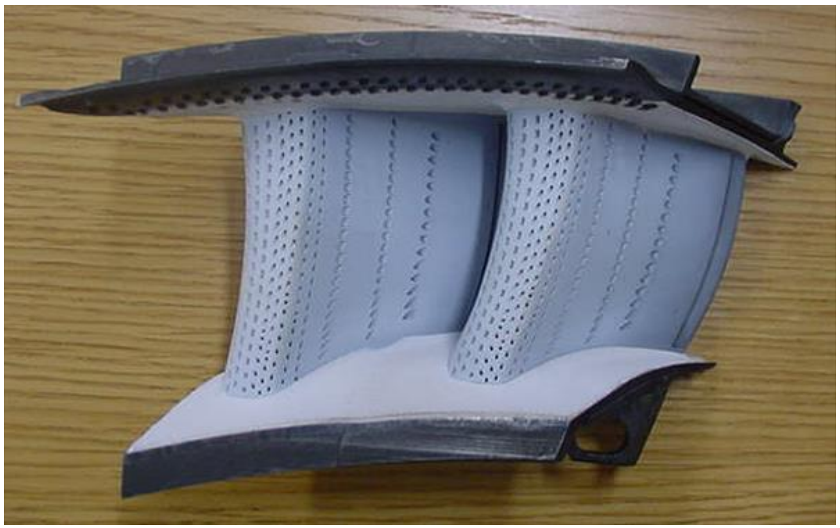
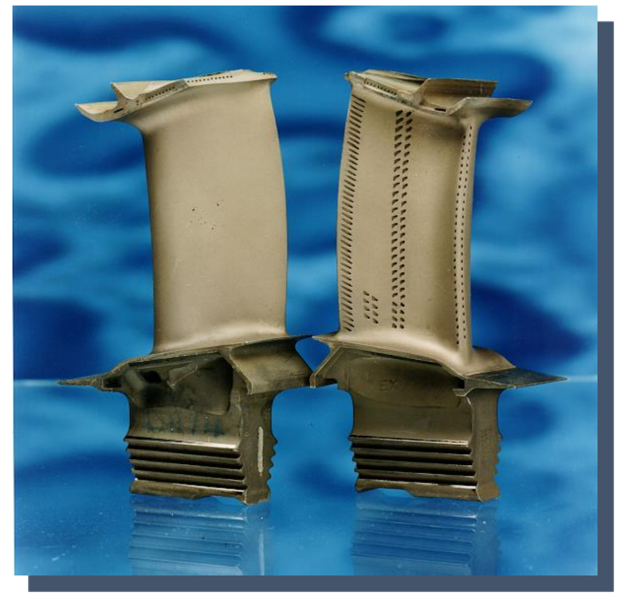
Lecture 13

TURBINES



Nozzle Guide Vanes

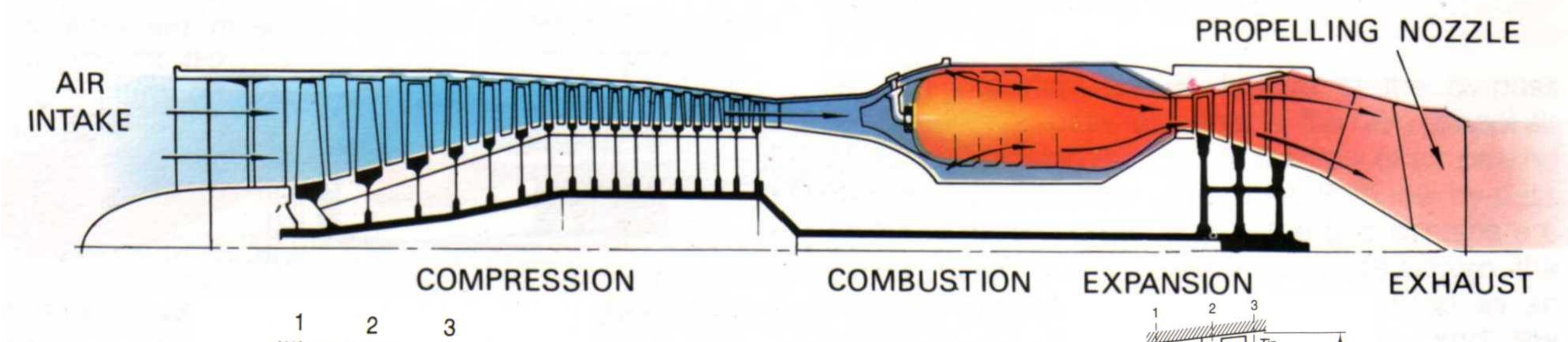


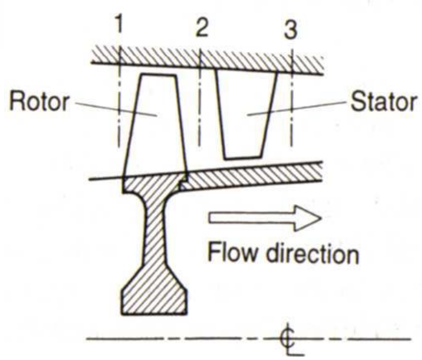
Turbine Blades

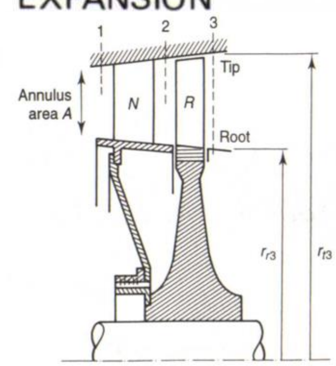
Objective: to describe the workings of the Turbine

Turbomachinery ~*Introduction*

- The **compressor** raises the pressure of the air before combustion
- The **turbine** extracts work from the hot high pressure combustion products to drive the compressor







Each stage consists of a row of rotor blades followed by a row of stator blades
Often preceded by an inlet guide vane

Each stage consists of a row of Nozzle Guide Vanes which direct the gas onto the rotor blade

TURBINES
Overall Principles

- Turbines provide the power to drive the Compressors, Accessories and Power Turbines

- Energy is extracted from the hot gases released from the Combustion Chamber and expanding them to lower Temperatures & Pressures

- Cycle calculations define an overall temperature drop & pressure drop at a given level of isentropic efficiency

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TURBINES
Overall Principles

- The rotational speed must be equal to that of the compressor, which is on the same shaft
- The Temperature used in cycle calculations is not the maximum temperature within the engine
- Cycle Temperatures:
  - Turbine Entry Temperature TET
  - Stator Outlet Temperature SOT

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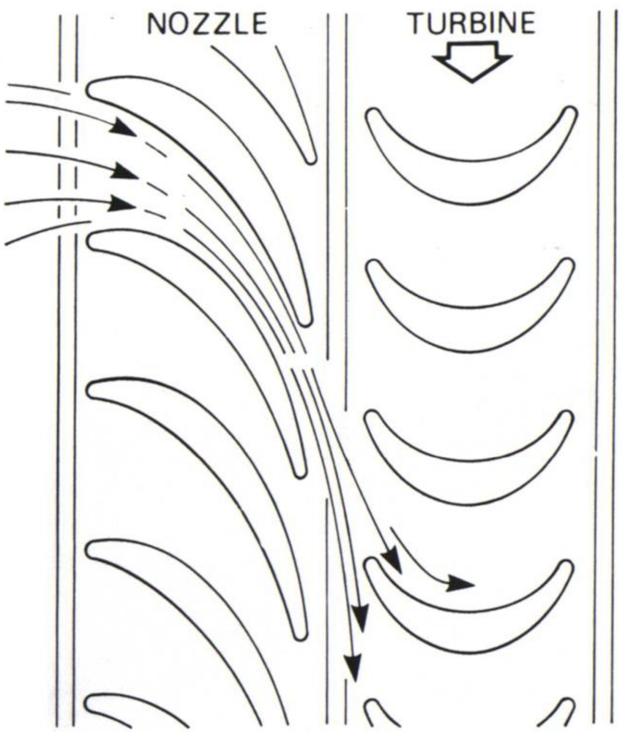
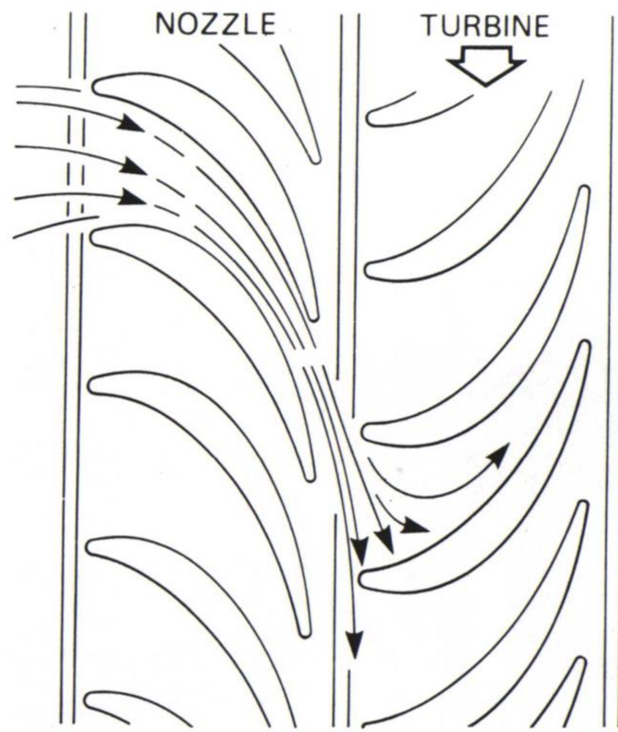
Comparison of a Pure Impulse & an Impulse/Reaction Turbine

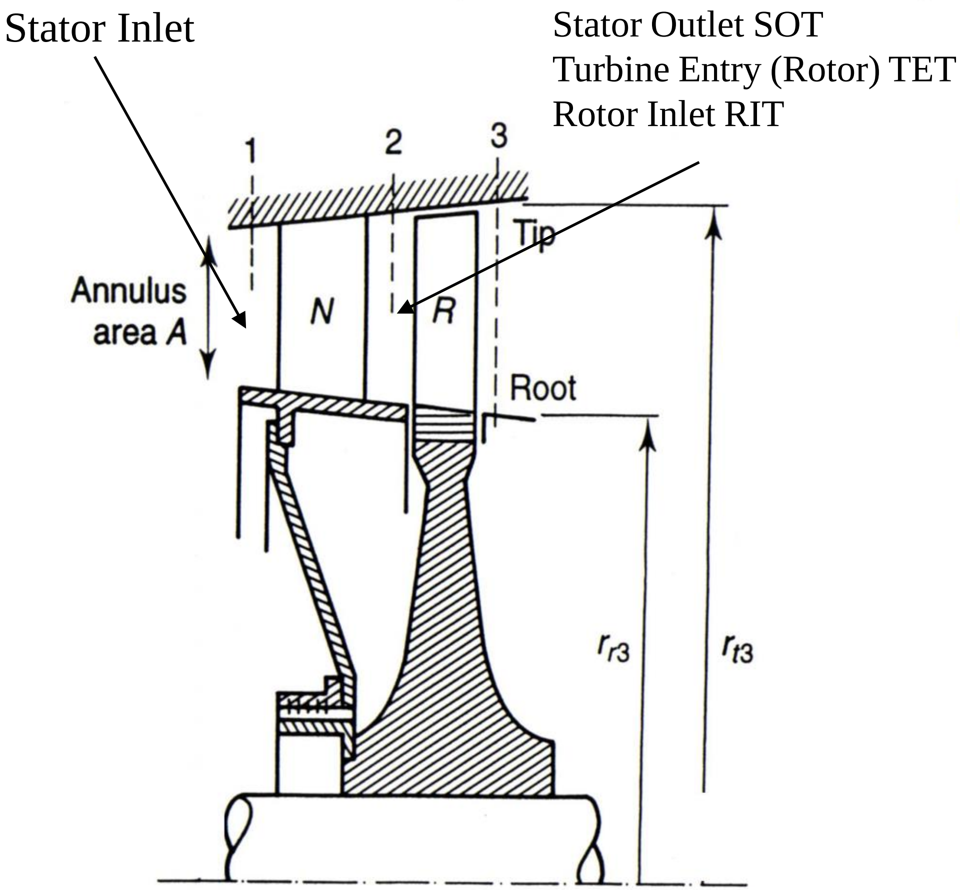


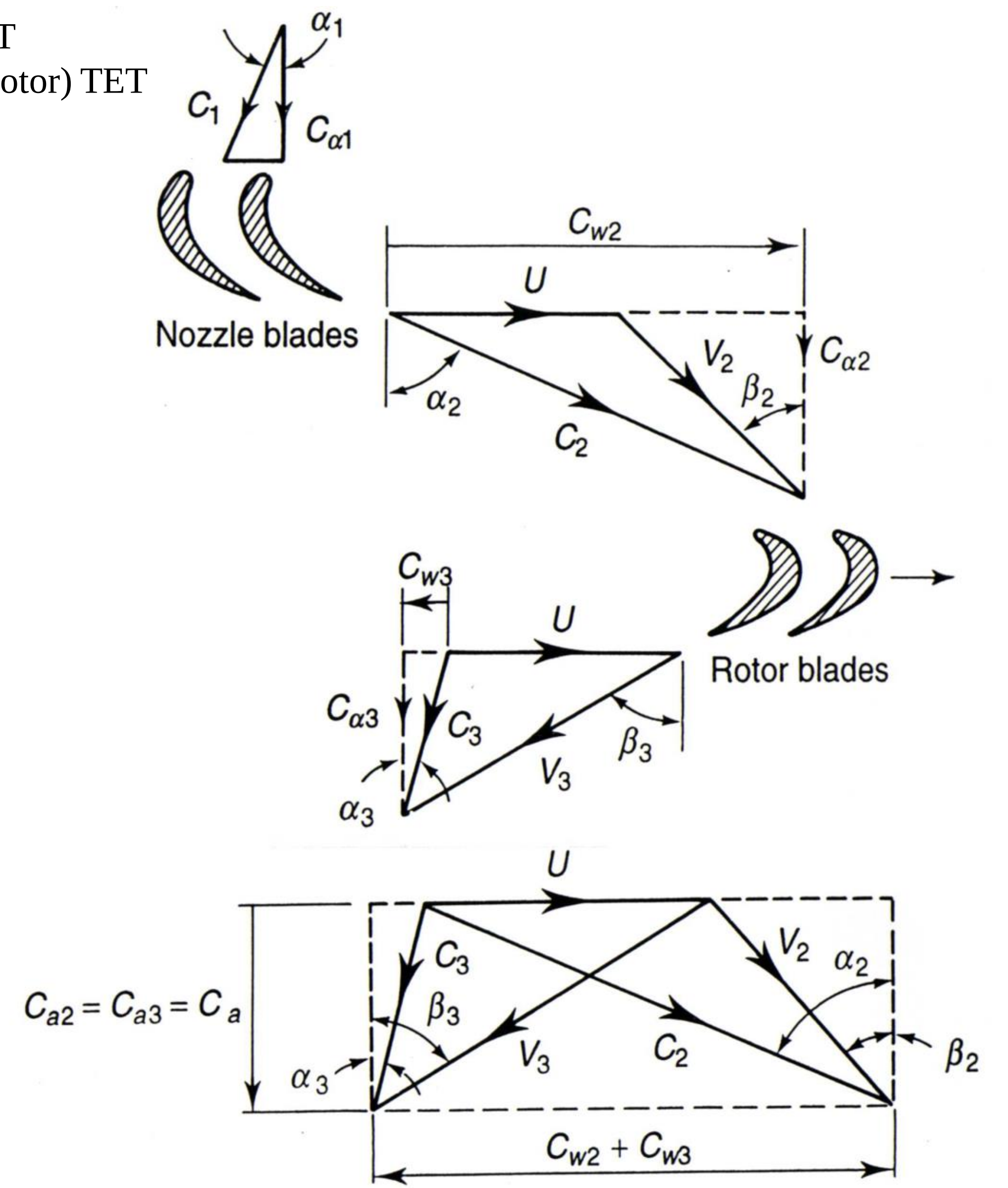
Turbine driven by the impulse of the gas flow only



Turbine driven by the impulse of the gas flow and its subsequent reaction as it accelerates through the converging blade passage

Axial Flow Turbine Stage





Deflection of flow in rotor = $\beta_2 + \beta_3$

Axial Flow Turbine Stage

In a single stage Turbine:

$$\alpha_1 = 0 \qquad C_1 = Ca_1$$

In a multi stage Turbine:

$$\alpha_1 = \alpha_3 \qquad C_1 = C_3$$

Assume constant axial velocity

$$C_{a1} = Ca_2 = Ca_3 = Ca$$

From velocity diagrams:

$$\frac{U}{C_a} = (\tan\alpha_2 - \tan\beta_2) = (\tan\beta_3 - \tan\alpha_3)$$

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Axial Flow Turbine Stage

Stage Work per unit mass flow $= U \cdot (Change\ in\ whirl\ velocity\ inlet\ to\ outlet)$

$$= U \cdot (Cw_2 + Cw_3) \qquad \textit{Note sign !}$$

$$= U \cdot C_a \cdot (\tan\alpha_2 + \tan\alpha_3)$$

$$\Delta h_{os} = C_p \cdot \Delta T_{os} = U \cdot C_a \cdot (\tan\beta_2 + \tan\beta_3)$$

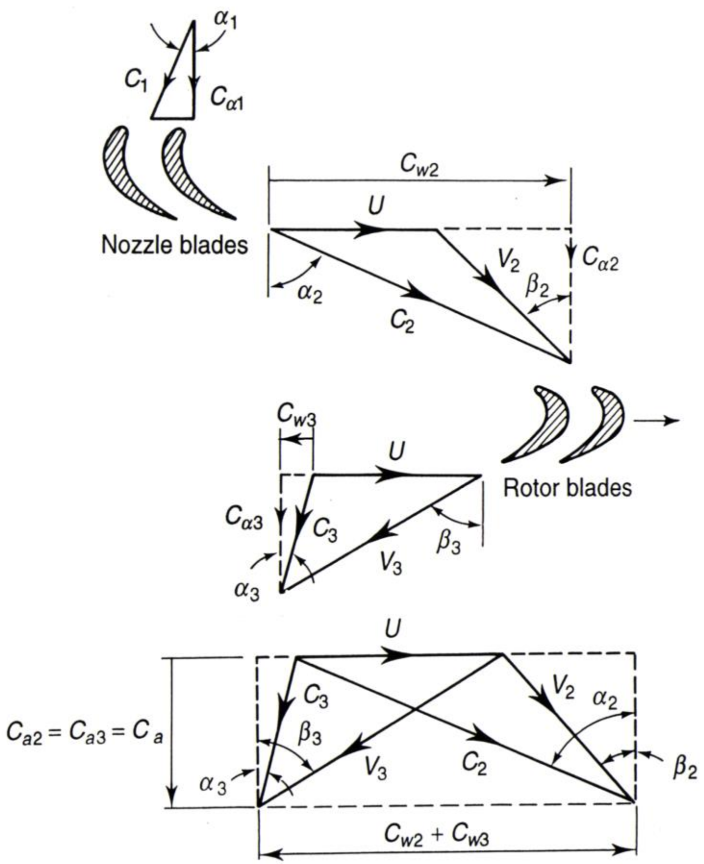
Where ΔT_{os} = Stagnation temperature drop in the stage

When inlet & outlet velocities are the same

$$C_1 = C_3 \cdot \Delta T_{os} = \Delta T_s$$

Stagnation Pressure ratio, $\frac{P_{01}}{P_{03}}$ can be found from $\Delta T_{os} = \eta_s T_{01}\left[1-\left(\frac{1}{p_{01}/p_{03}}\right)^{\frac{\gamma-1}{\gamma}}\right]$

Axial Flow Turbine Stage



	NGV	ROTOR
Total Temperature	Constant	Decrease
Enthalpy	Constant	Decrease
Static Temperature	Decrease	Decrease
Total Pressure	Small Decrease	Decrease
Static Pressure	Decrease	Decrease
Relative Velocity	N/A	Increase
Absolute Velocity	Increase	Decrease
Density	Decrease	Decrease

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Dimensionless Parameters in Turbine Design

Blade loading coefficient: ψ = Temperature drop coefficient

$$\psi = \frac{\Delta h_{os}}{\frac{1}{2}U^2} = \frac{c_p(\Delta T_{os})}{\frac{1}{2}U^2} = \frac{2Ca}{U}(\tan \beta_2 + \tan \beta_3)$$

Degree of reaction: λ = Fraction of stage expansion occurring in rotor, usually defined in terms of static temperature:

$$\lambda = \frac{T_2 - T_3}{T_1 - T_3}$$

$$\lambda = \frac{C_a}{2U} \cdot (\tan \beta_3 - \tan \beta_2)$$

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Dimensionless Parameters in Turbine Design

Flow coefficient: ϕ = Ratio of axial velocity to blade speed

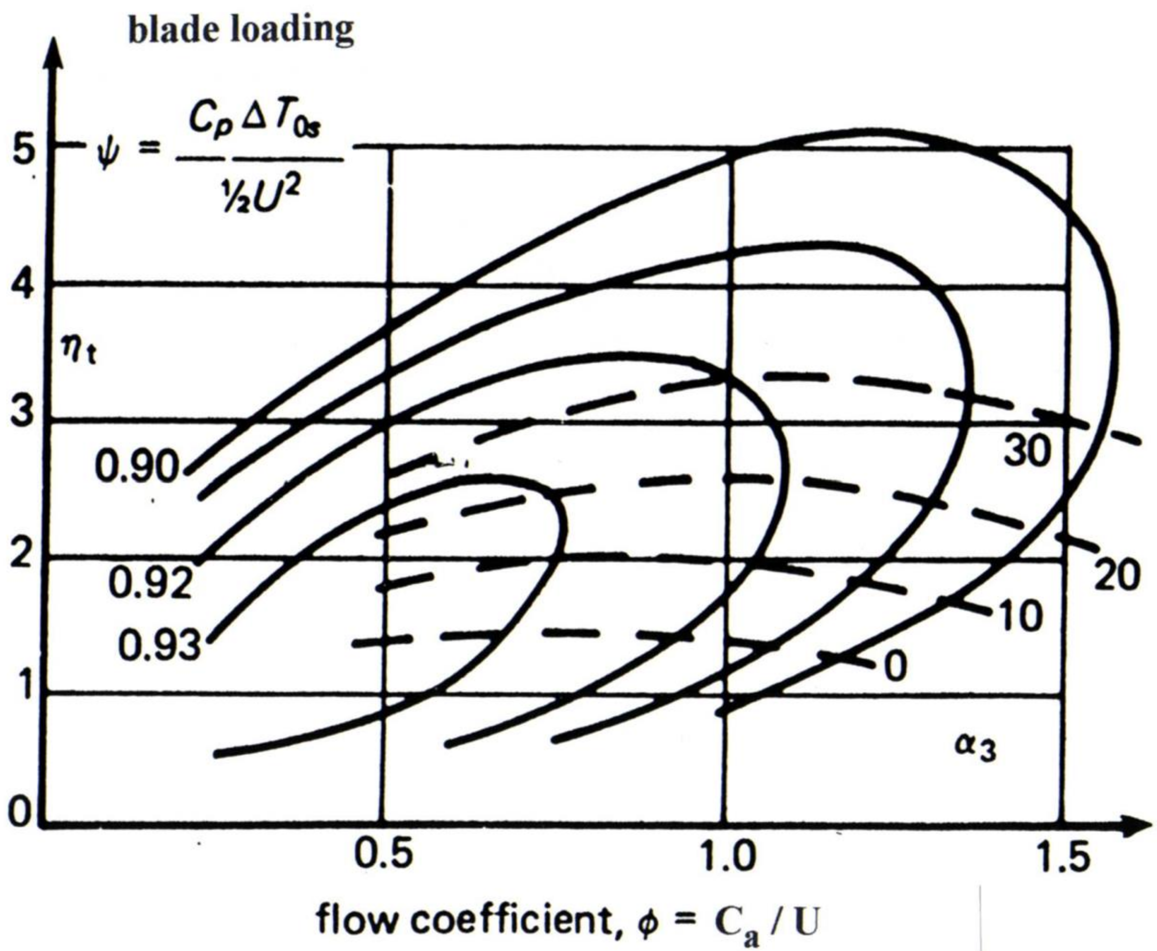
$$\phi = C_a/U$$

Hence:

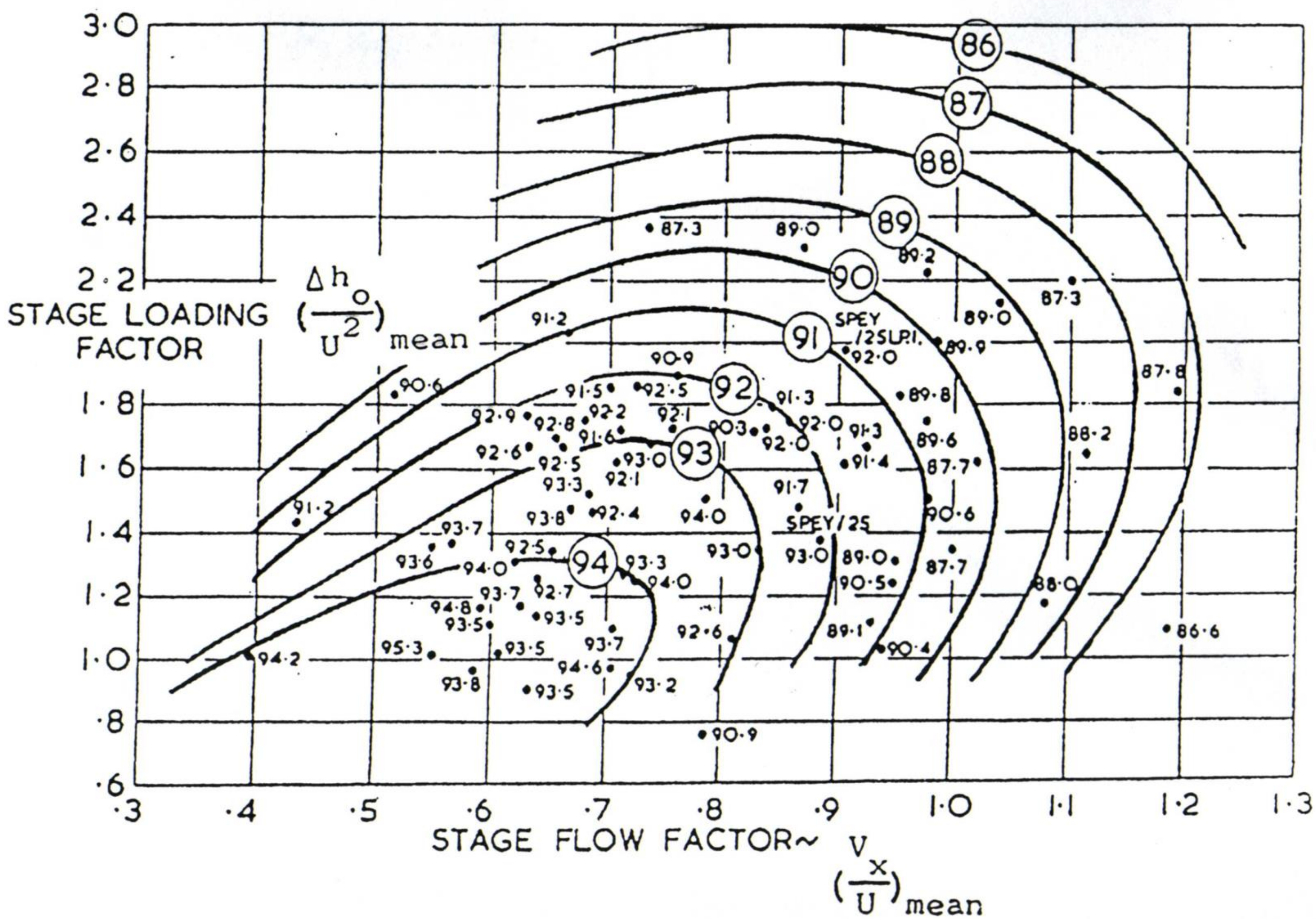
$$\psi = 2\phi\,(\tan\boldsymbol{\beta_2} + \tan\boldsymbol{\beta_3})$$

$$\lambda = \frac{\phi}{2}(\tan\boldsymbol{\beta_3} - \tan\boldsymbol{\beta_2})$$

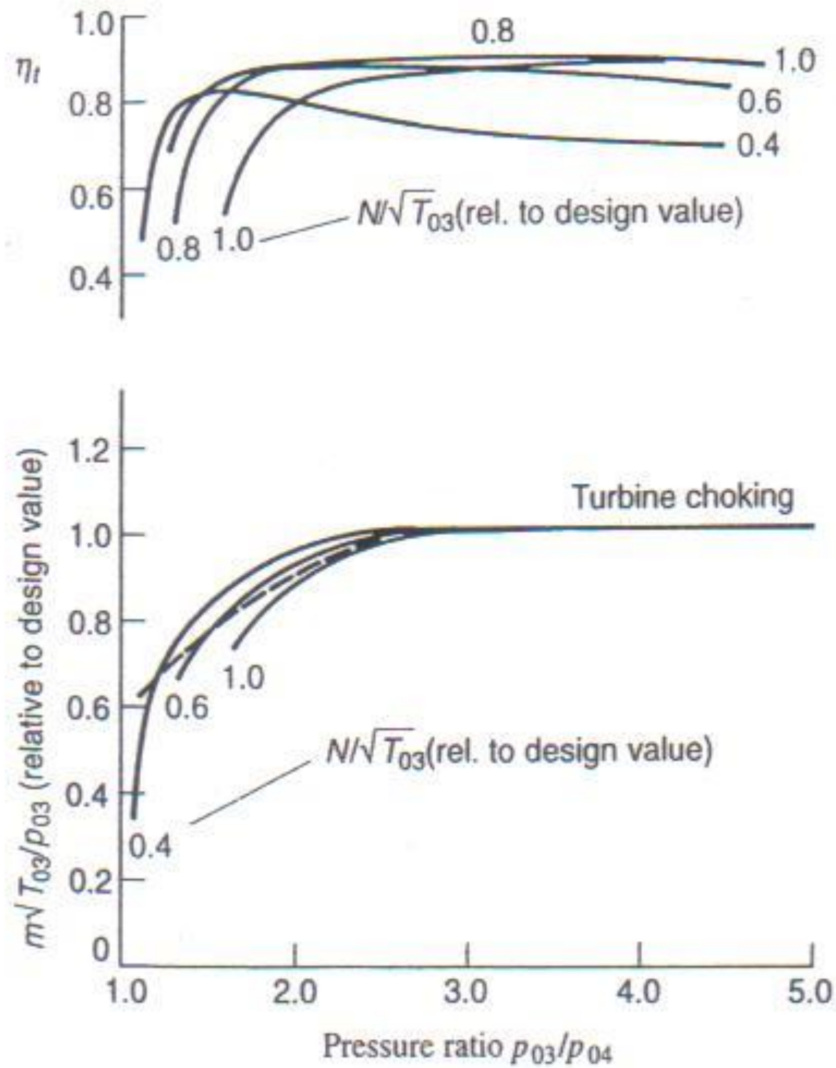
Turbine Efficiency Contours versus Blade Loading & Flow Coefficient



Turbine Efficiency Contours versus Blade Loading & Flow Coefficient



Turbine Characteristics



- Efficiency over most of operating range, constant.
- No change in flow function with speed once flow is choked.
- Most HP turbines operate in a choked condition.
- LP turbines will have more of their operations in the non choked region.

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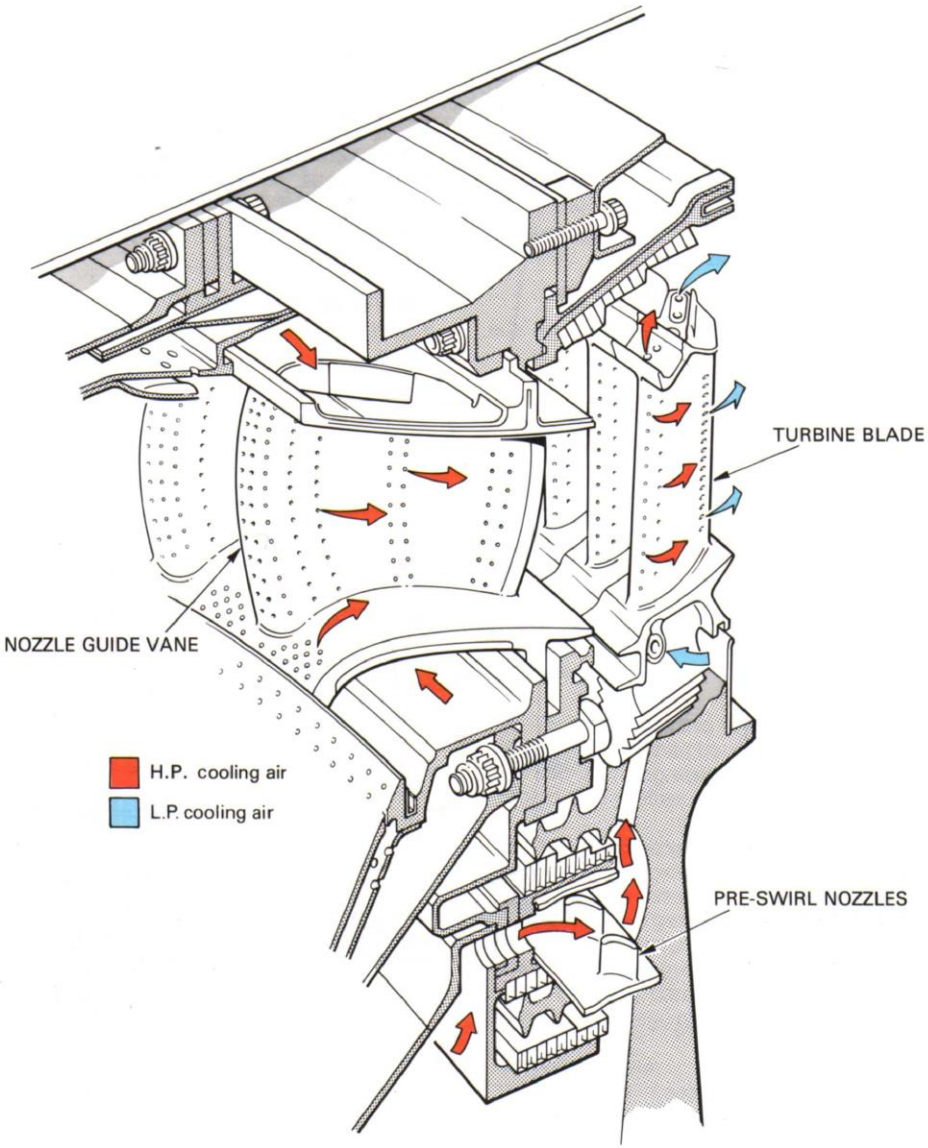
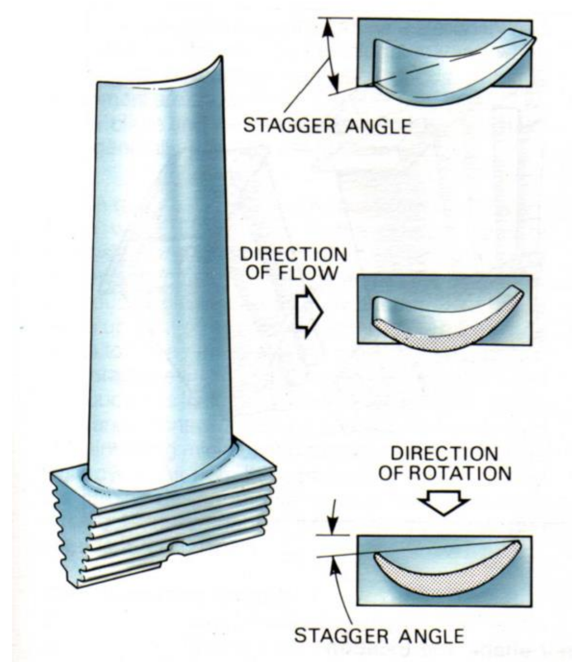
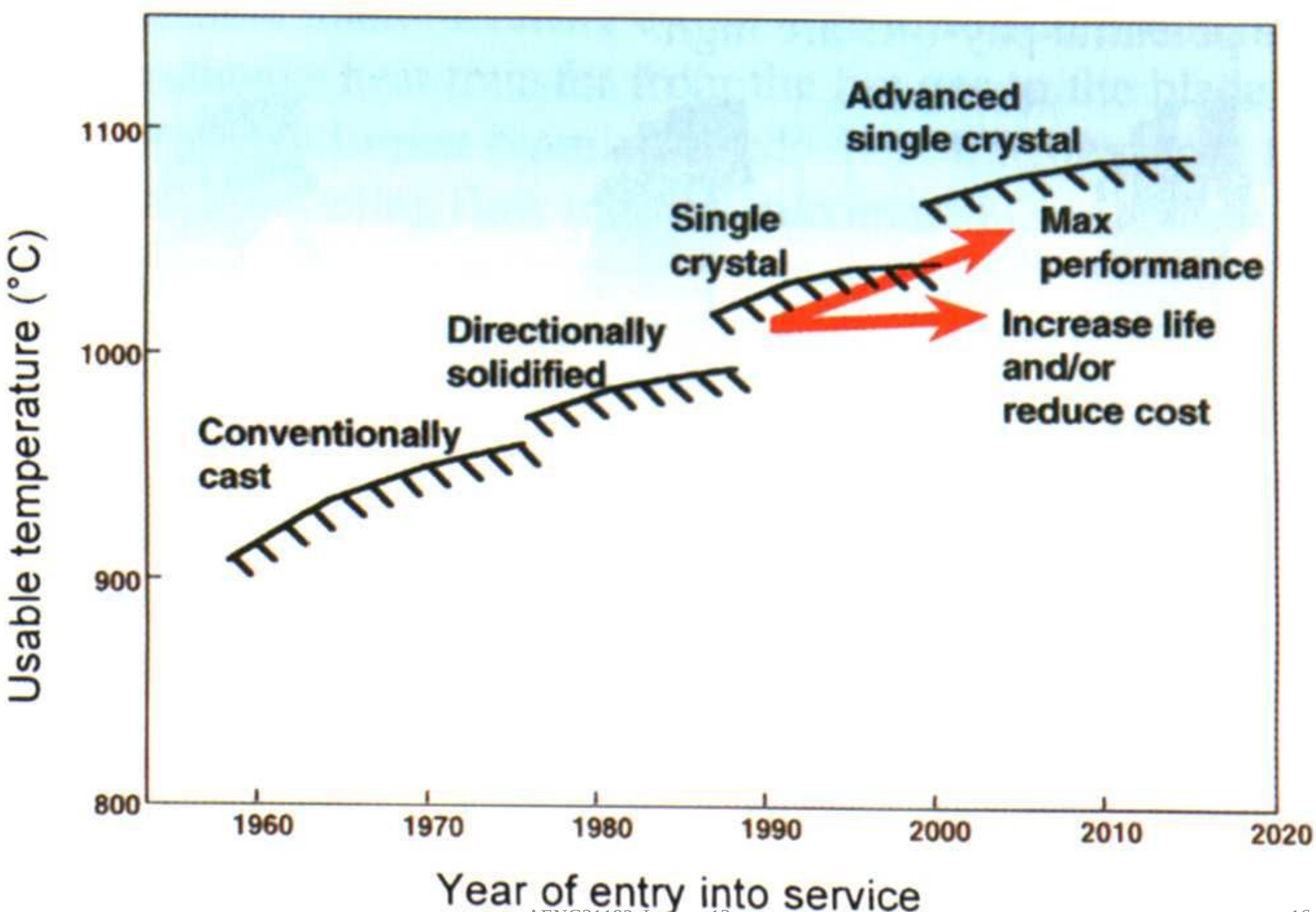
Turbine Layout



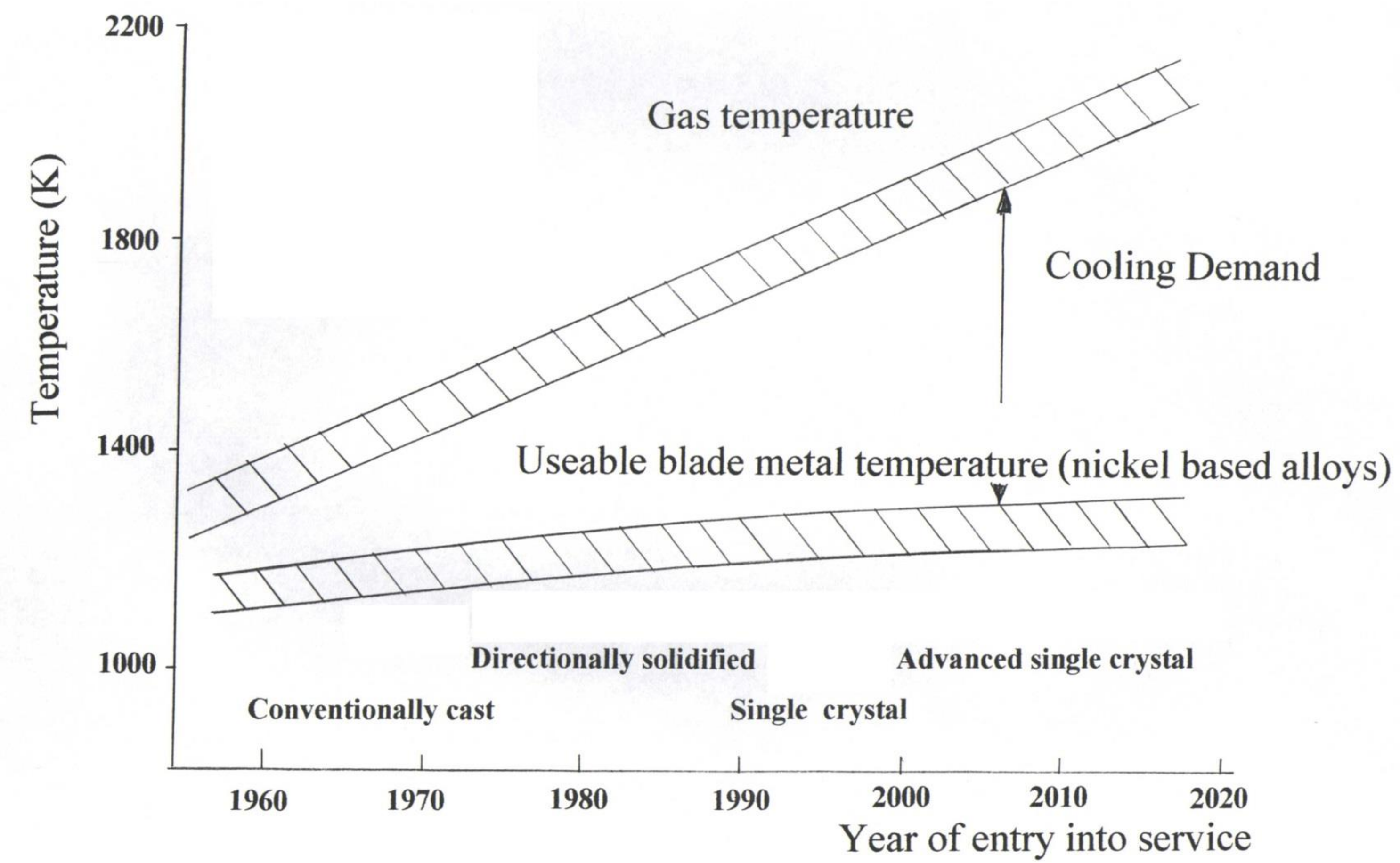


A typical uncooled turbine blade showing twisted contour

Turbine blade temperature capability



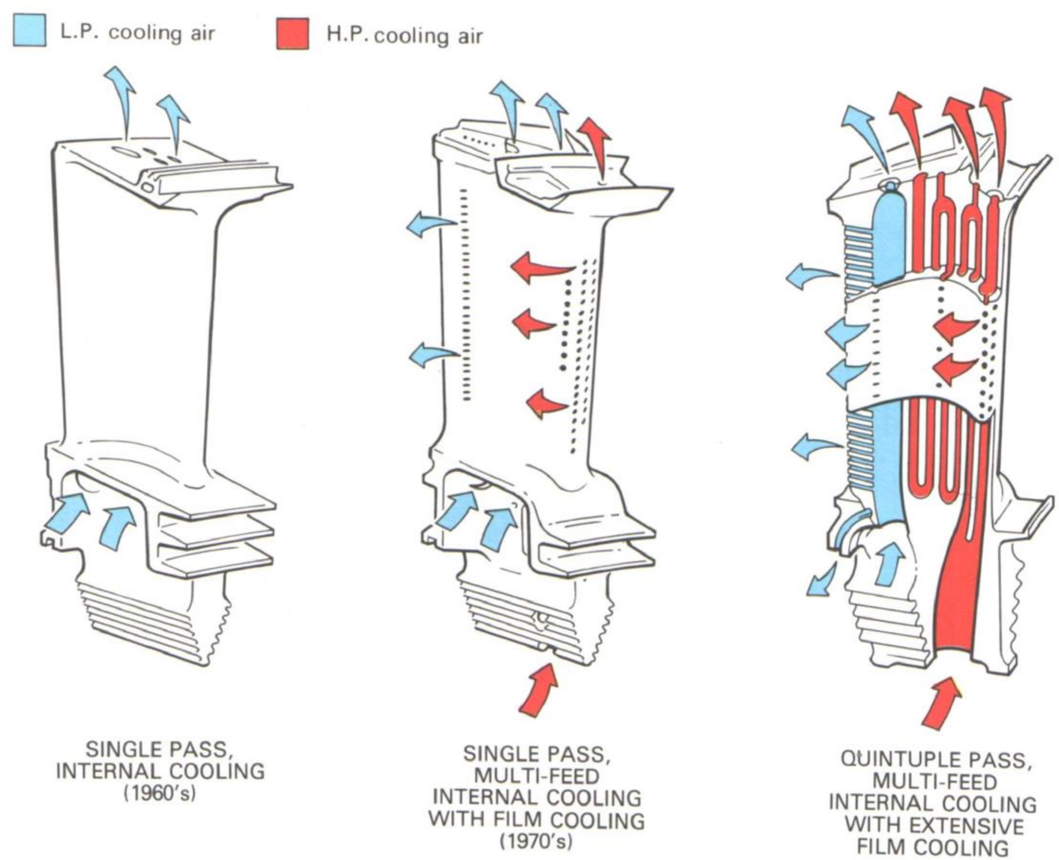
Turbine cooling



- High temperature gives high thermodynamic efficiency
- Blades must be cooled
- Balance between efficiency cost and life

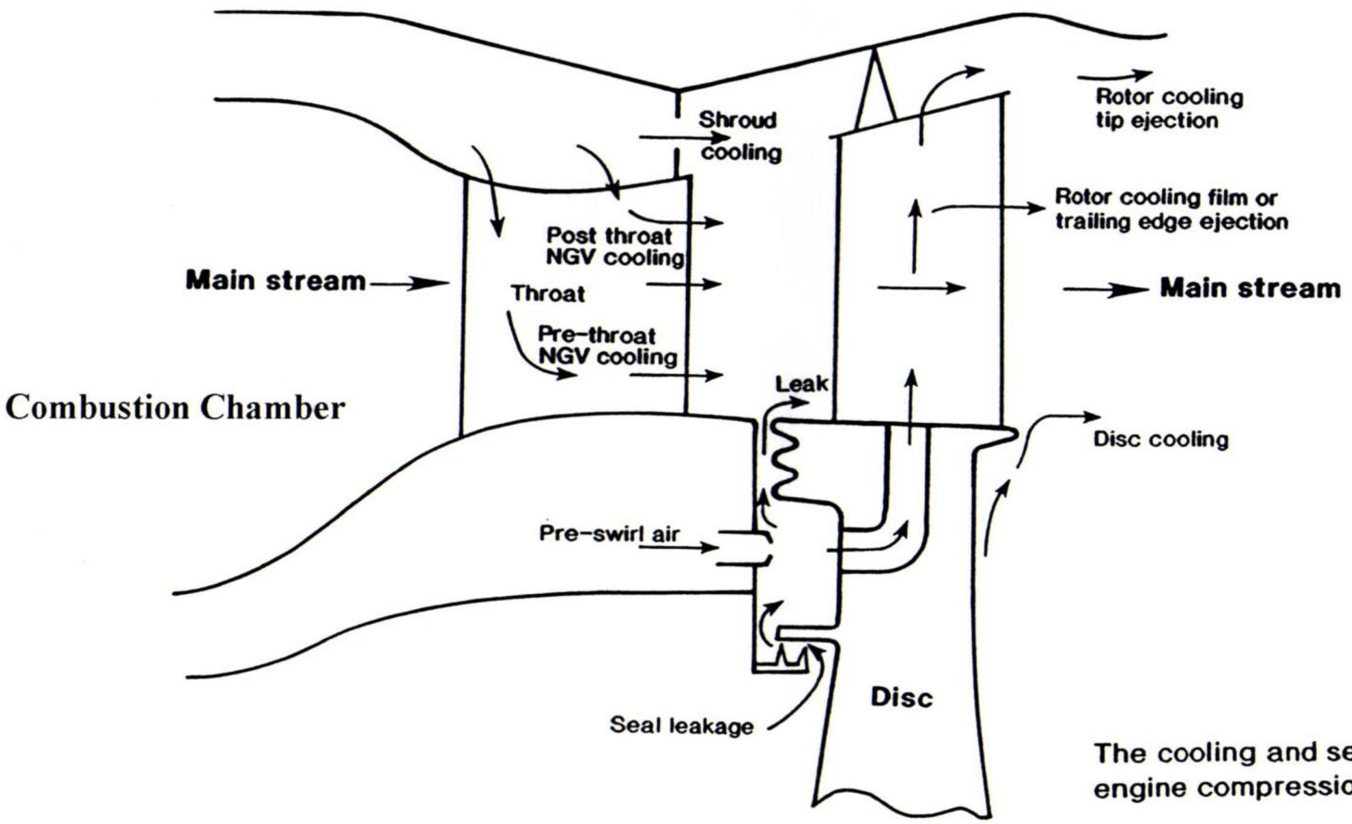
The Development of HP Turbine Blade Cooling Systems

- Multi-pass convection and film cooling
- Cooling system designed to avoid 'hot spots'
- Must cool sufficiently to achieve blade life
- Requires knowledge of the heat transfer



Courtesy of Rolls Royce

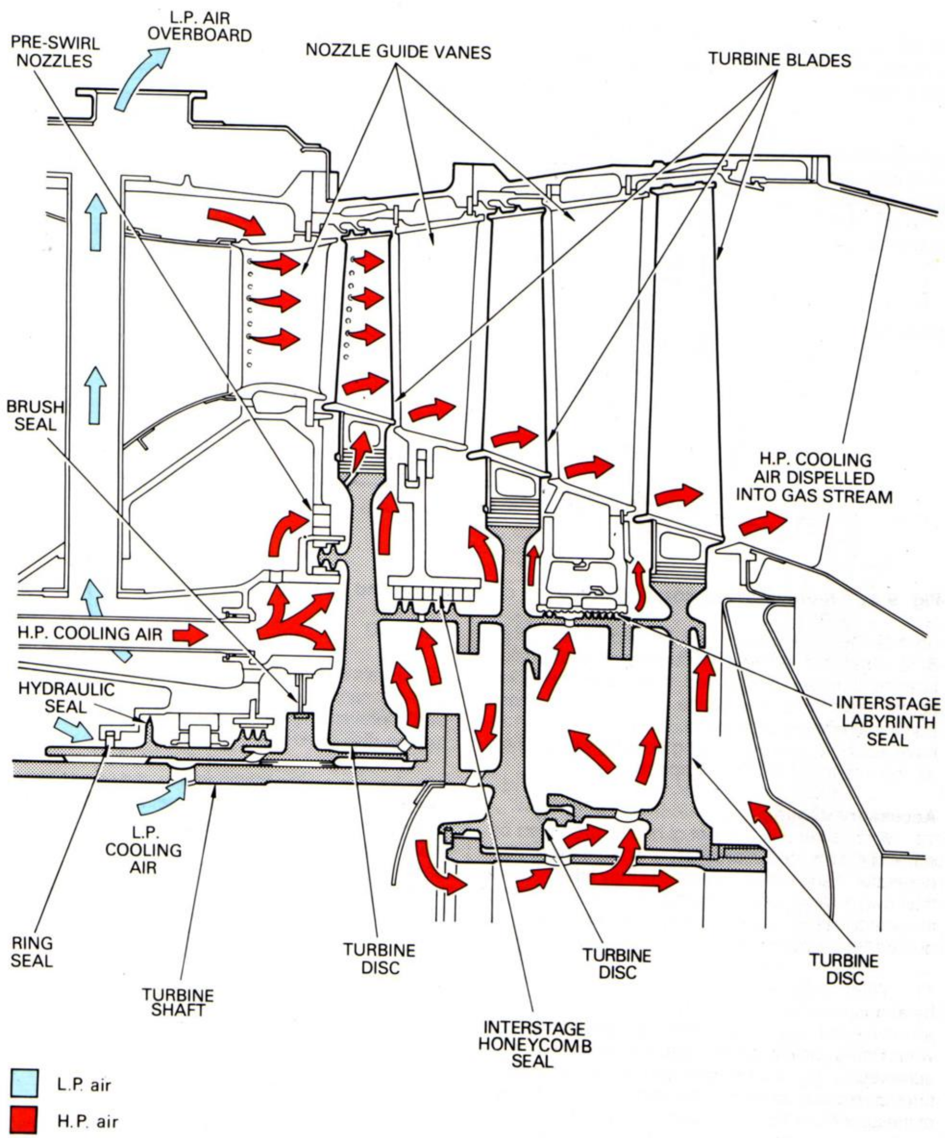
Typical Turbine Cooling System
Schematic



The cooling and sealing air source is the engine compression system

There is a performance loss associated with the provision of cooling and sealing air.

Typical Turbine Cooling System



Turbine blade metal temperatures

Cooling Effectiveness

$$= \frac{T_b - T_{cr}}{T_{g\,rel} - T_{cr}}$$

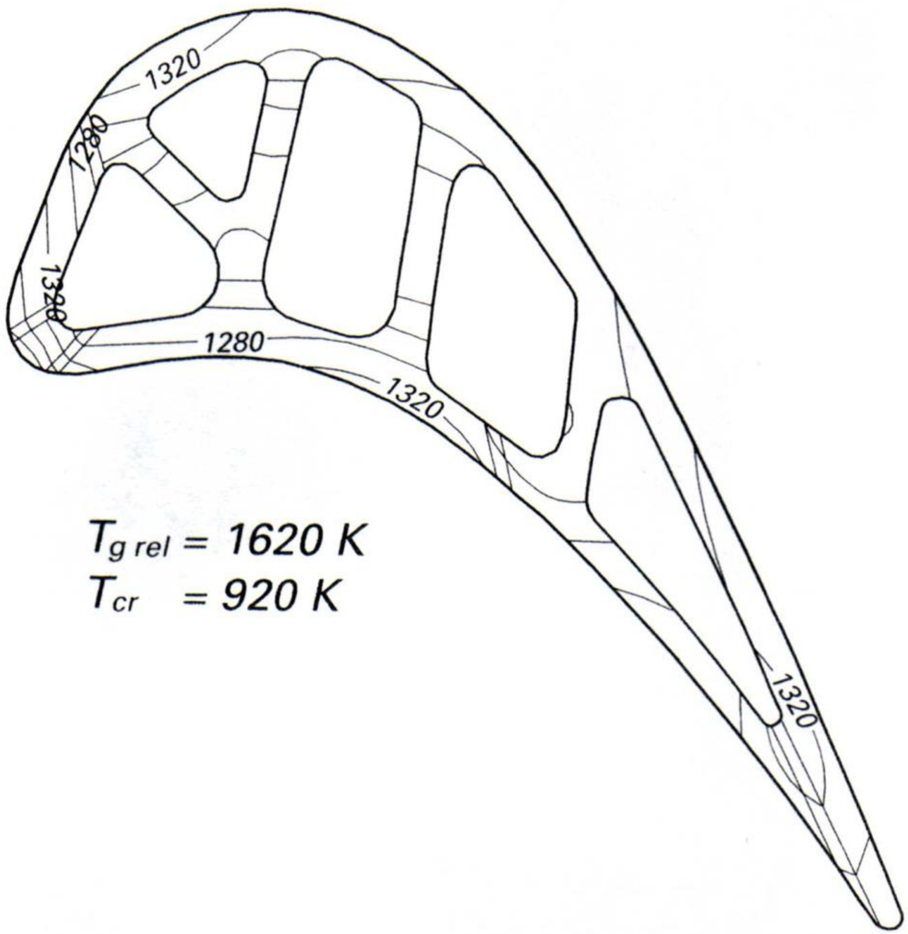
Where:

$\mathbf{T_b}$ = Mean blade metal Temperature

$\mathbf{T_{cr}}$ = Cooling Air Temperature

$\mathbf{T_{g\,rel}}$ = Mean Gas Temperature

Cooling airflow must be kept to a minimum



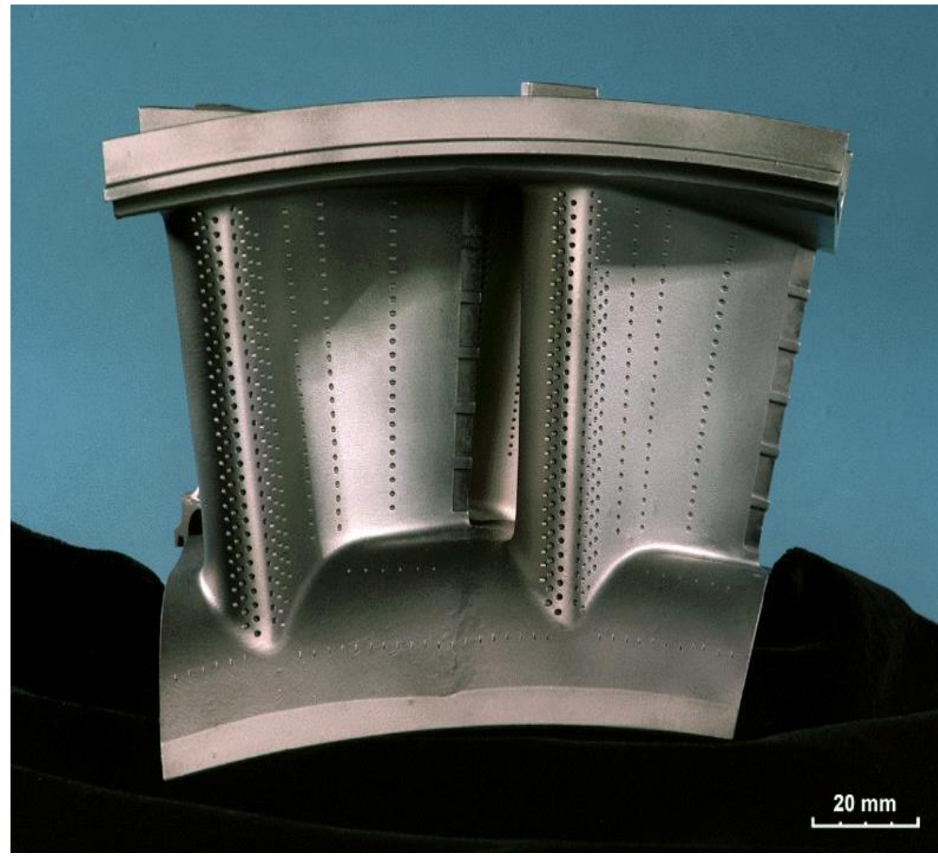
Film cooled HP nozzle guide vane

Turbine Materials

Nickel based Super-alloys

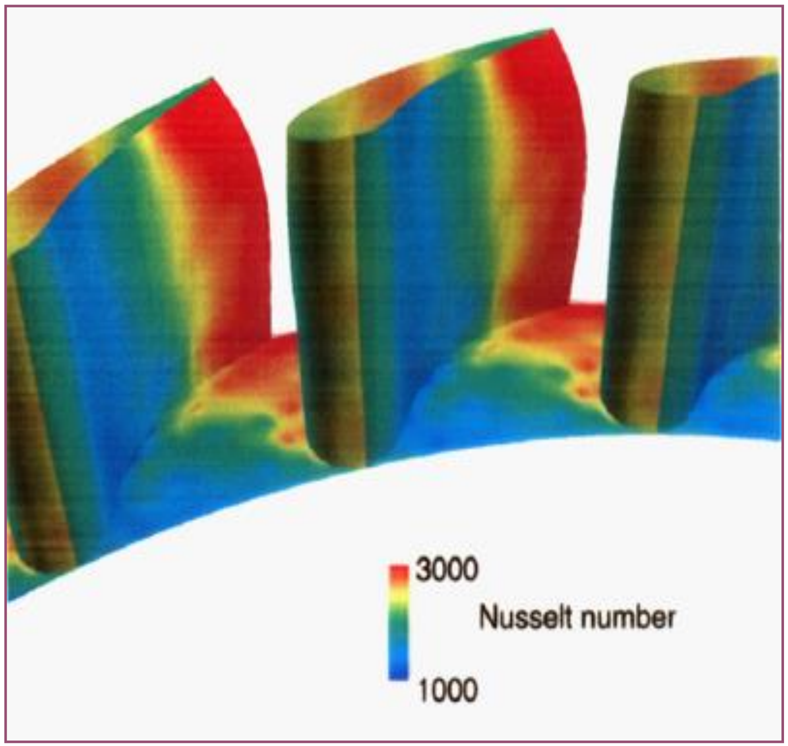
Typically: Nimonic 115

Nickel	**57.3%**
Cobalt	**15%**
Chromium	**15%**
Aluminium	**5%**
Titanium	**4%**
Molybdenum	**3.5%**
Carbon	**0.16%**
Zirconium	**0.04%**
Boron	**0.014%**

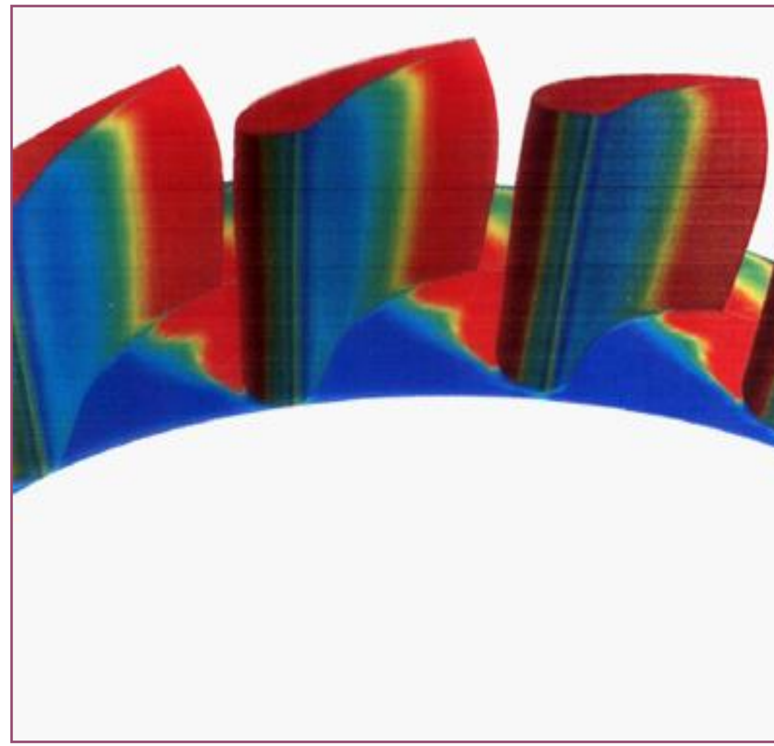


Film cooled HP nozzle guide vane

Experimental Measurement



CFD Prediction



Turbine Blades

Conventionally cast

Directionally solidified

Single crystal

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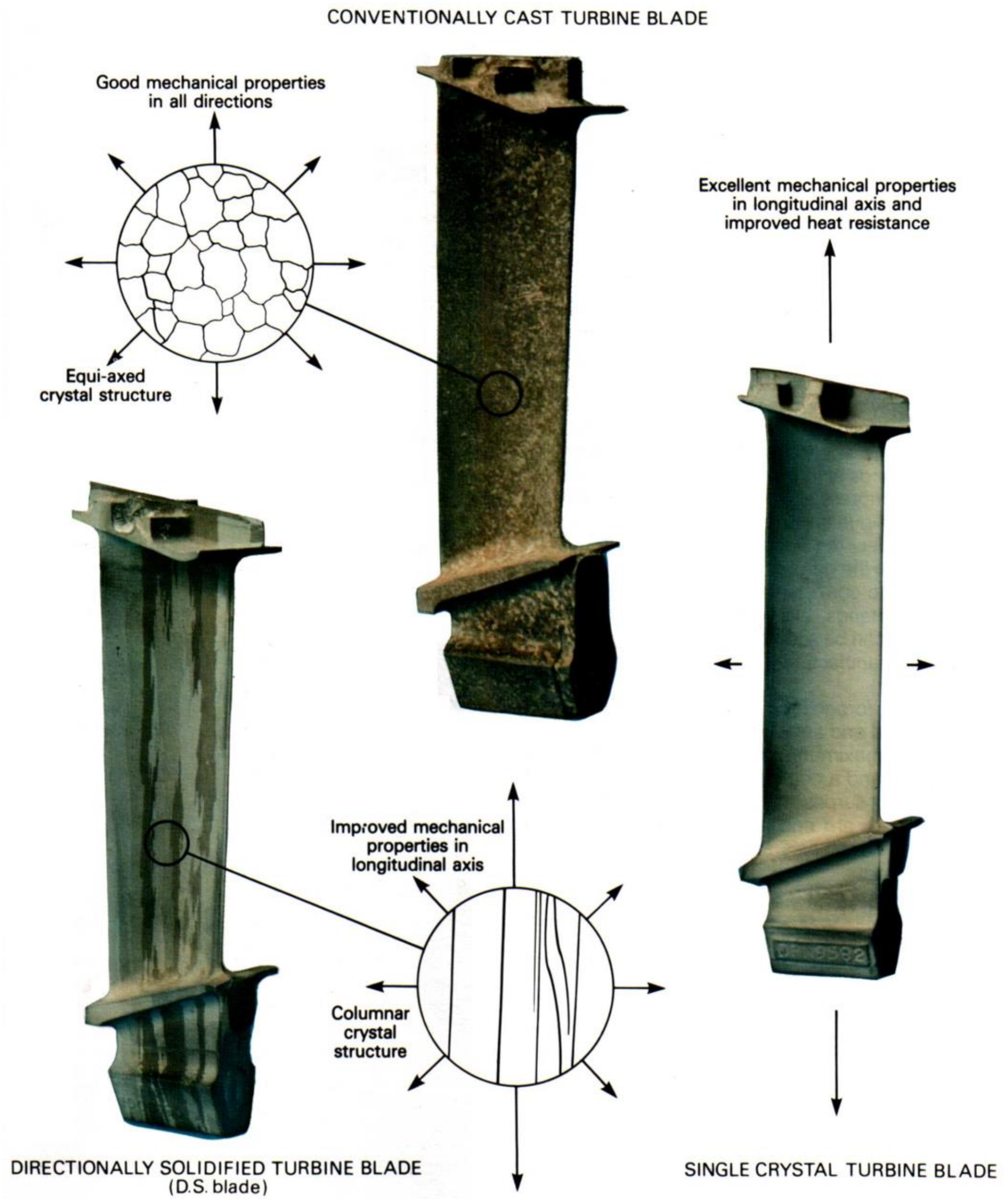
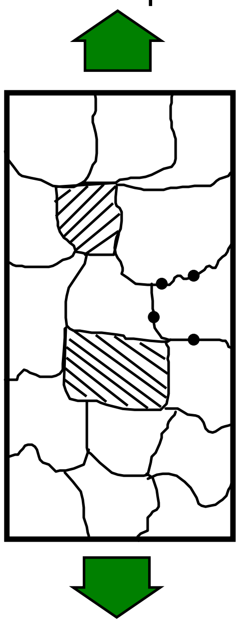


Compressors → Compressors → Compressors Turbines → Hotter → Turbines Combustors → Even hotter!

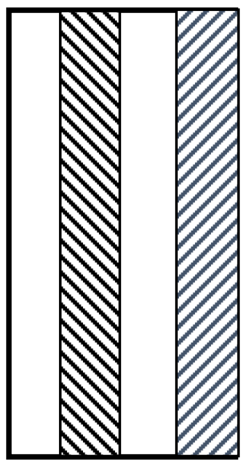
Titanium → Steel → Nickel based alloys eg. Nimonics → Ceramics

Creep

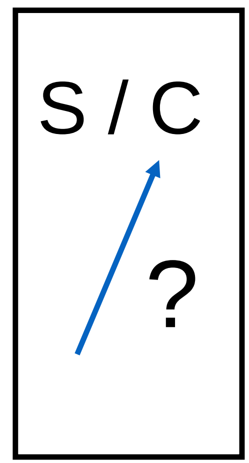


Conventional castings

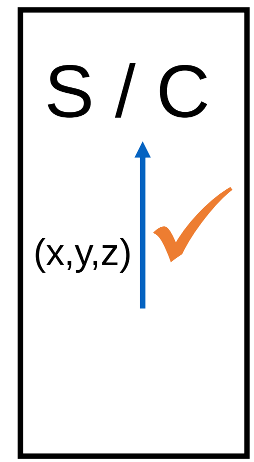
Grain boundary stabilising precipitates
Limited heat treatment and composition



Directionally solidified

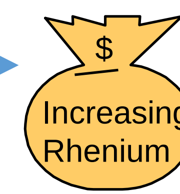


Single crystal 'random'



Single crystal 'orientation control'

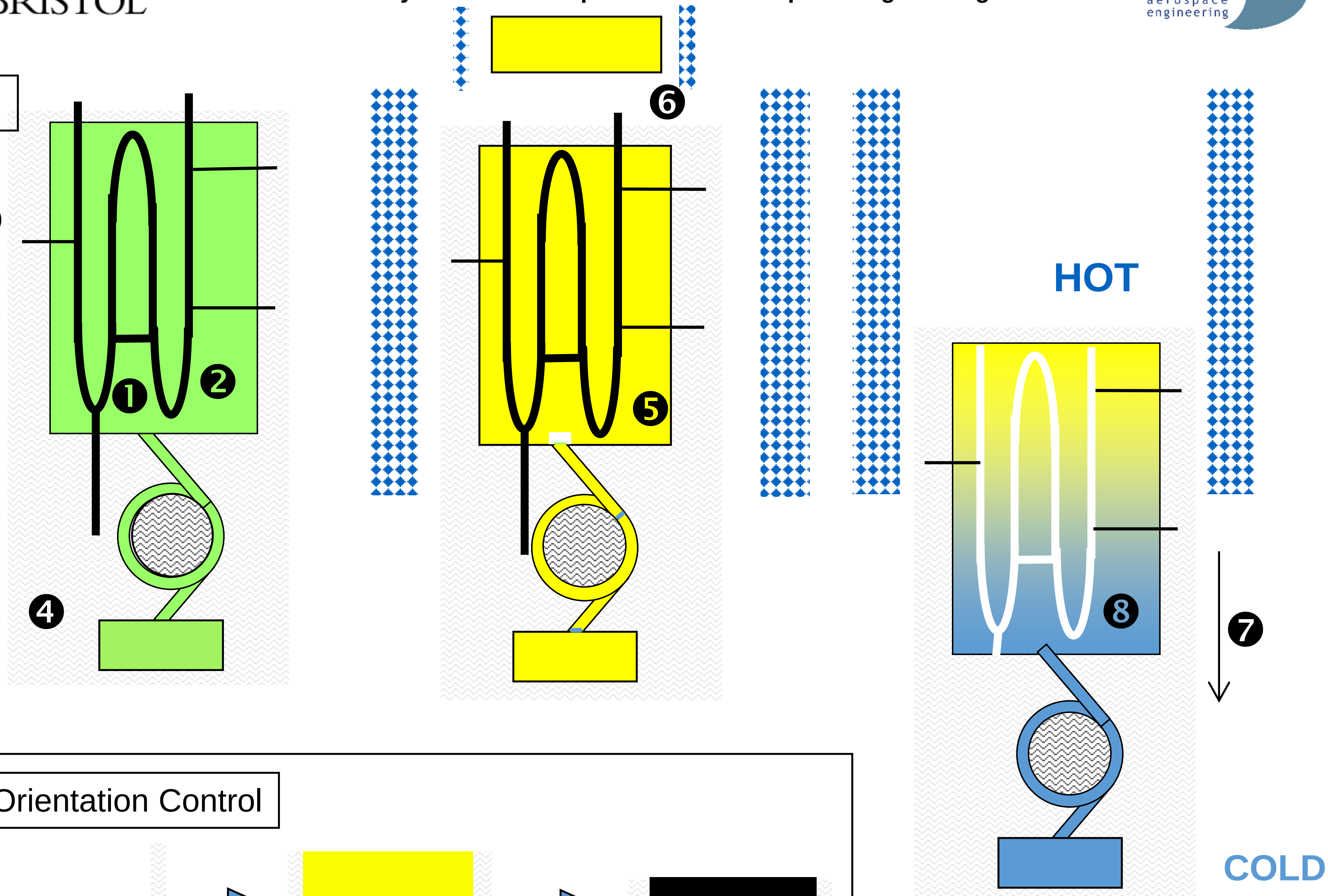
CM$X4 ➔ RR2000 ➔ RR3000 ➔ RR3010

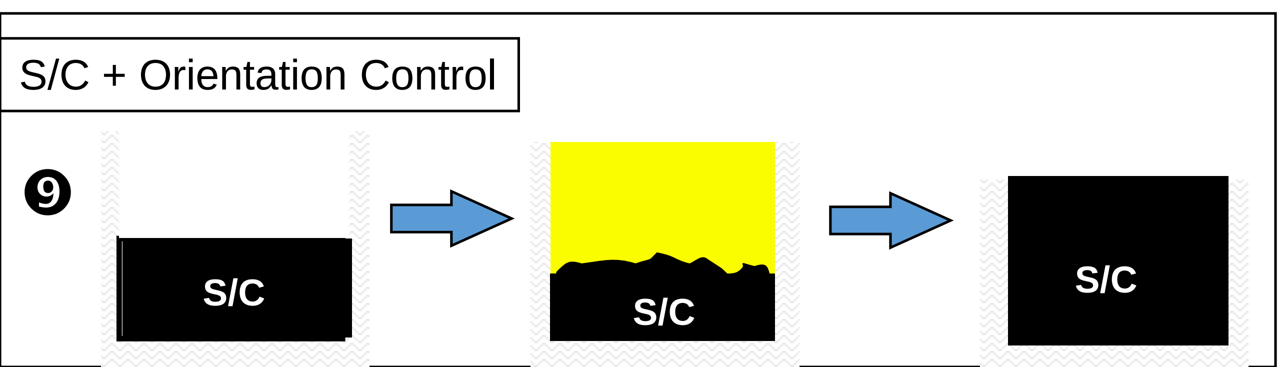


No gain boundaries /stabilisers
More freedom in heat treatment and composition

Big fat Rhenium atoms disrupt dislocation mechanisms

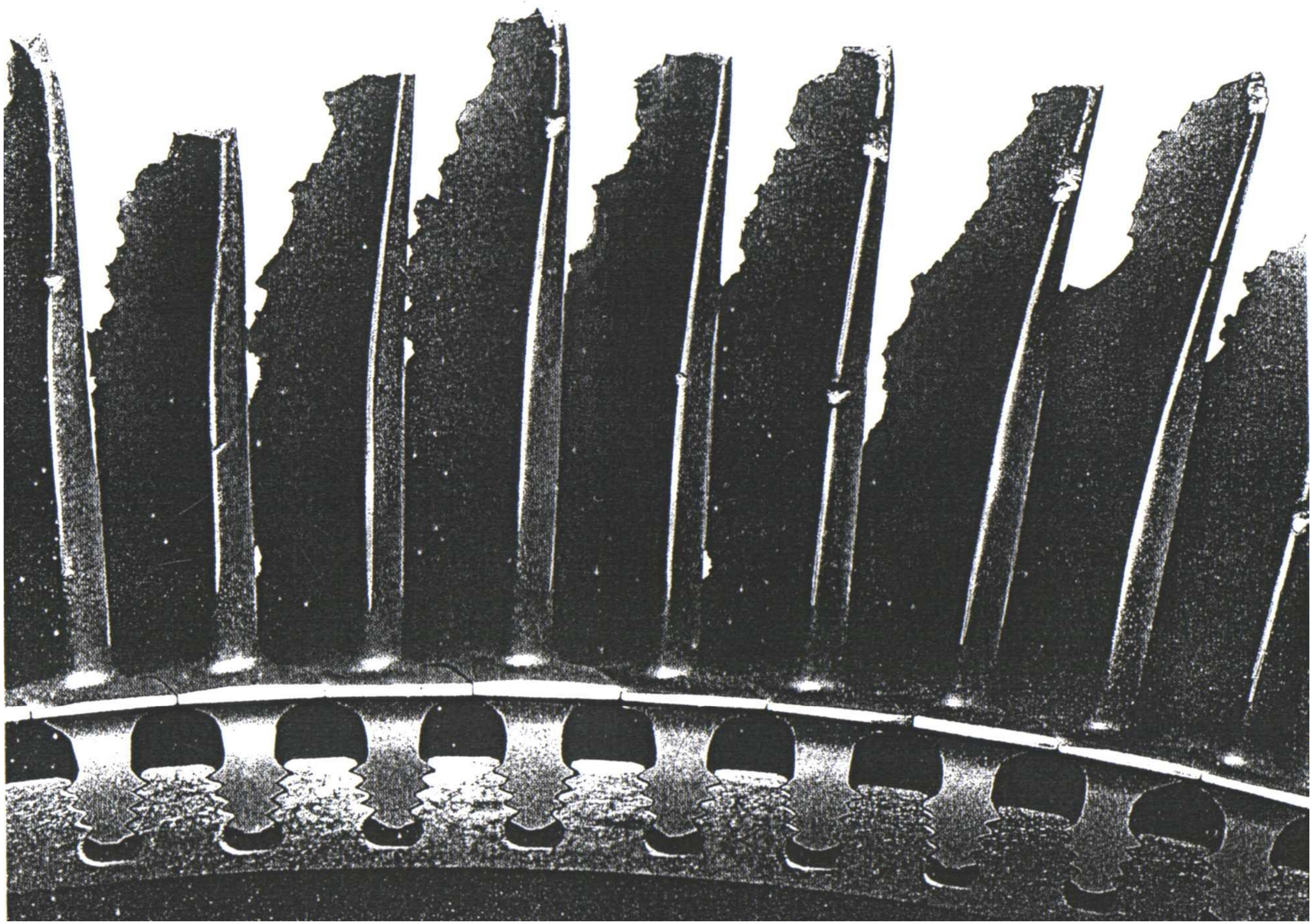
Blade materials



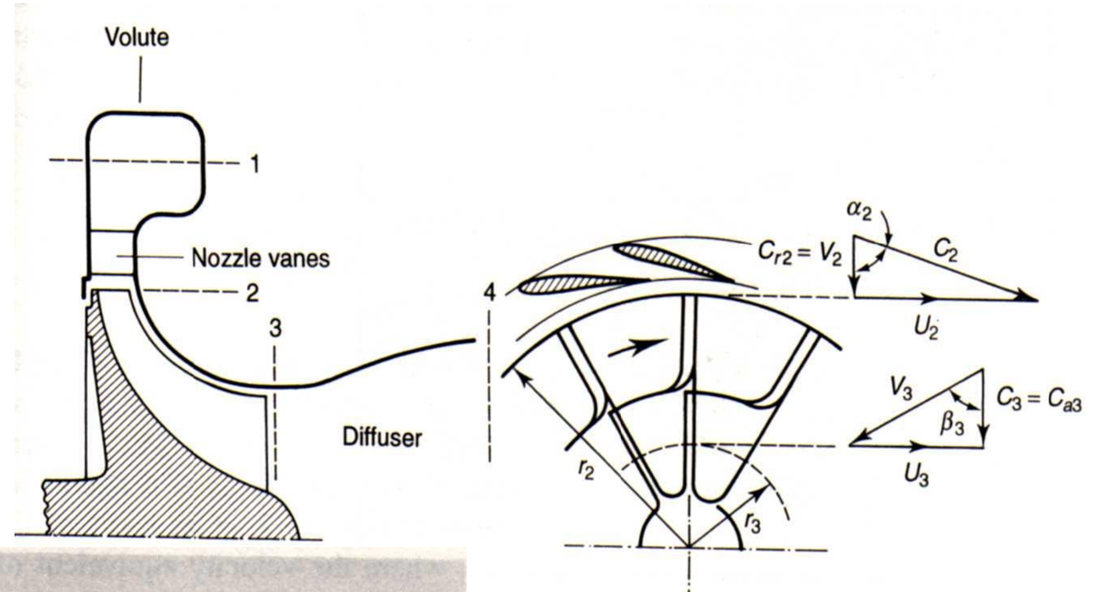


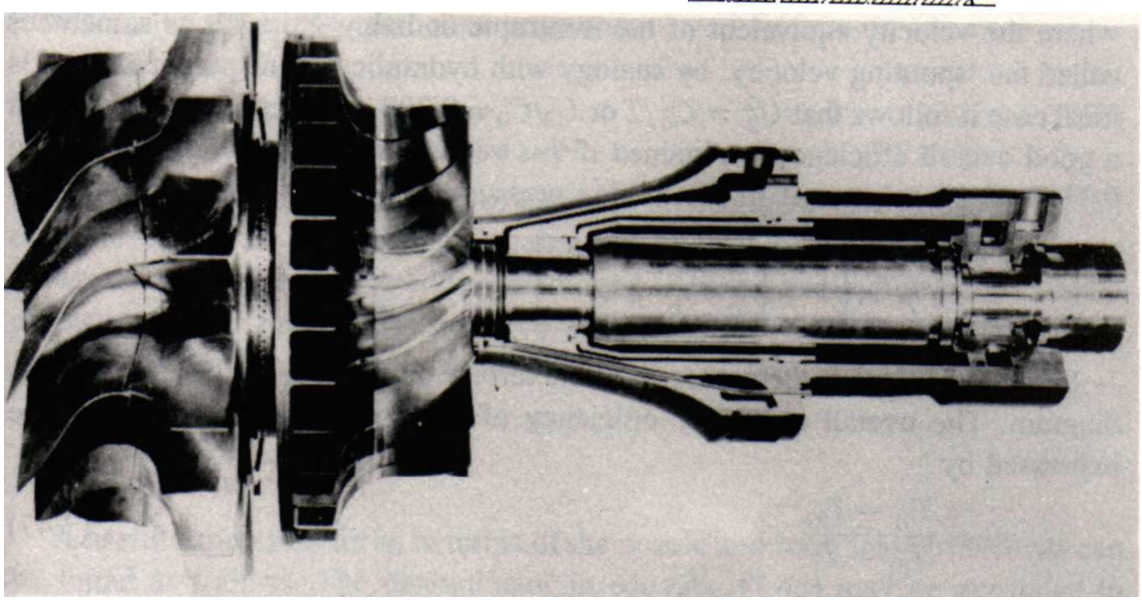
Single crystal lost wax casting

Uncooled Turbine blades



Radial Inflow Turbine

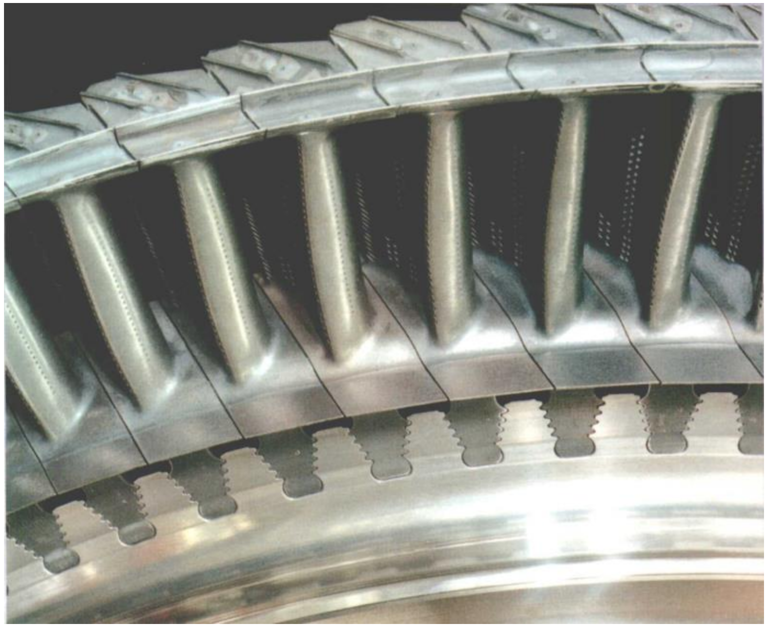




Back to back CF Compressor & radial inflow turbine

Key Lessons from Lecture 13

- Aerodynamics not a real problem
- Materials & cooling key to high cycle efficiency
- Complex three dimensional, highly viscous flow
- Flow is inherently unsteady
- Gas temperatures up to 1600 deg C
- Centrifugal loading of 30,000 g



The Engine Control System

To describe how the engine is controlled