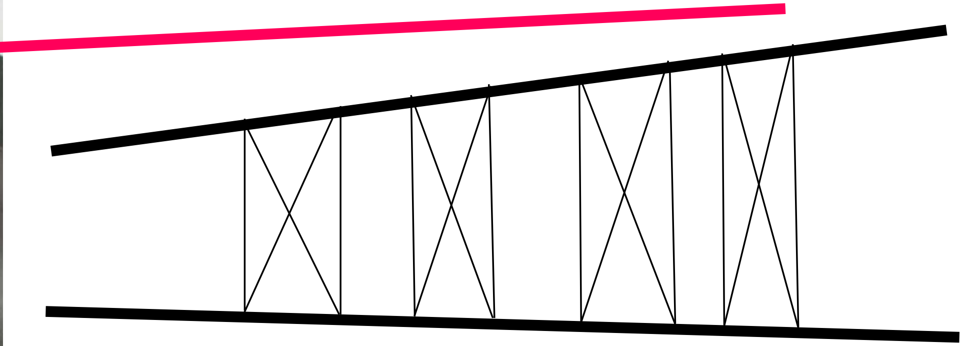




1900 - 1940. Mainly steam turbines.

Designs based on mean line velocity triangles with some cascade testing.

Free vortex design introduced in late 1920’s but not generally accepted until Whittle in late 1930’s.



Mean Line.

Mainly untwisted blading

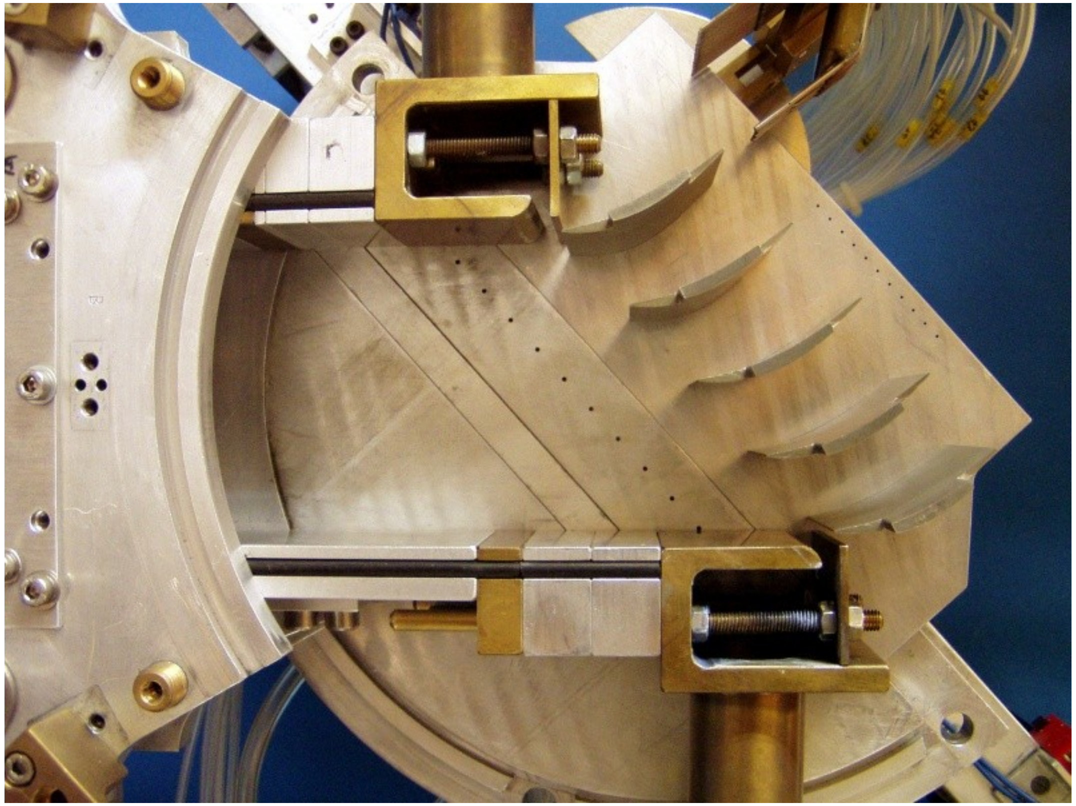
1940-1950 Intensive development of the jet engine.

Much of the basic science came from NGTE, Pyestock (RAE).

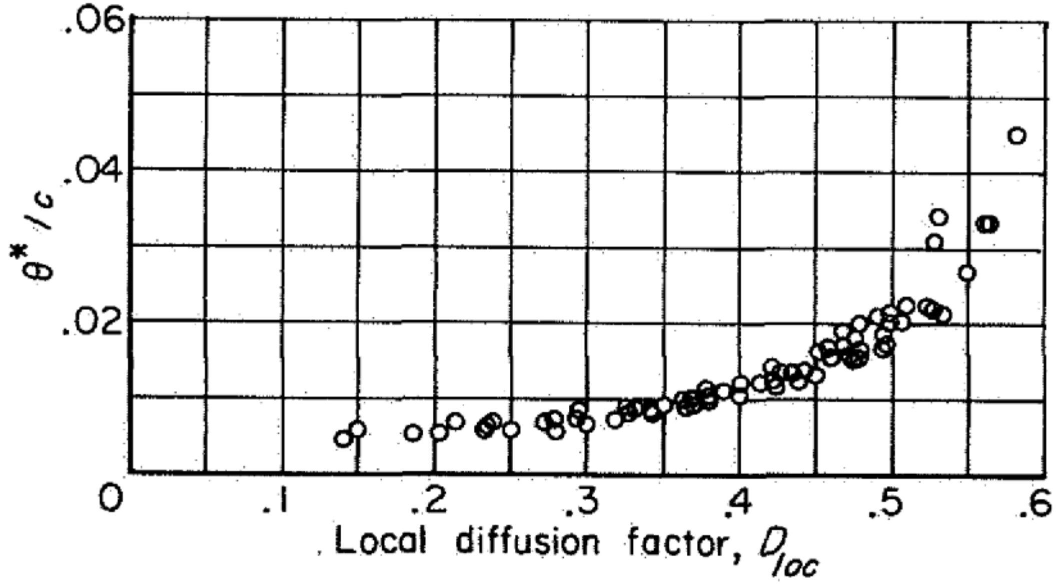
Cascade testing leads to correlations as the basis of design.

- Howell
- Carter
- Ainley & Mathieson

Some of these are still in use.

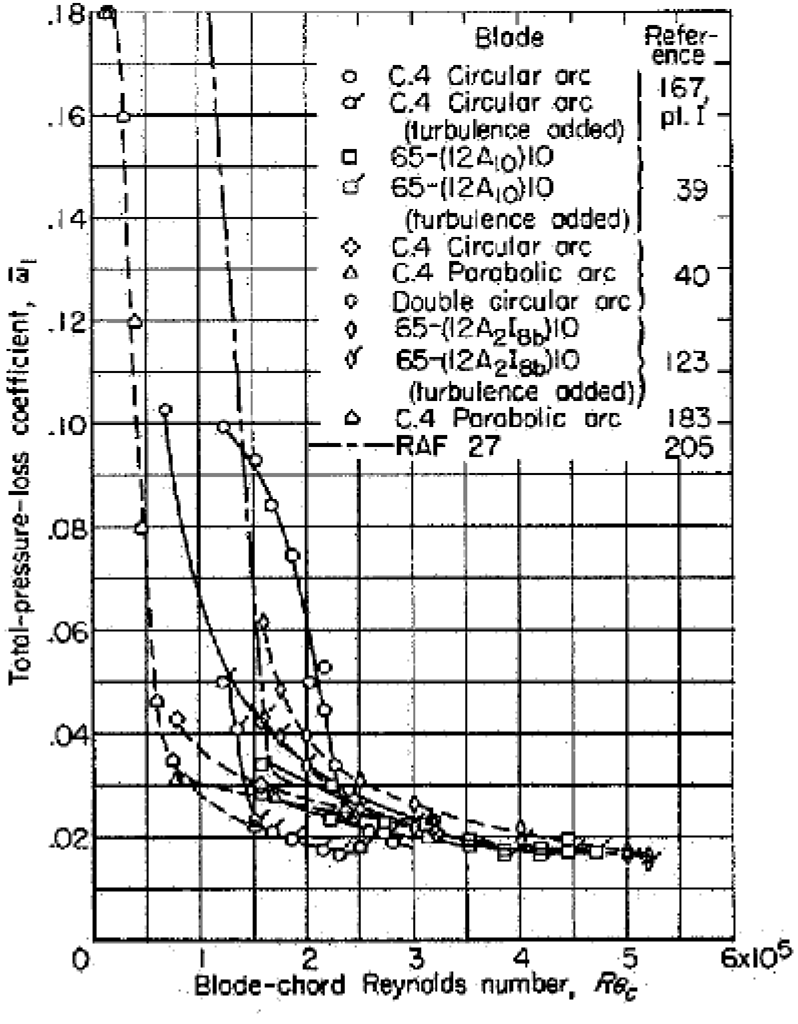


Effect of diffusion



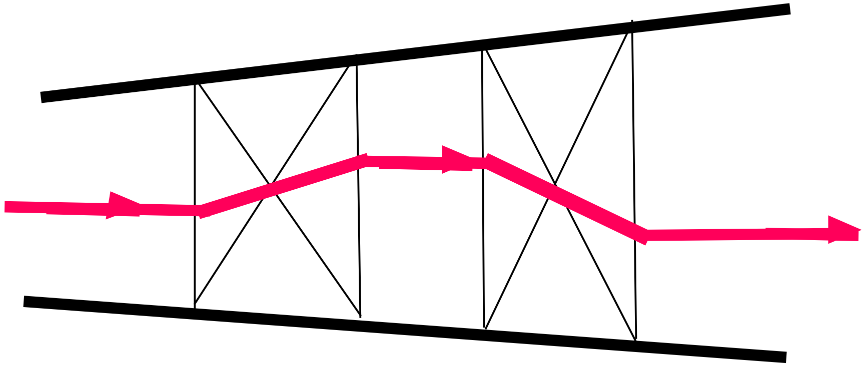
$$D_{loc}=\left(1-\frac{V_2}{V_1}\right)+\frac{\Delta V_\theta}{2\sigma V_1}$$ per NACA-65

Effect of Reynolds



1950-1960. Radial Equilibrium used to predict the spanwise variation in velocity, etc . Assumes all the streamline shift occurs within the blade rows.

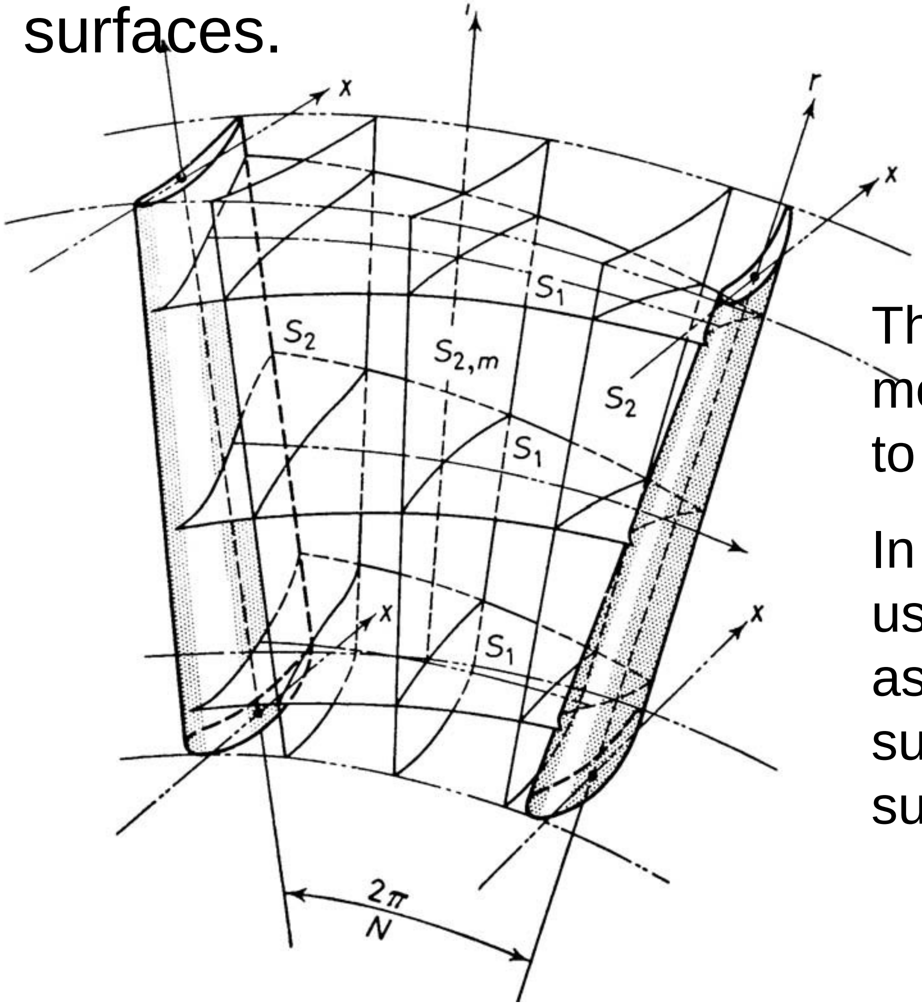
$$dP/dr = \rho V_\theta^2/r.$$ -> Twisted blading.



Using standard blade sections, C4, DCA, T6, etc.

The Avon and Olympus engines were almost certainly designed in this way

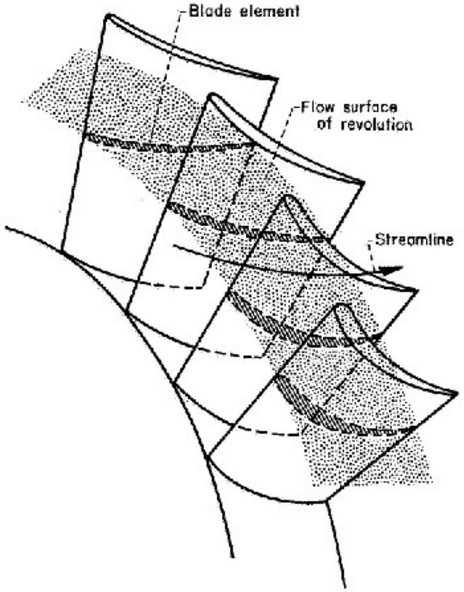
Early 1950’s - Wu published his theory for predicting 3D flow by iterating between solutions on S2 (hub to tip) and S1 (blade to blade) stream surfaces.

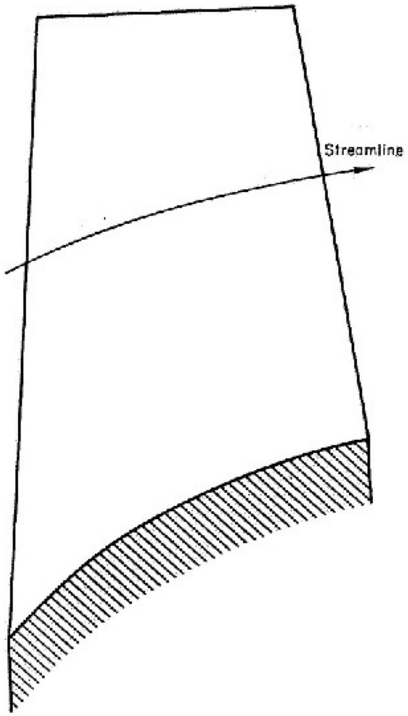


This was far ahead of its time as no methods (or computers) were available to solve the resulting equations.

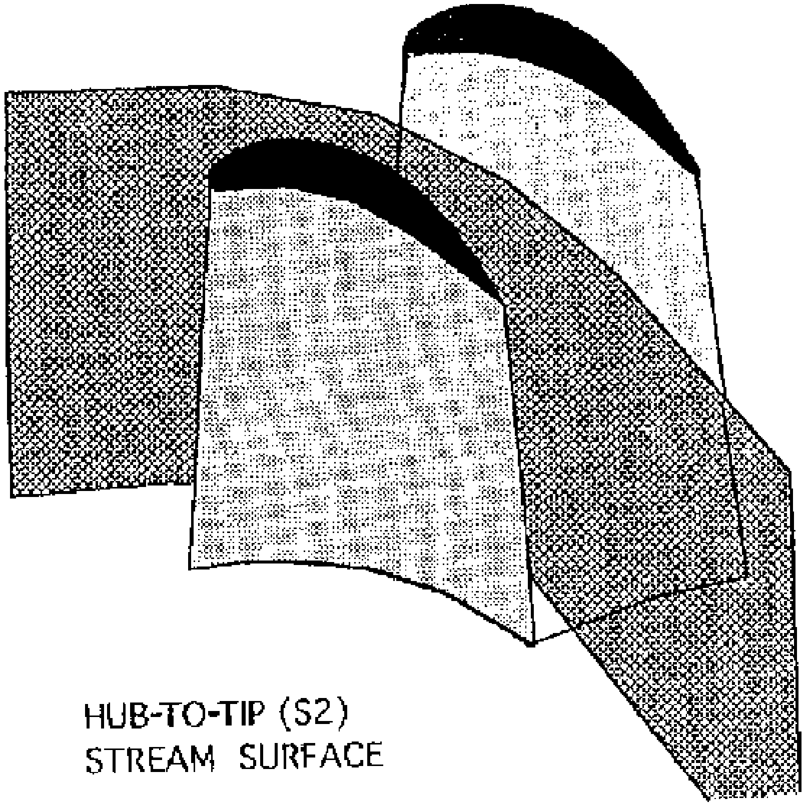
In fact the method has seldom been used in its full complexity. We usually assume a single axisymmetric S2 surface and several untwisted S1 surfaces.

S1 – blade-to-blade





S2 – meridional



The S2 (hub to tip or throughflow) solution has become the “backbone” of turbomachinery design.

Initially there was rivalry between the matrix-stream function method and the streamline curvature method of solving the equations.

Stream Function method

$$\rho r\,Vx = \frac{d\psi}{dr}$$

$$\rho r\,Vr = -\frac{d\psi}{dx}$$

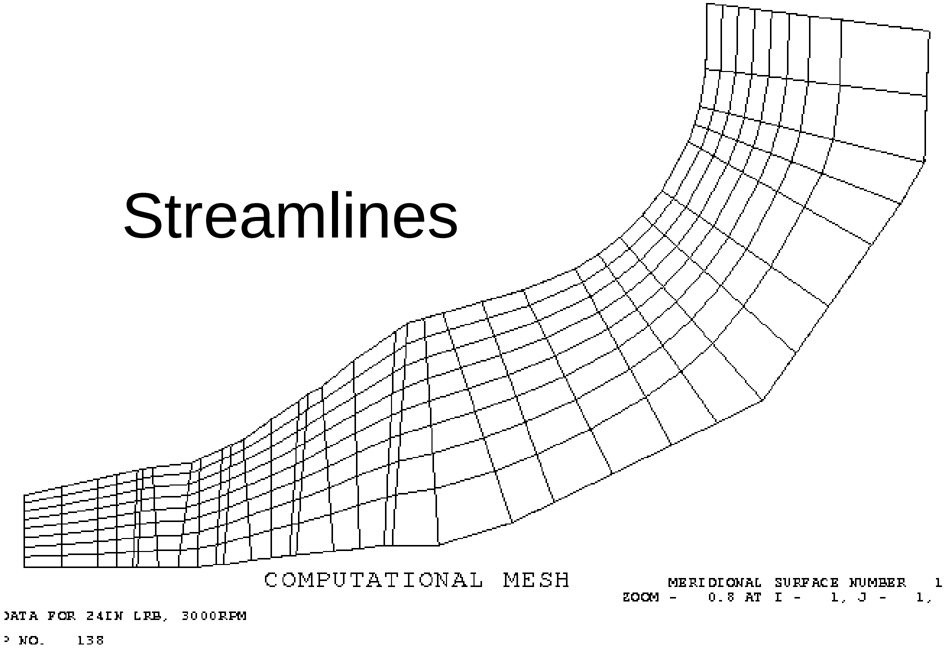
$$\longrightarrow \nabla^2\psi = Fcn\left(\frac{dh}{dr}, T\frac{ds}{dr}, \frac{d(rV_\theta)}{dr}, \frac{d\psi}{dr}, \frac{d\psi}{dx}, etc\right)$$

Streamline curvature method

$$Vm\frac{dVm}{dr} = Fcn\left(\frac{dh}{dr}, T\frac{ds}{dr}, \frac{drV_\theta}{dr}, \frac{V_m^2}{r_c}, \frac{dV_m}{dm}, etc\right)$$

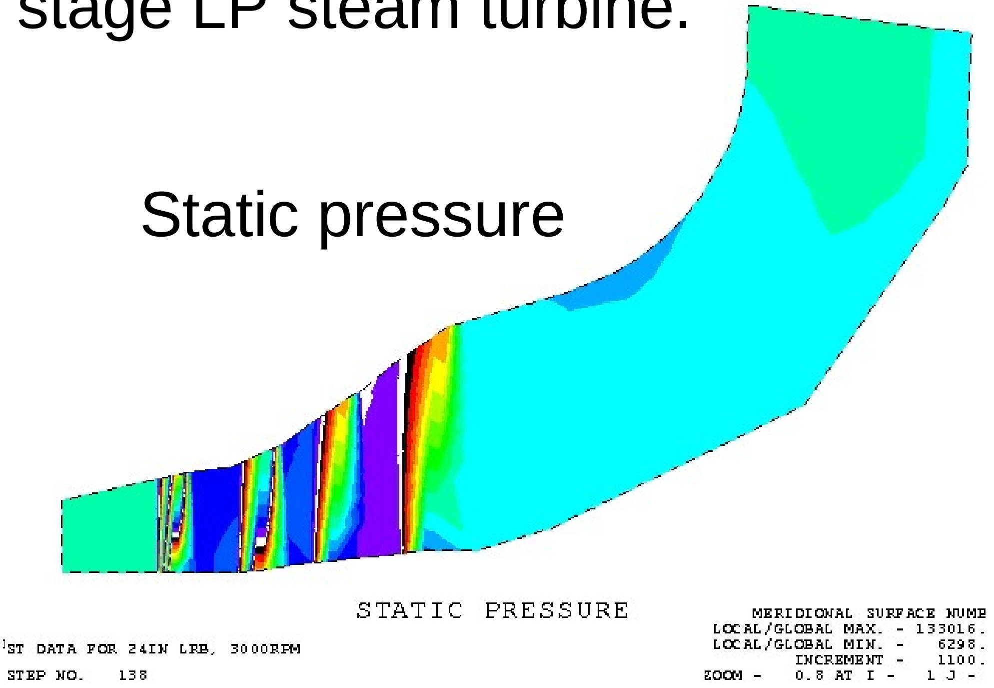
The streamline curvature method has become dominant mainly through its relative simplicity and its superior ability to deal with supersonic flows.

Extensions to deal with multiple choked turbines, as in LP steam turbines, were developed in the 1970's. These brought about significant improvements in LP steam turbine performance.



Streamlines

4 stage LP steam turbine.



Static pressure

Loss and deviation correlations remain an essential part of any throughflow method.

In fact the method may be thought of as a means of applying the correlations to a non-uniform flow. The accuracy of the results is determined more by the accuracy of the correlations than by that of the numerical method.

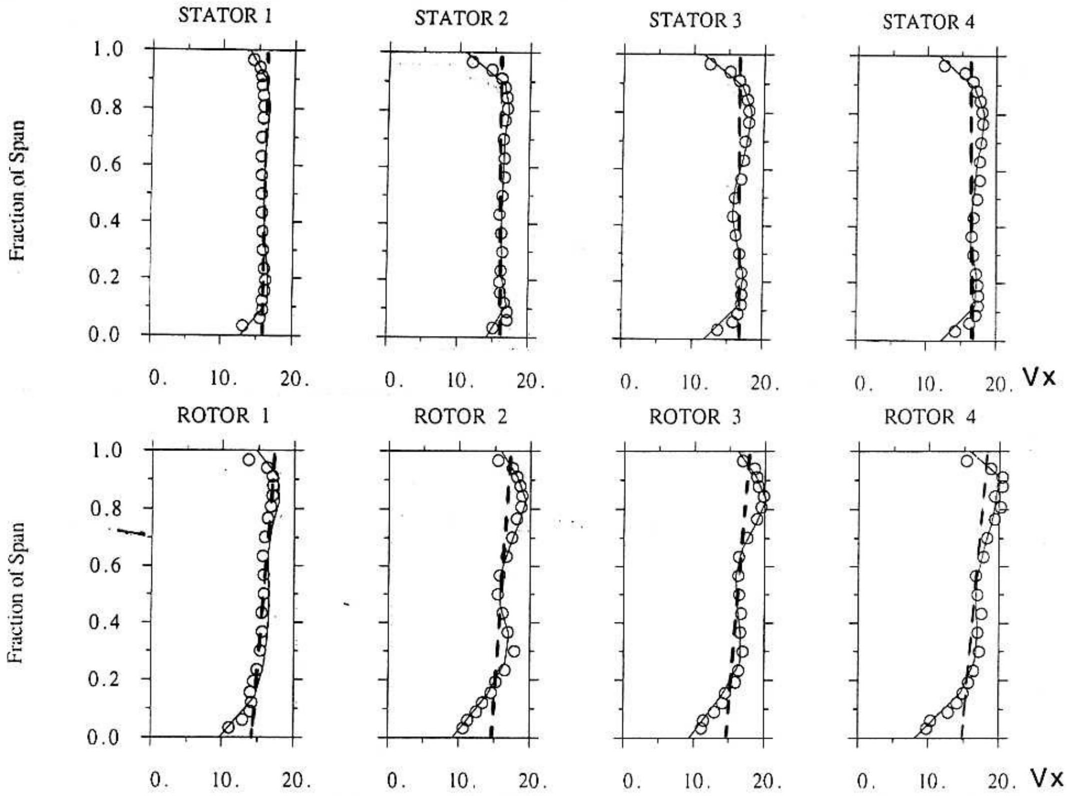


Fig 8. Measured and calculated axial velocity profiles through a 4 stage axial turbine.

oooooooooooo Measured
———————— Calculated using measured flow angles
- - - - - - - - - - - - Calculated using design flow angles.

Throughflow calculation for a 3 stage turbine using:

a) design

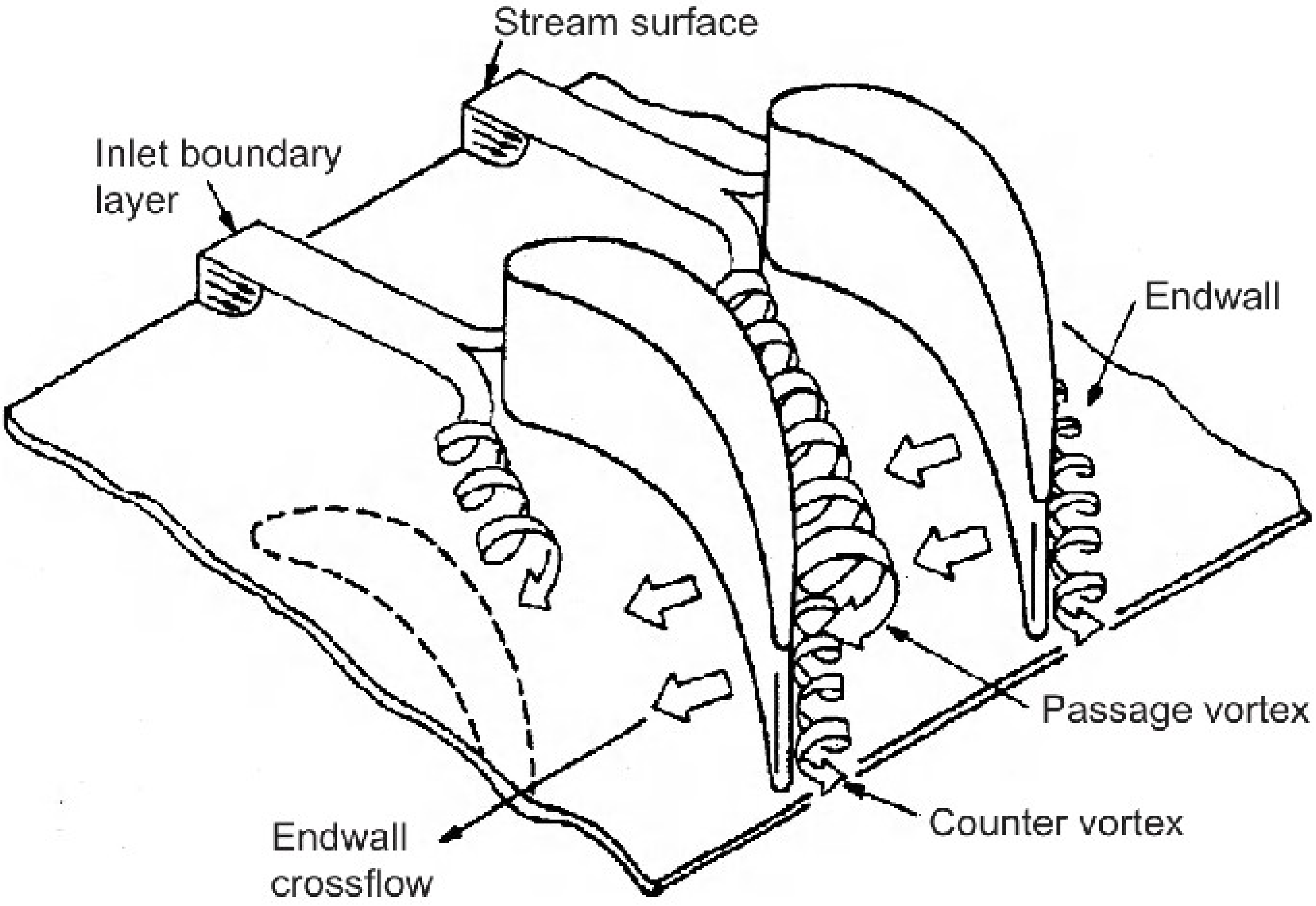
b) measured

blade exit flow angles.

- Stream function and streamline curvature methods were fast but difficult to extend to transonic flow. They are no longer used.
- Velocity potential methods were fast and able to cope with small amounts of supersonic flow but shock waves were not well captured. They are still used.
- Time marching solutions were much slower but are able to cope with high Mach numbers and to capture shock waves. They are now the dominant method.

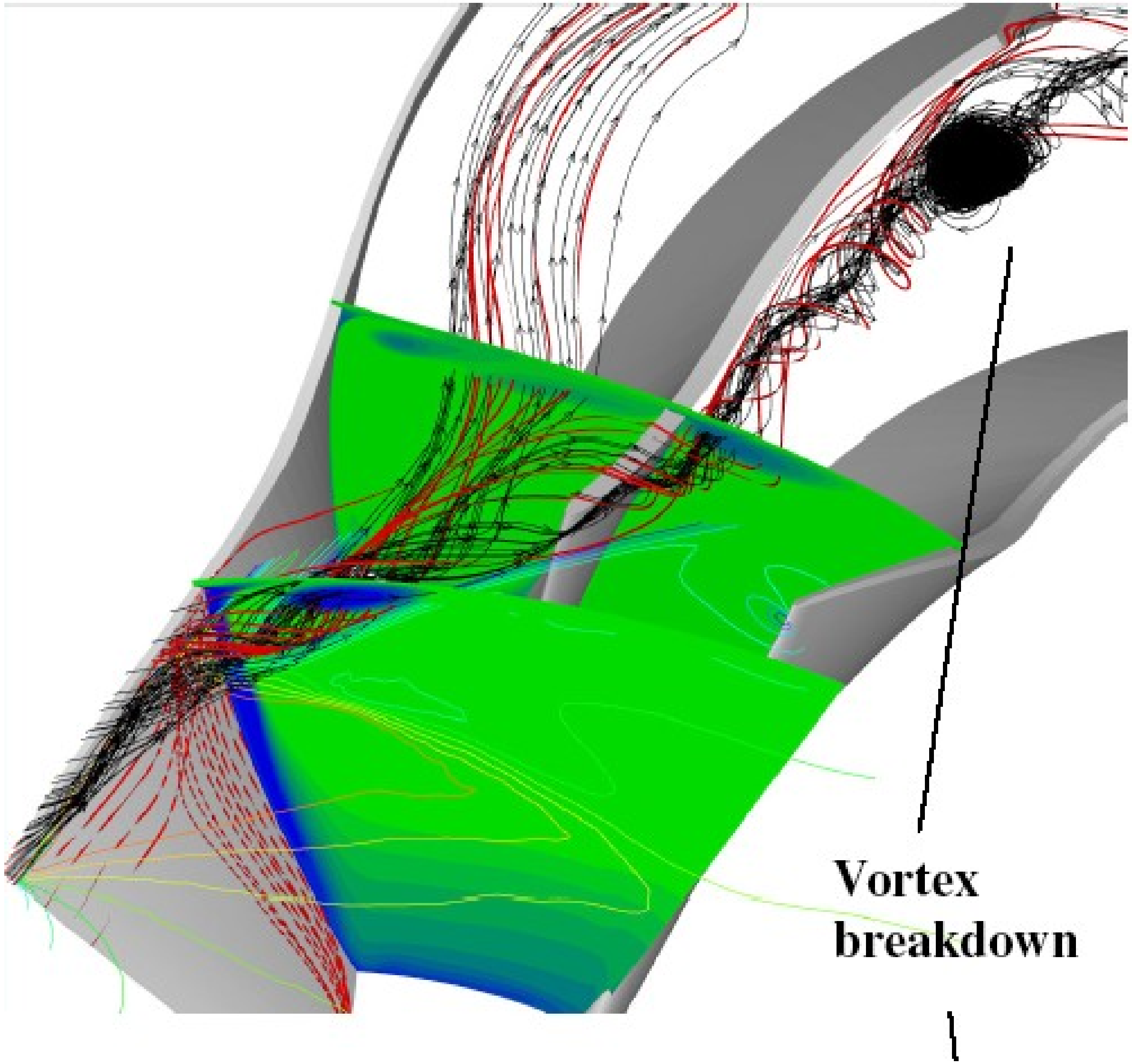
This type of method was used to develop “controlled diffusion” blading for axial compressors, giving significant improvements in performance.

Secondary flows / 3D effects



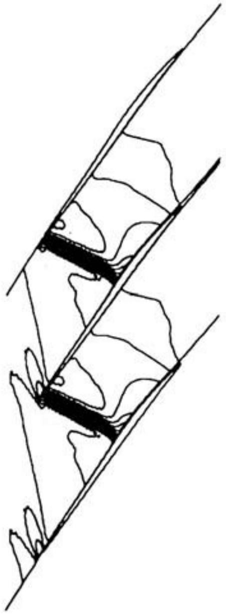
CFD is now an essential part of all turbomachinery design, including radial and mixed flow machines.

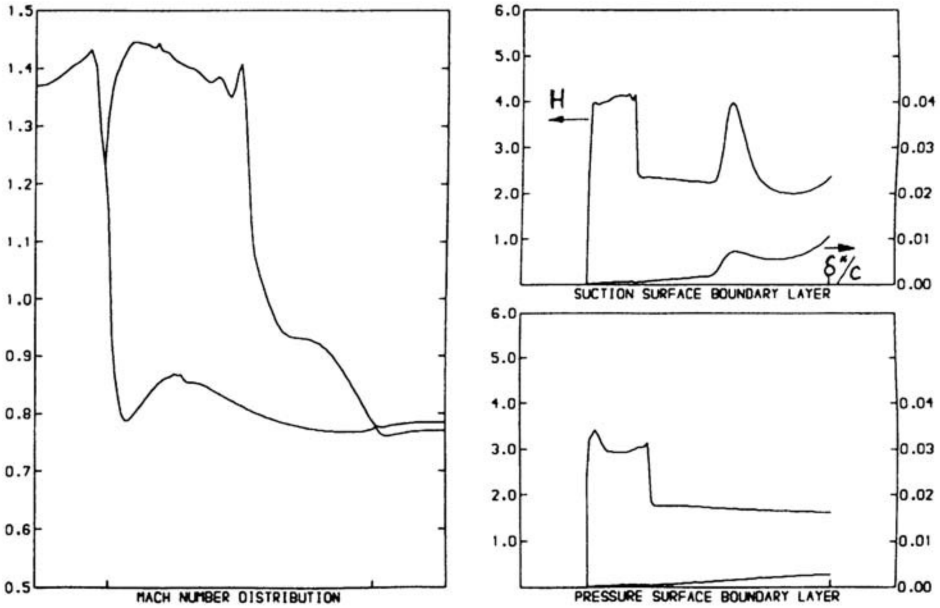
The flow in a centrifugal compressor is found to be dominated by tip leakage.



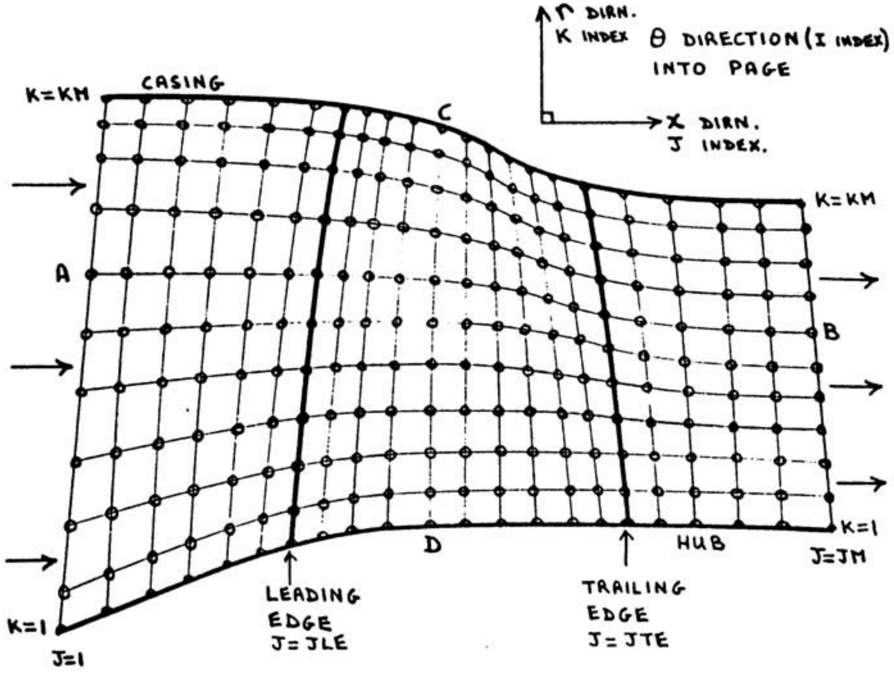
Although transonic compressors (fans) were initially developed without any flow calculation methods, the time marching methods allowed their design to be put on a much more sound footing.

A widely used method, including boundary layers, was developed by Calvert & Ginder at Pyestock.





The time marching method had the advantage of being readily extended to fully 3D flow. This was done in the mid 1970’s .



A typical coarse grid for early 3D calculations.

Initially the available computers only allowed coarse grid solutions, typically 4000 (10x40x10) grid points. Although this seriously limited their accuracy the 3D methods soon lead to improved physical understanding of 3D effects such as blade sweep and blade lean.

In particular it was discovered that blade lean could have an extremely powerful effect on the flow. This had been neglected by previous methods.

When low aspect ratio blades are leaned the constant static pressure lines remain almost “frozen” .

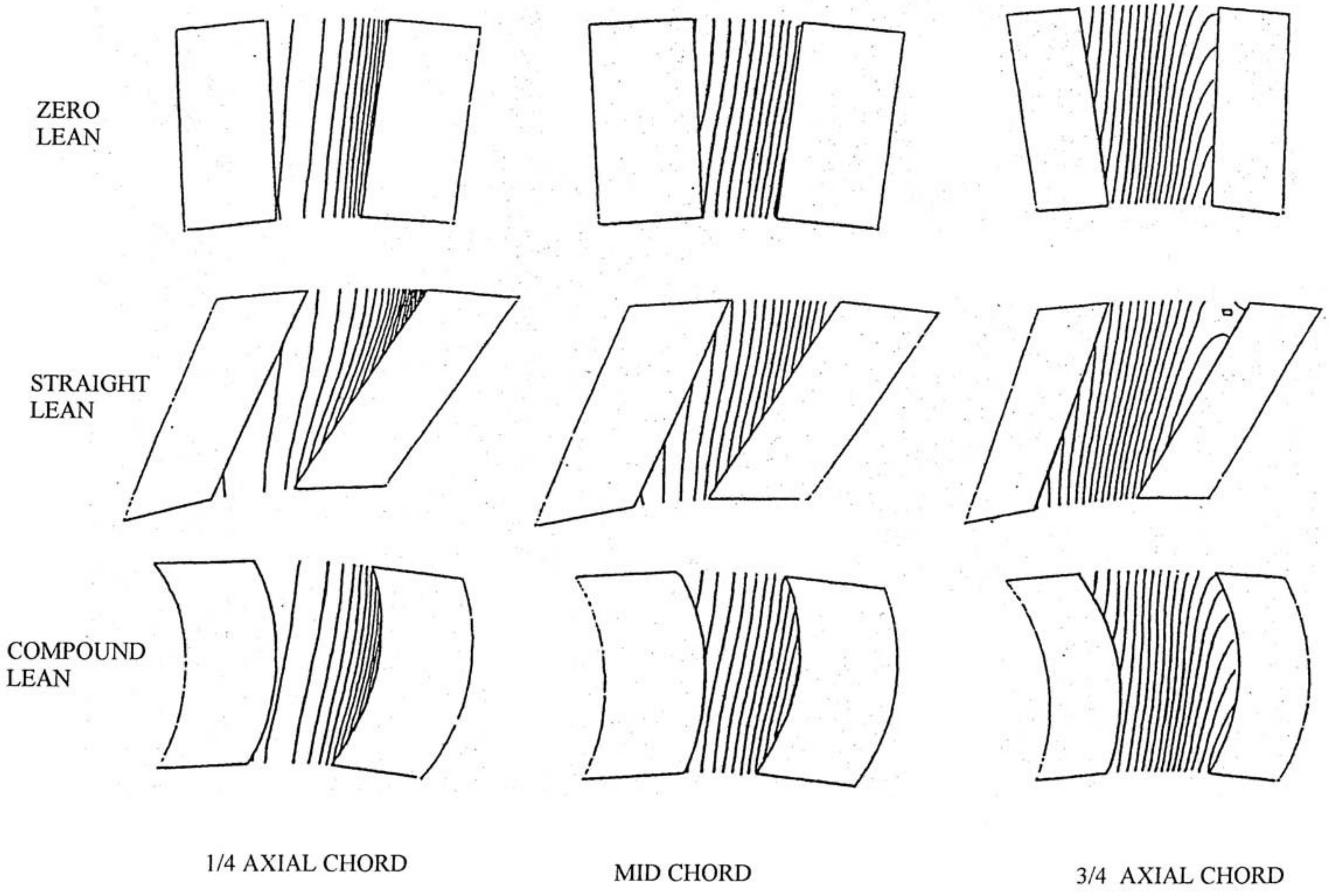
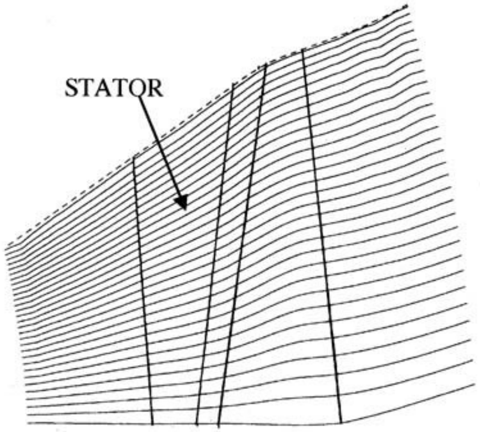


FIG 14. STATIC PRESSURE CONTOURS THROUGH A TURBINE STATOR WITH DIFFERENT STACKINGS. SUCTION SURFACE TO RIGHT OF PASSAGE.

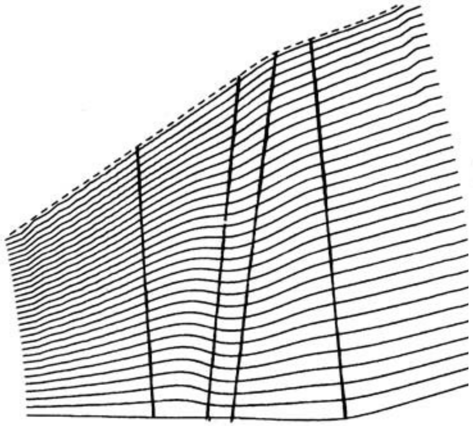
For high aspect ratio blades, leaning the stator, with the pressure surface inclined inwards, can be very beneficial in increasing the root reaction. This has been exploited in LP steam turbines where older designs often suffered from negative root reaction.

THE PRESSURE CAN BE INCREASED BY LEANING THE LAST STATOR BLADES AWAY FROM THE RADIAL DIRECTION SO THAT THEY EXERT A RADIALLY *INWARDS* FORCE ON THE STEAM PASSING THROUGH THEM.

THIS CAUSES THE STREAMLINES TO MOVE *OUTWARDS*.

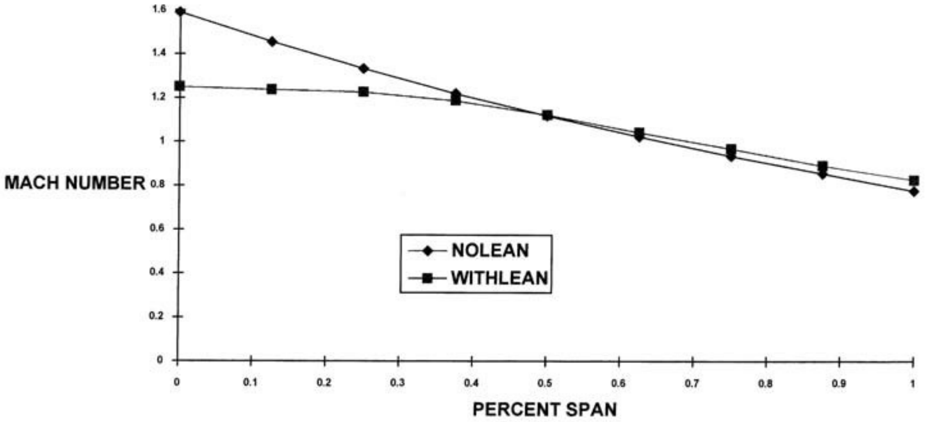


STREAMLINES WITH NO LEAN

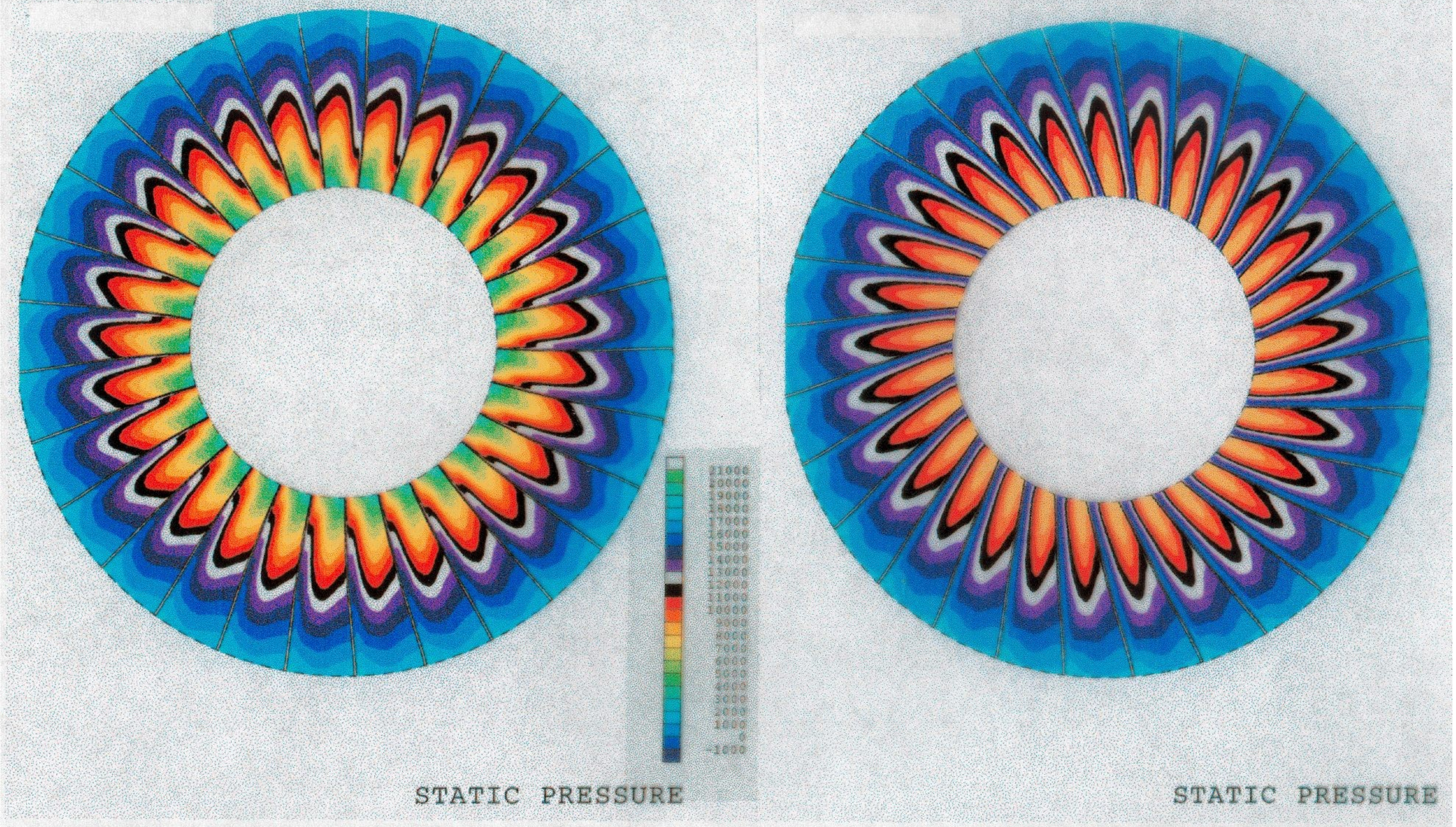


STREAMLINES WITH LEAN

FIG 13. MACH NUMBER DISTRIBUTION AFTER THE LAST STATOR ROW OF A LARGE STEAM TURBINE



STATIC PRESSURES AT THE STATOR TRAILING EDGE

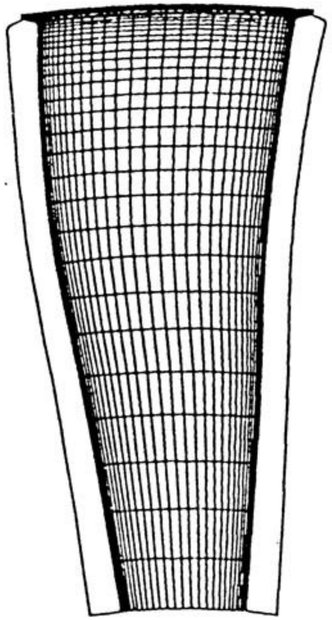


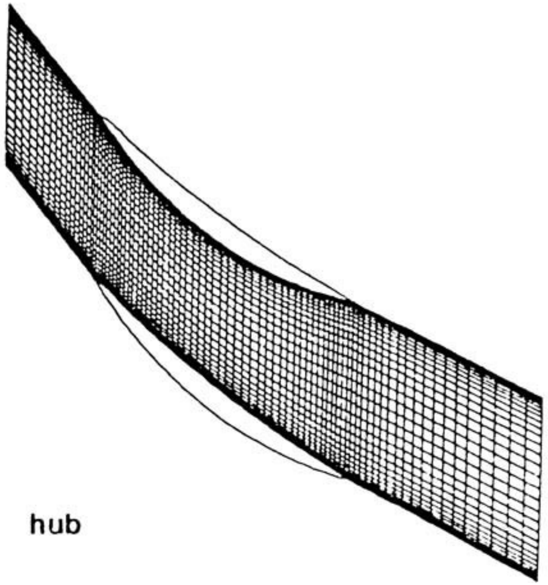
WITH NO LEAN ON STATORS

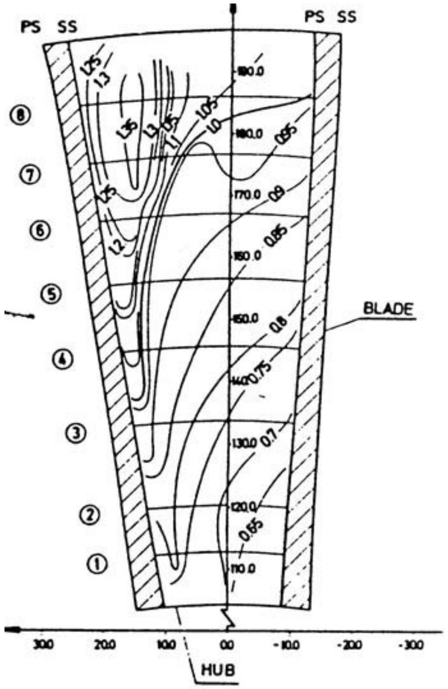
WITH LEAN ON STATORS

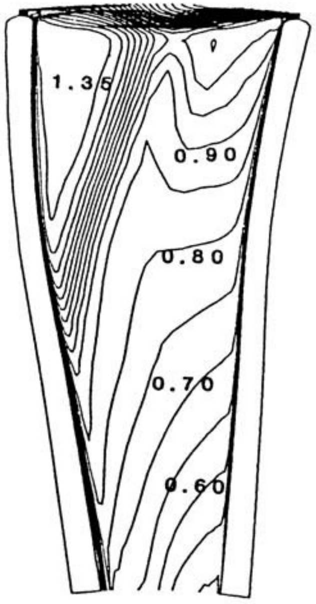
The move from Euler to Navier-Stokes solutions mainly depended on advances in computer power. This became available in the mid 1980’s. A widely used method was developed by Dawes.

Initially relatively coarse grids (33x60x33) were used with mixing length turbulence models and wall functions. Despite this useful results were obtained, especially for transonic fans.

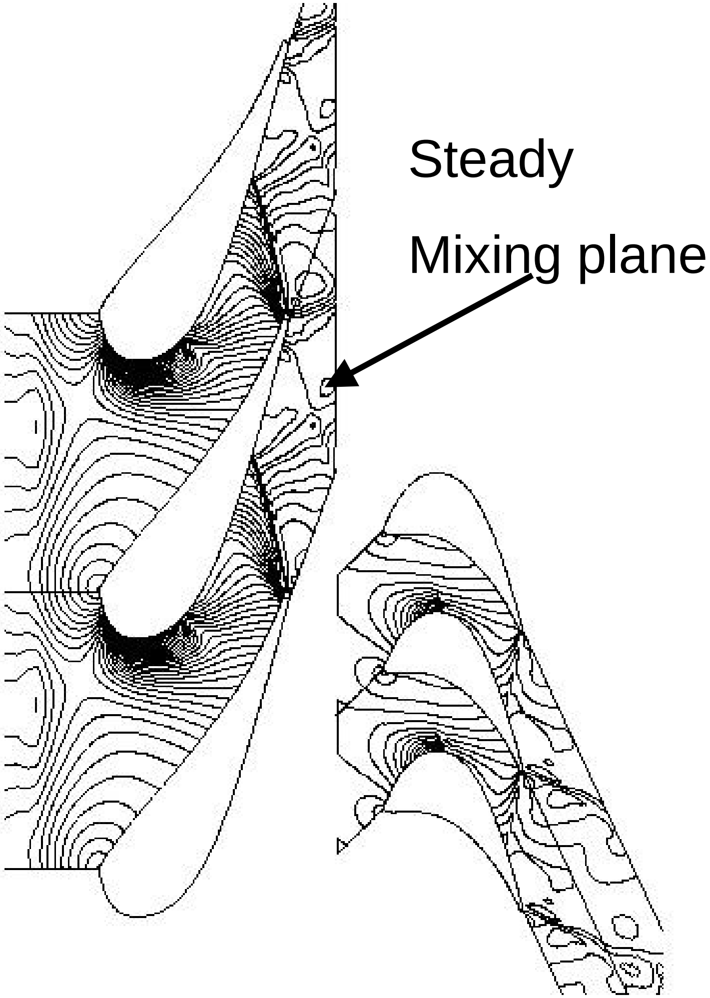


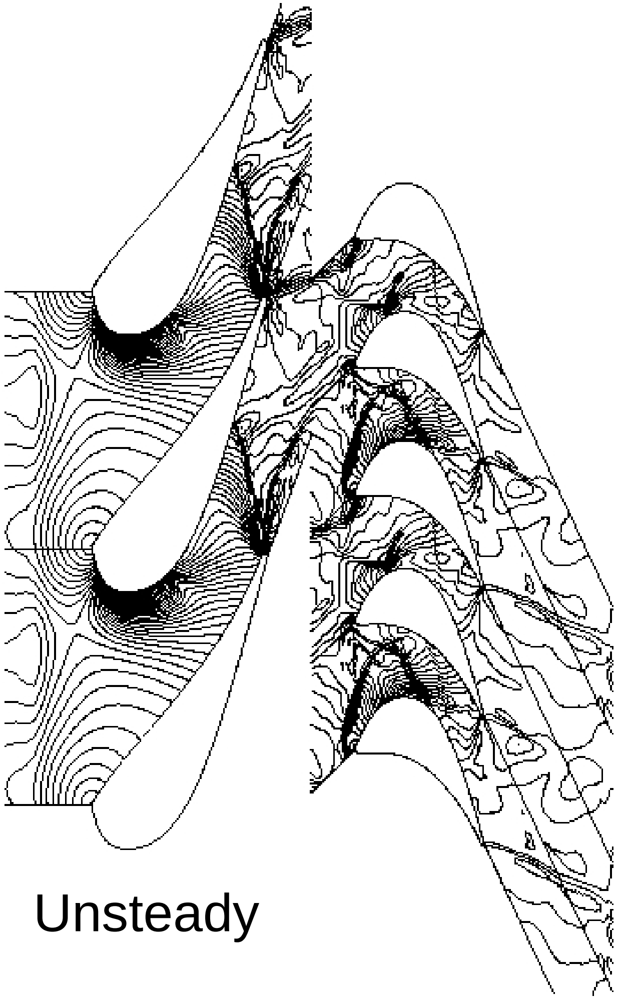






The next development, around 1990, was the ability to calculate multiple blade rows in a single steady calculation. This was achieved by the inclusion of mixing planes between blade rows so that each row “sees” a circumferentially uniform, hence steady, inlet boundary.

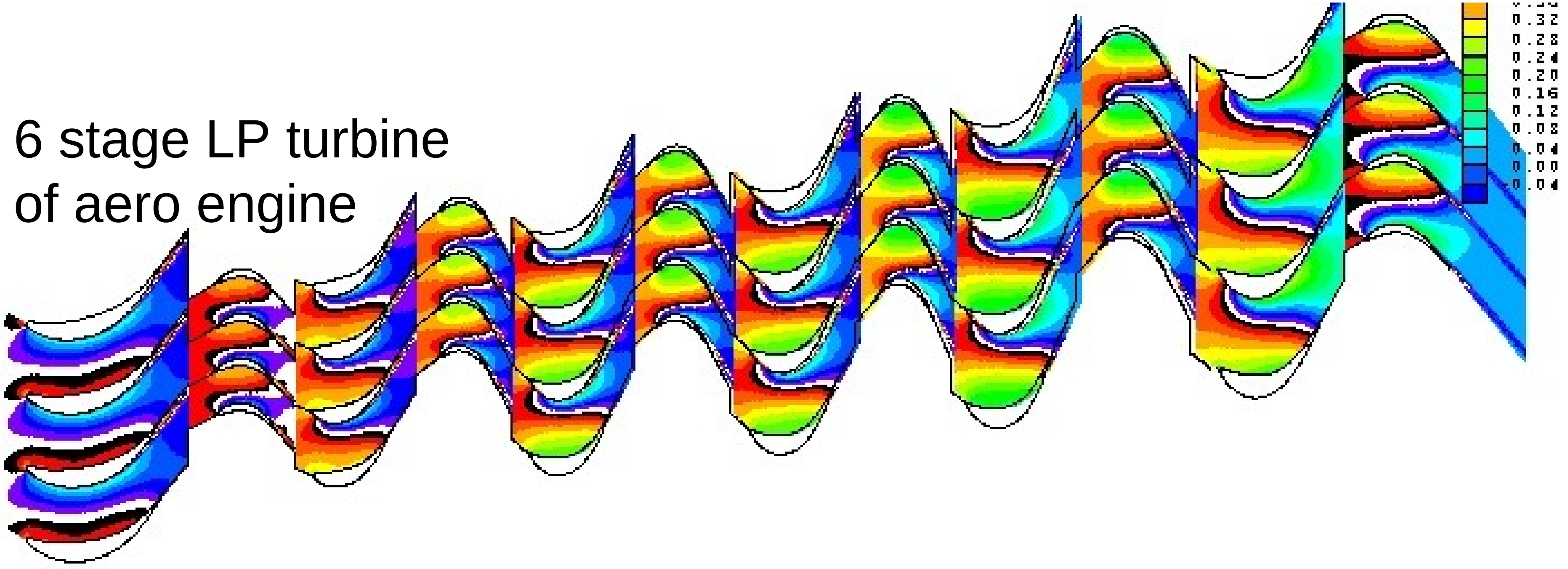




3D viscous calculations for multistage machines are now routine.

Formulation of a correct mixing plane model is one of the most difficult problems in CFD.

Adamcyzk has developed an alternative “average passage” model which claims to include some measure of the unsteady effects. This is slower and more complex but is widely used in the USA.



6 stage LP turbine
of aero engine

Blade Profiling

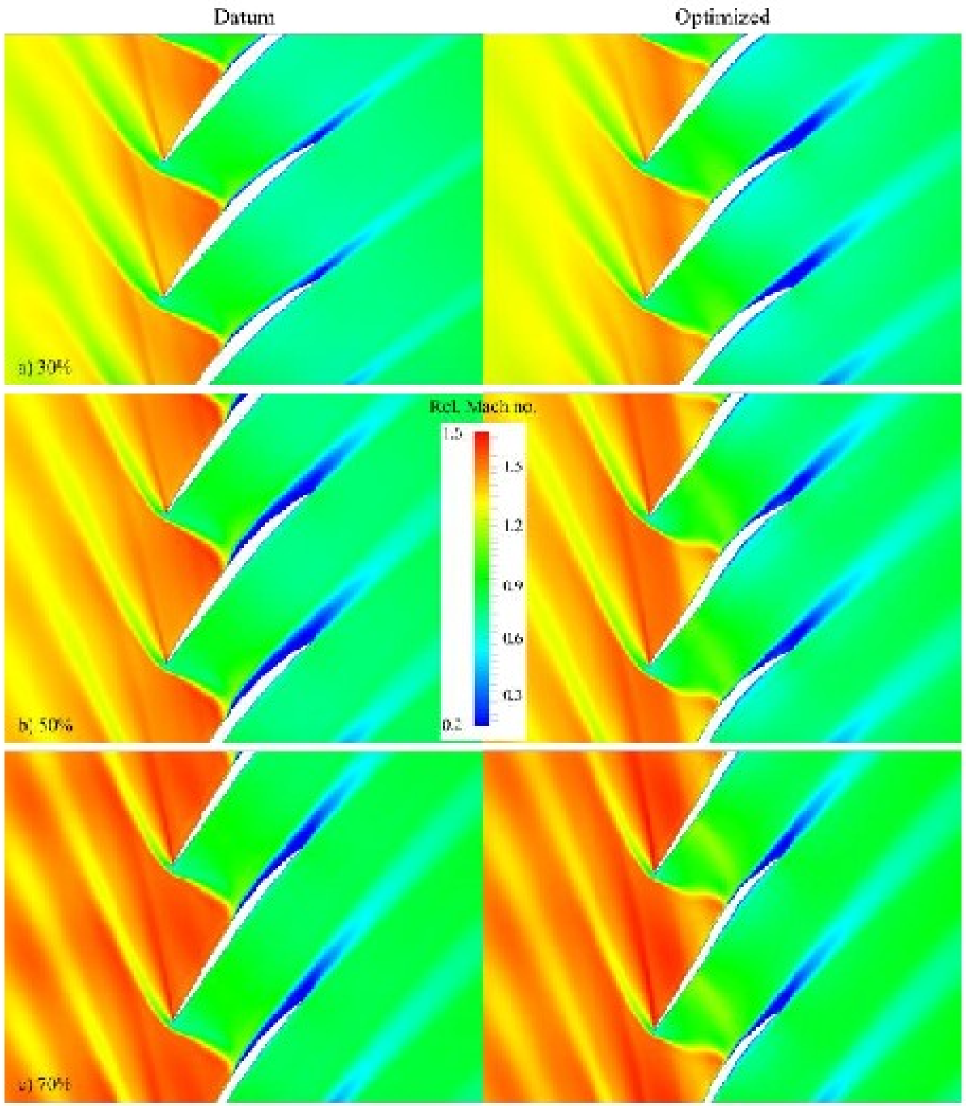
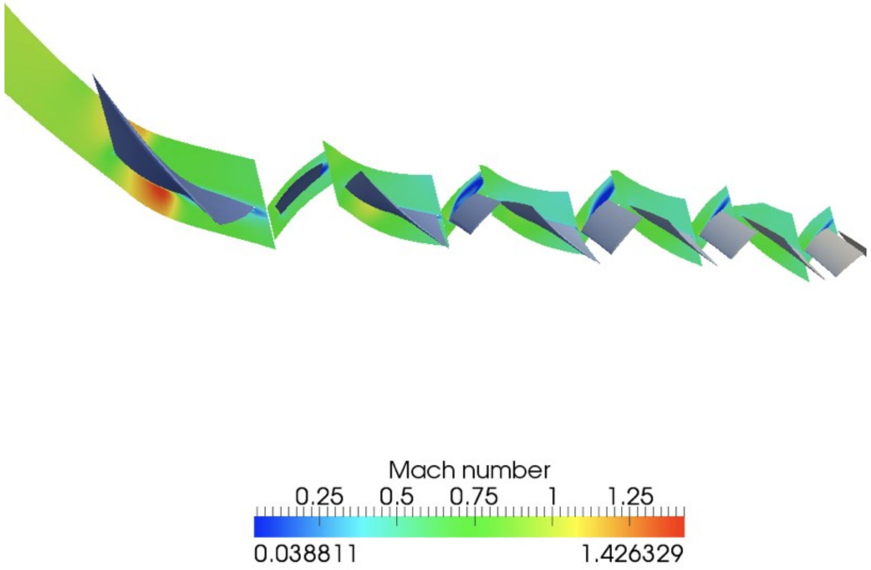
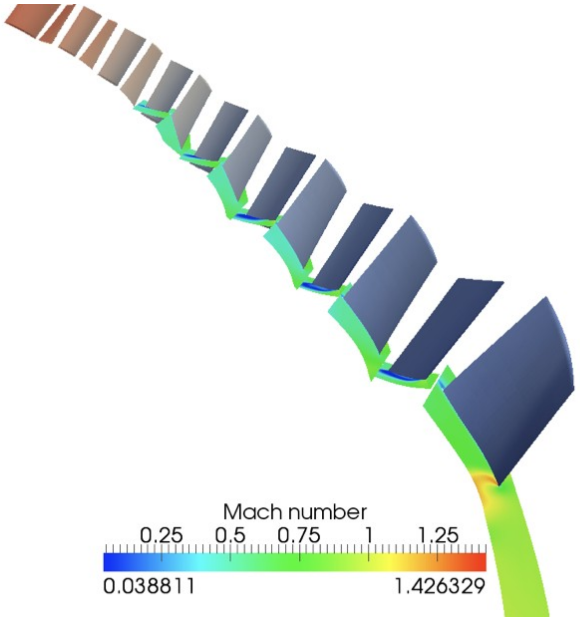


FIGURE 15. RELATIVE MACH NUMBER CONTOUR COMPARISON AT 30% (a), 50% (b) AND 70% (c) SPAN

3D viscous calculations for multistage machines are now routine.





Sweep and Lean

70s

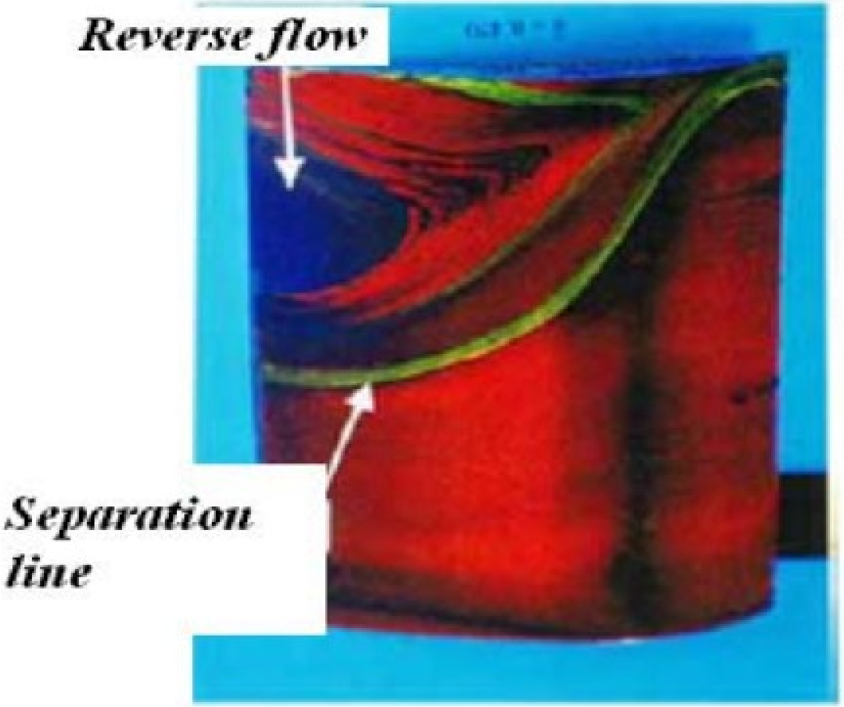
80s

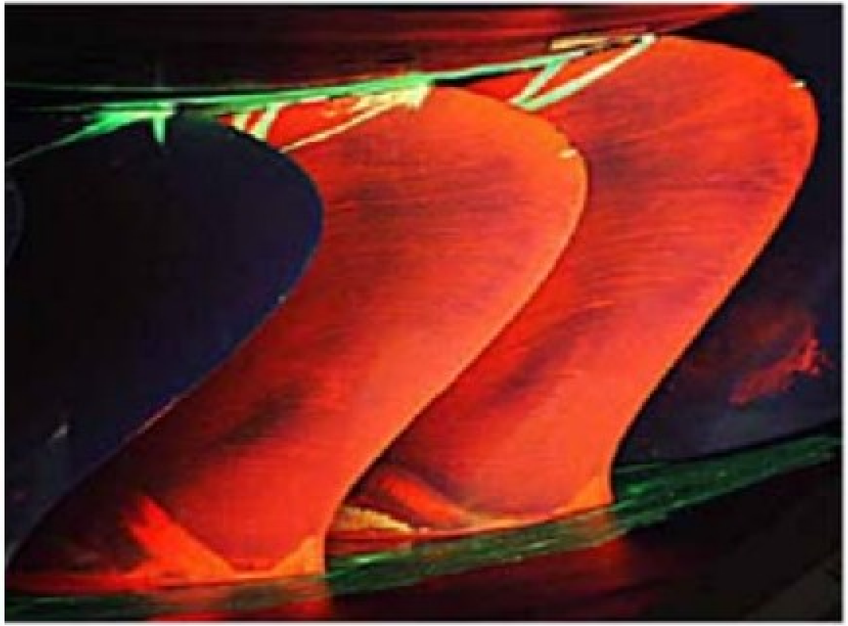
90s

2000 -

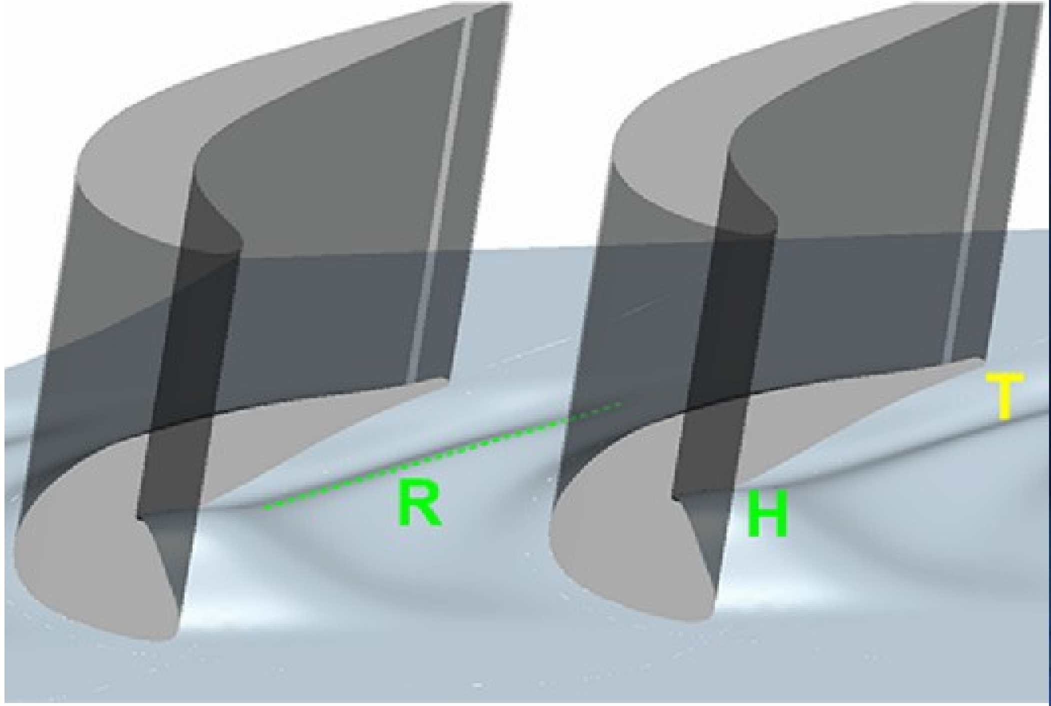
TRENT 1000 FAN

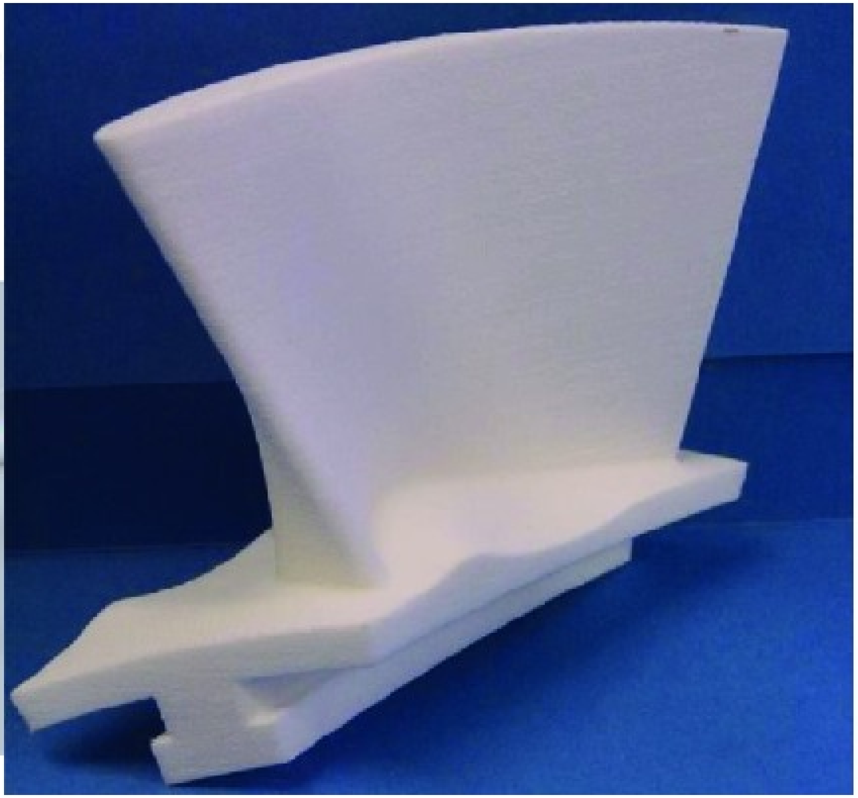
Sweep and Lean



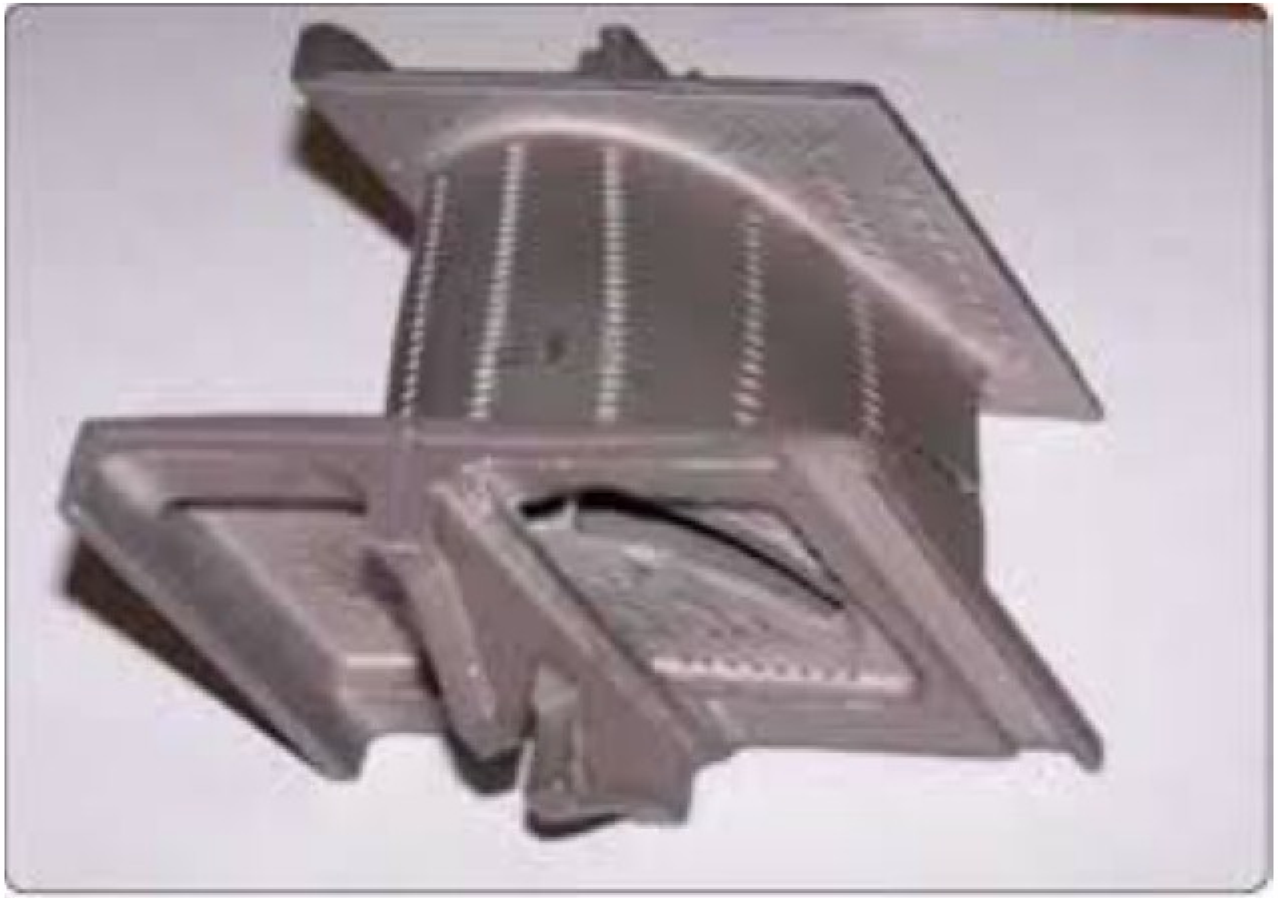


Endwall profiling

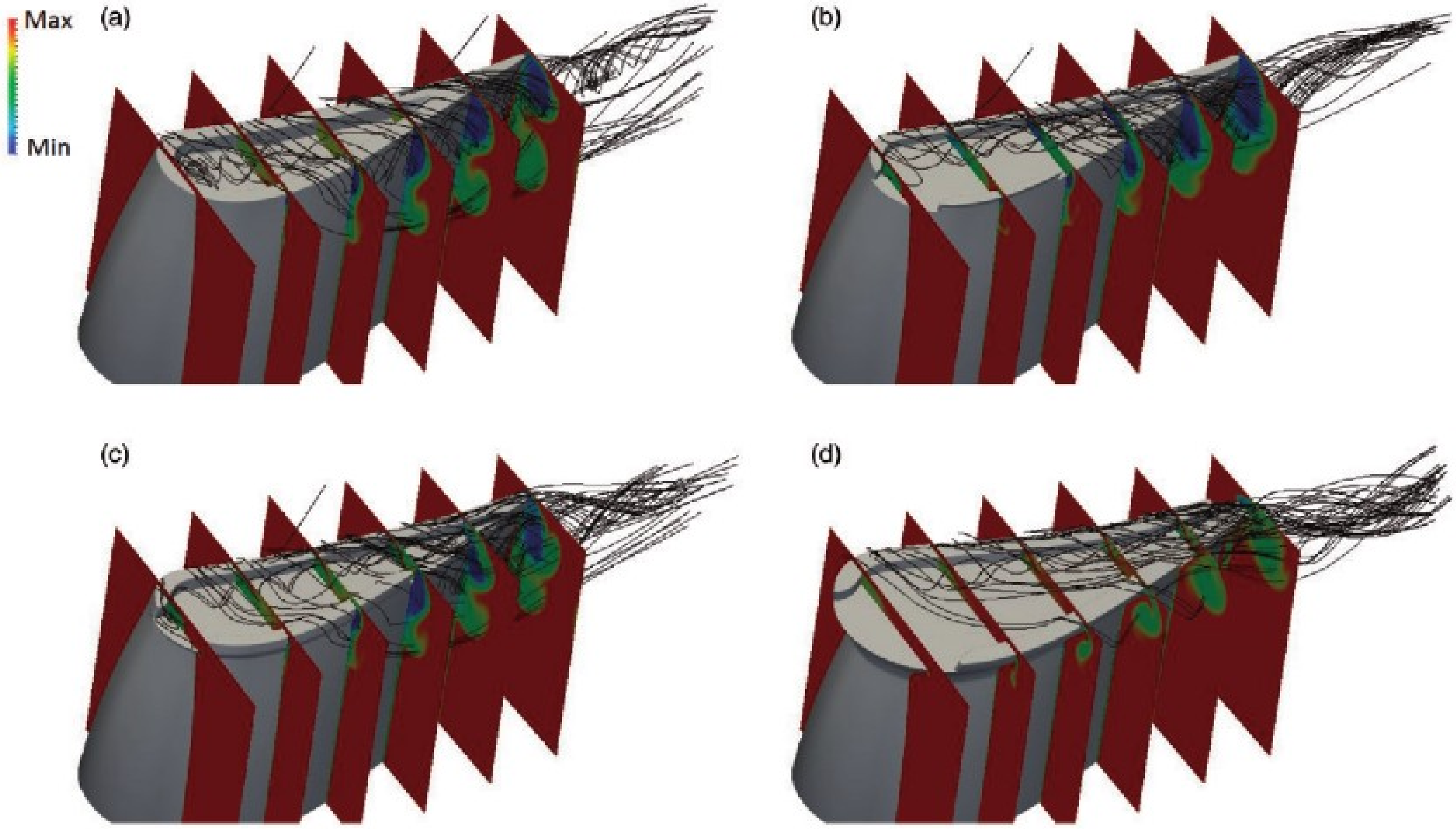




Tip treatments



Tip treatments



Design Process

Strumenti

Mean-line design

- leggi di conservazione
- correlazioni

Through-flow design

- equazioni semplificate
- correlazioni
- 2D CFD

3D-design

- 3D CFD

SOME LIMITATIONS OF CFD

It is very important to realise that CFD is not an exact science. As designers are more and more exposed to CFD results and less and less to experimental results it is very important that they understand what CFD results can be trusted and what can not.

This is particularly important when CFD is used in conjunction with optimisation software to produce an “optimum” design within certain constraints.

The optimiser will very likely exploit weaknesses in the CFD.

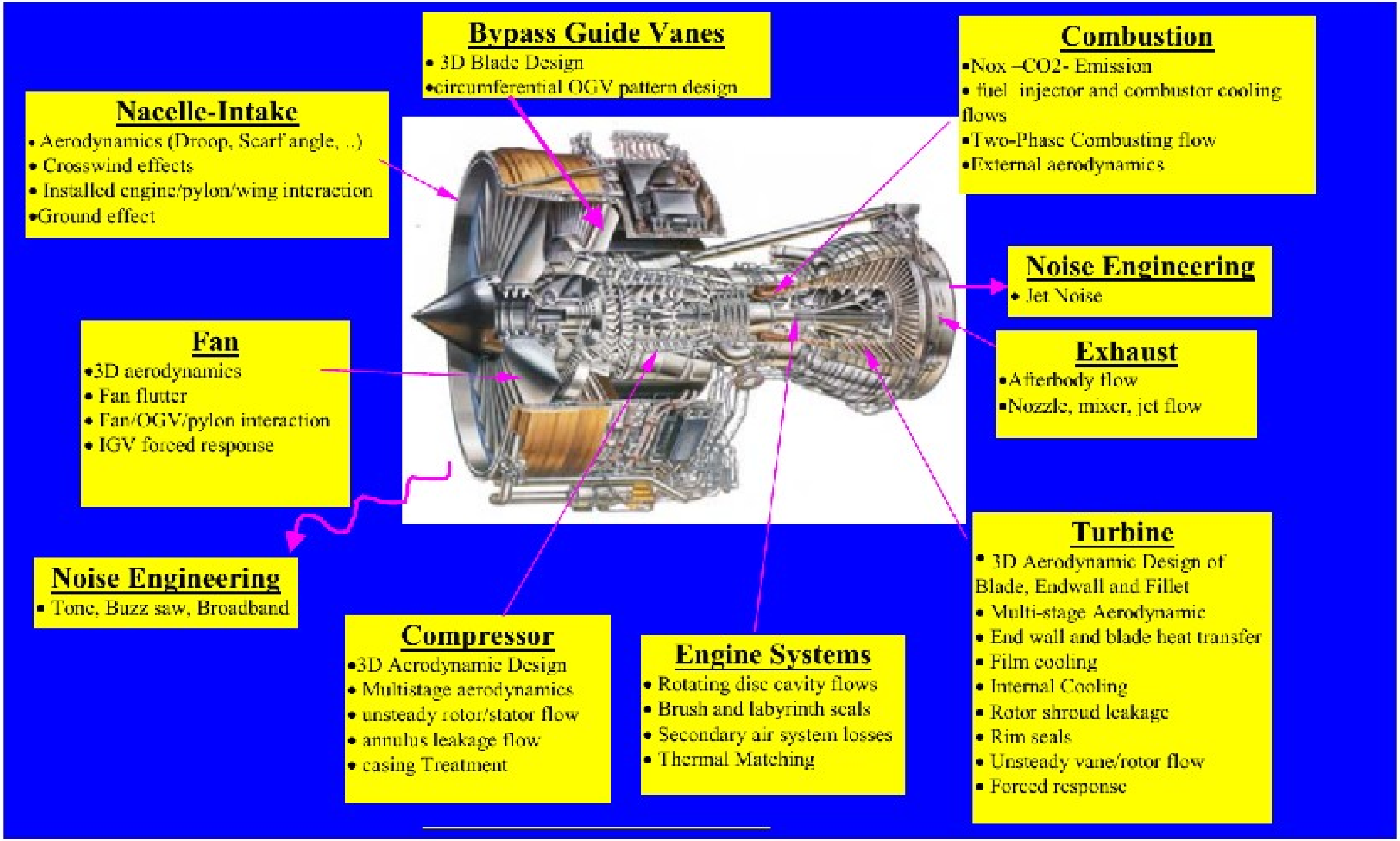
Challenges in CFD:

- Boundary layer transition
- Turbulence modelling
- Endwall loss
- Leakage loss
- Compressor leading edge flow
- Turbine trailing edge flow
- Effects of small geometrical features
- Unsteady losses

So, errors in CFD may be due to:

Modelling errors	Turbulence, transition, mixing planes
Unknown boundary conditions	Endwall boundary layers, Free stream turbulence, inlet profiles, cooling and leakage flows
Unknown geometry	Tip gaps, leading edge shape, sharpness of corners, blade deflection and deformation.

Introduzione - Impieghi della CFD



Bypass Guide Vanes
- 3D Blade Design
- circumferential OGV pattern design

Combustion
- Nox –CO2- Emission
- fuel injector and combustor cooling flows
- Two-Phase Combusting flow
- External aerodynamics

Nacelle-Intake
- Aerodynamics (Droop, Scarf angle, ..)
- Crosswind effects
- Installed engine/pylon/wing interaction
- Ground effect

Noise Engineering
- Jet Noise

Fan
- 3D aerodynamics
- Fan flutter
- Fan/OGV/pylon interaction
- IGV forced response

Exhaust
- Afterbody flow
- Nozzle, mixer, jet flow

Noise Engineering
- Tone, Buzz saw, Broadband

Turbine
- 3D Aerodynamic Design of Blade, Endwall and Fillet
- Multi-stage Aerodynamic
- End wall and blade heat transfer
- Film cooling
- Internal Cooling
- Rotor shroud leakage
- Rim seals
- Unsteady vane/rotor flow
- Forced response

Compressor
- 3D Aerodynamic Design
- Multistage aerodynamics
- unsteady rotor/stator flow
- annulus leakage flow
- casing Treatment

Engine Systems
- Rotating disc cavity flows
- Brush and labyrinth seals
- Secondary air system losses
- Thermal Matching