- Recap: Lecture 19, 9th October 2015, 1530-1655 hrs.
  - 3D flow analysis in axial turbines
    - Free Vortex flow
    - Constant nozzle exit angle, α_2
    - Arbitrary vortex case, $C_w = r^n$
  - Cooling of turbine blades

Turbine blade cooling

- For a given pressure ratio and adiabatic efficiency, the turbine work per unit mass is proportional to the inlet stagnation temperature.
- Therefore, typically a 1% increase in the turbine inlet temperature can cause 2-3% increase in the engine output.
- Therefore there are elaborate methods used for cooling the turbine nozzle and rotor blades.
- Turbine blades with cooling can withstand temperatures higher than that permissible by the blade materials.

Turbine blade cooling

- Thrust of a jet engine is a direct function of the turbine inlet temperature.
- Brayton cycle analysis, effect of maximum cycle temperature on work output and efficiency.
- Materials that are presently available cannot withstand a temperature in excess of 1300 K.
- However, the turbine inlet temperature can be raised to temperatures higher than this by employing blade cooling techniques.
- Associated with the gain in performance is the mechanical, aerodynamic and thermodynamic complexities involved in design and analysis of these cooling techniques.

Turbine blade cooling

- The environment in which the nozzles and rotors operate are very extreme.
- In addition to high temperatures, turbine stages are also subjected to significant variations in temperature.
- The flow is unsteady and highly turbulent resulting in random fluctuations in temperatures.
- The nozzle is subjected to the most severe operating conditions.

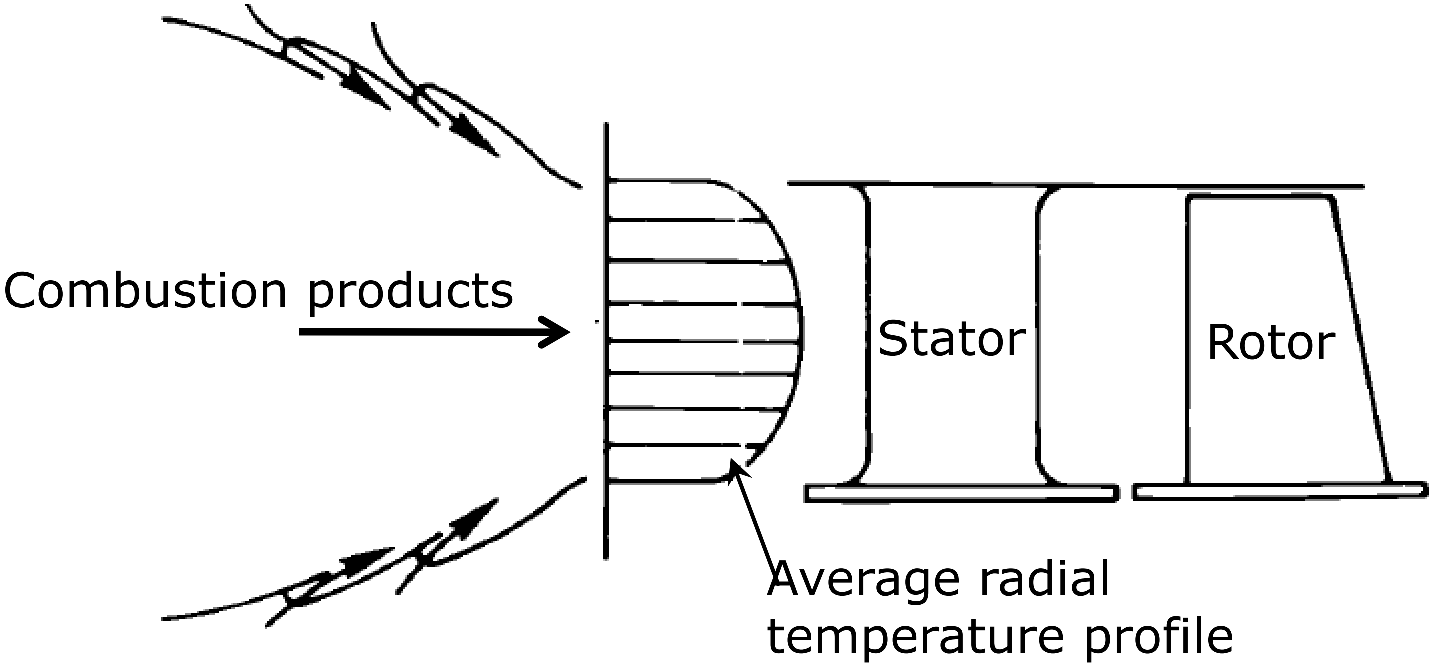
Turbine blade cooling

- Because the relative Mach number that the rotor experiences, it perceives lower stagnation temperatures (about 200-300 K) than the nozzle.
- However the rotor experience far more stresses due to the high rotational speeds.
- The highest temperatures are felt primarily by the first stage.
- Cooling problems are less complicated in later stages of the turbine.

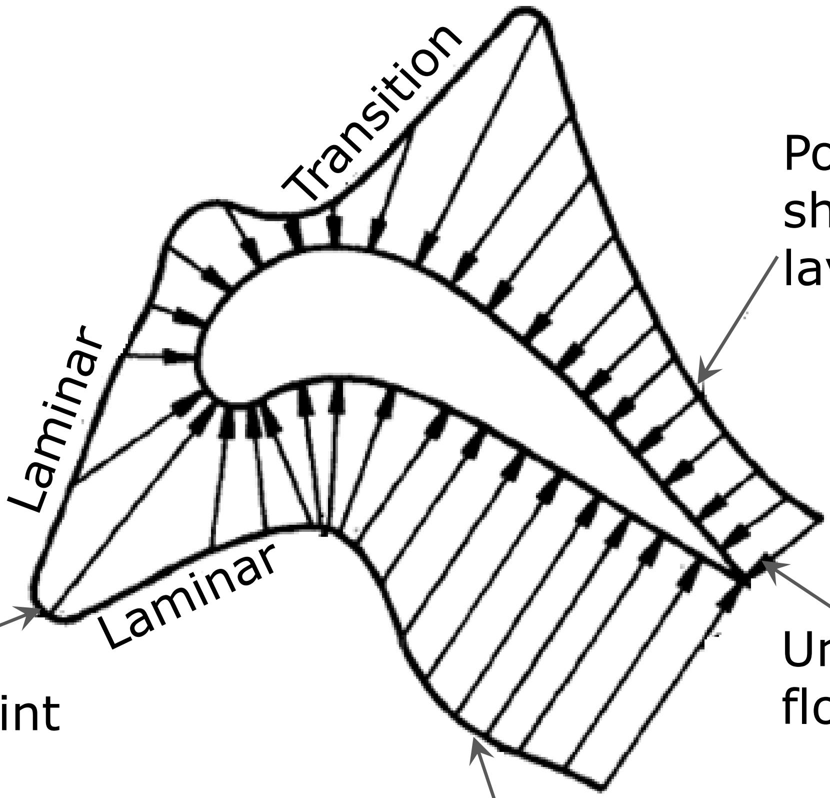
Turbine blade cooling

- There are several modes of failure of a turbine blade.
  - Oxidation/erosion/corrosion
    - Occurs due to chemical and particulate attack from the hot gases.
  - Creep
    - Occurs as a result of prolonged exposure to high temperatures.
  - Thermal fatigue
    - As a result of repeated cycling through high thermal stresses.

Turbine blade cooling



Average temperature profile entering a turbine stage



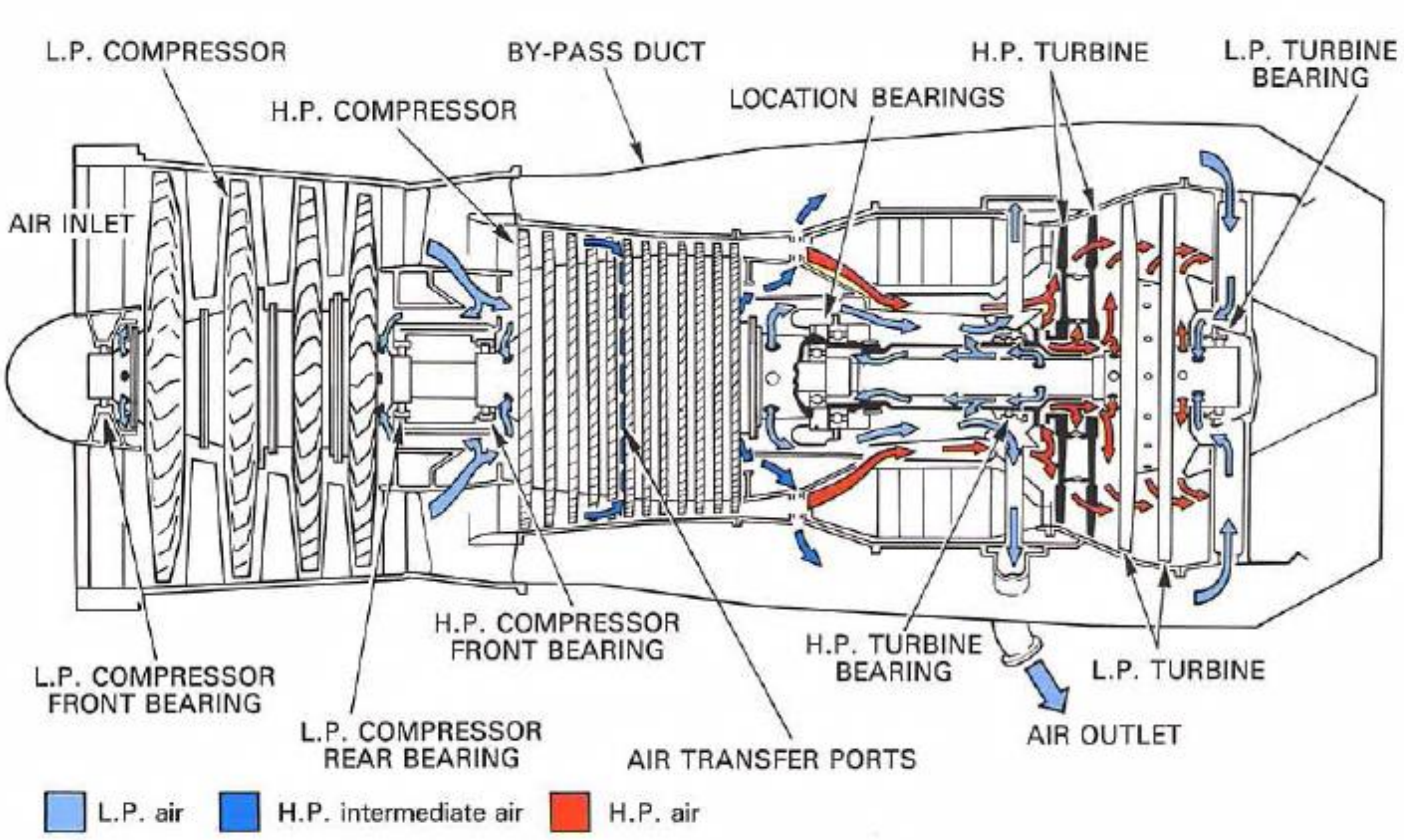
Possibility of shock-boundary layer interaction

Stagnation point

Unsteady wake flow

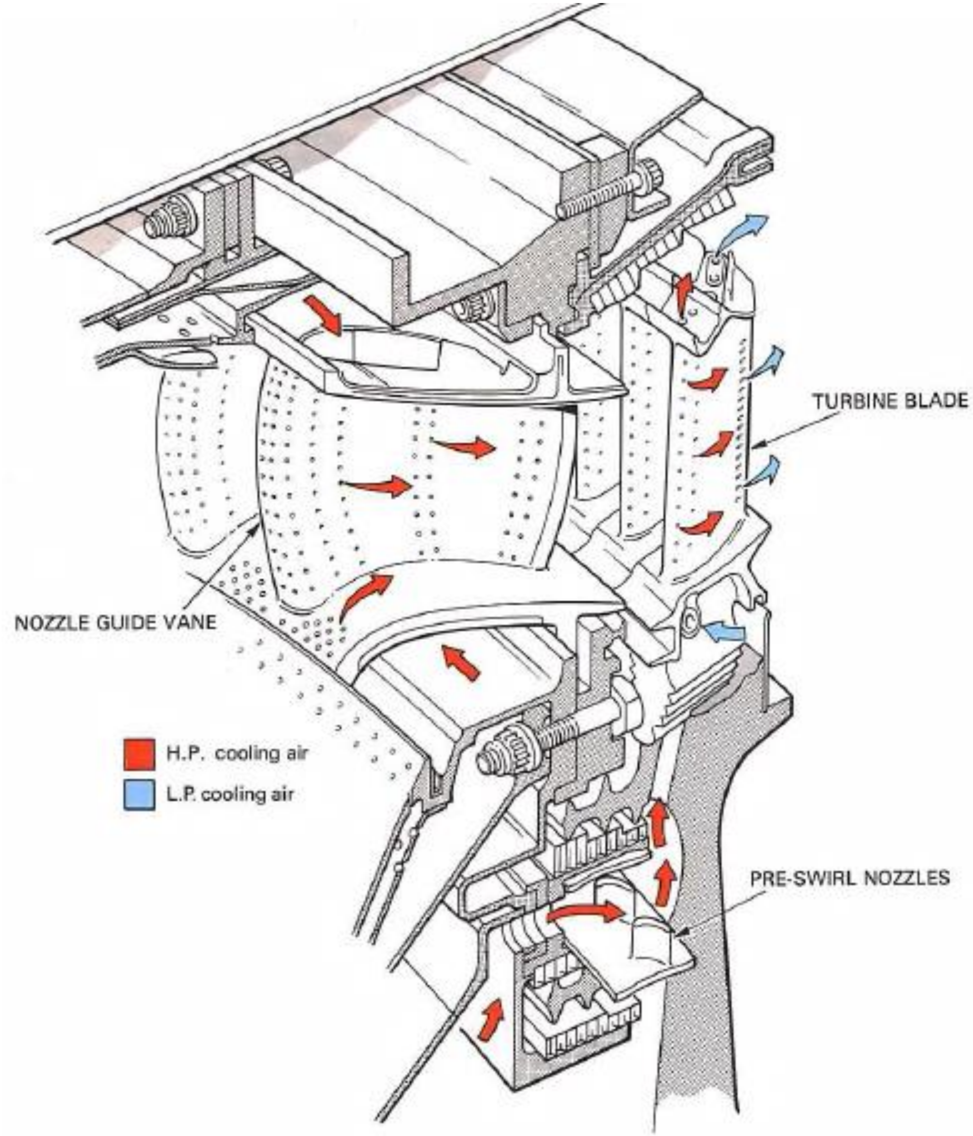
Possibility of transition followed by relaminarisation

Variation of heat transfer around a turbine blade



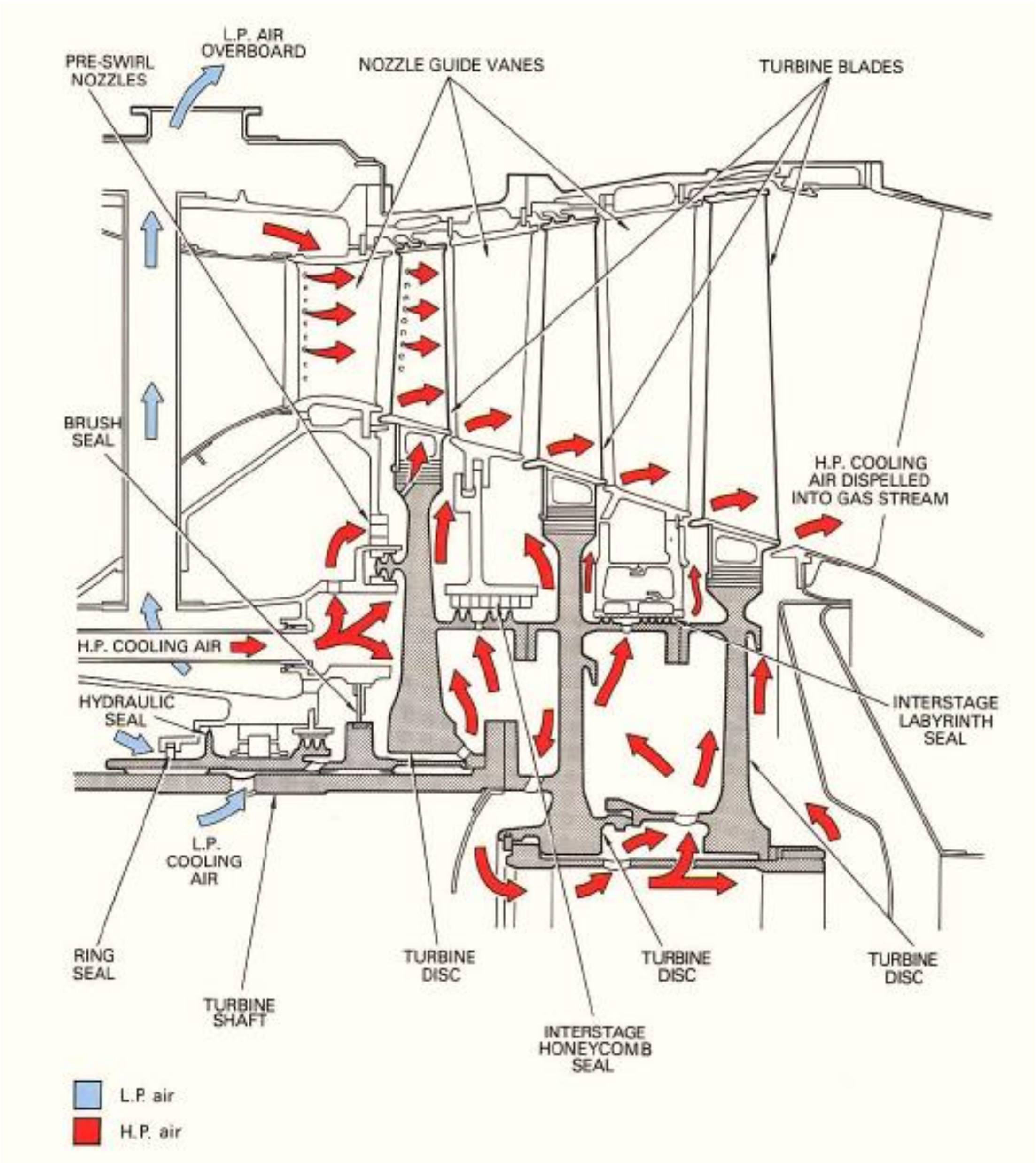
Airflow pattern from compressor to turbine

Source: The Jet Engine, Rolls Royce, 1994



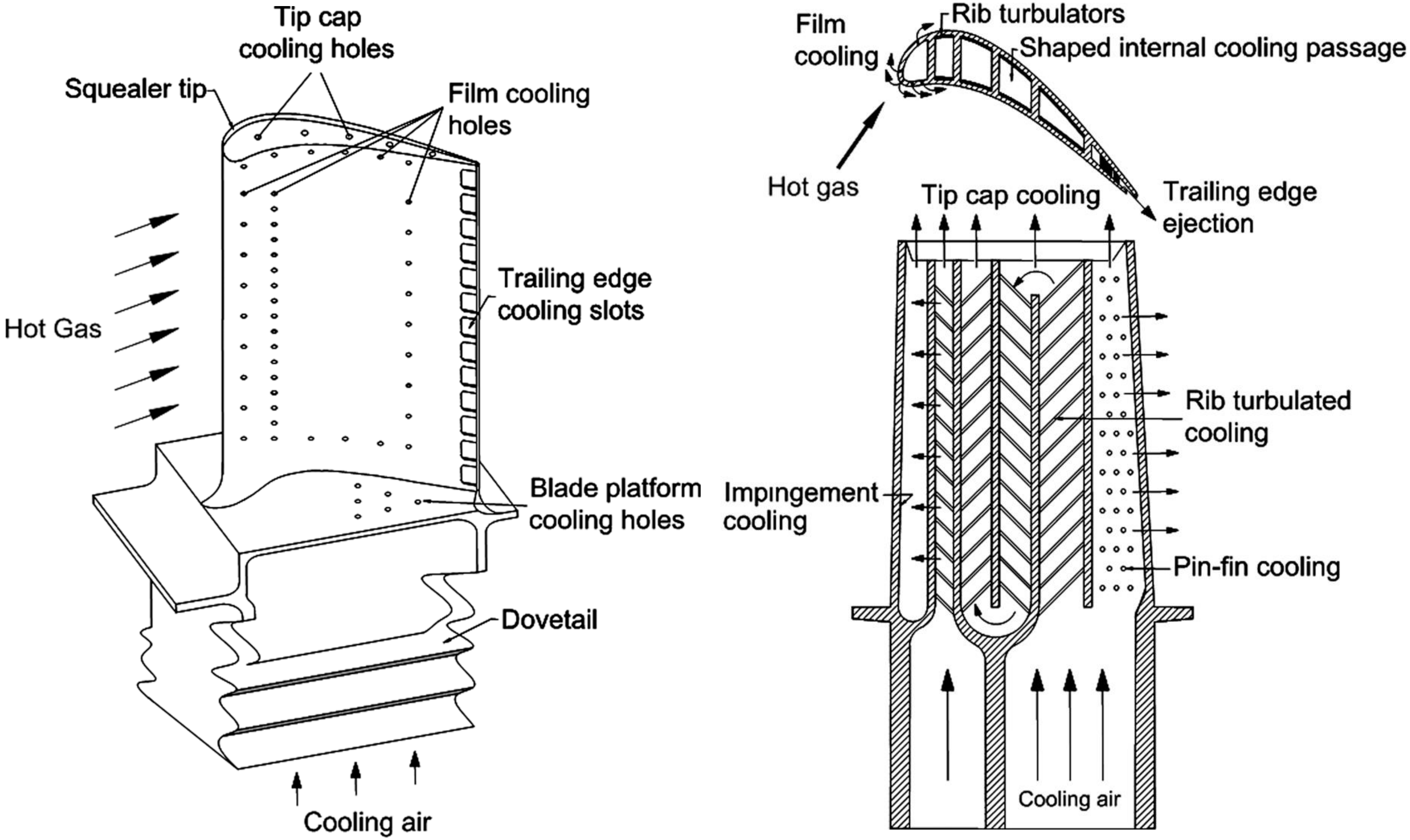
Nozzle cooling arrangement

Source: The Jet Engine, Rolls Royce, 1994



Blade cooling and sealing arrangement

Source: The Jet Engine, Rolls Royce, 1994



The schematic of a modern gas turbine blade with common cooling techniques

Source: Recent Studies in Turbine Blade Cooling, Han, Int. Journal of Rotating Machinery

Fundamentals of heat transfer

- Heat transfer by convection
  - Unlike in a solid, heat transfer in a fluid can take place through conduction as well as convection.
  - In general, the temperature and velocity fields are coupled and have strong influence on each other.
  - In modern day turbines, velocity as well as temperature gradients are high.
  - Forced convection is the dominant phenomena in turbine flows.

Fundamentals of heat transfer

- In a typical turbine blade, the boundary layer developing on the blade surface and the freestream temperature are of interest.
- The boundary layer that acts as a buffer between the solid blade and the hot freestream, offers resistance to heat transfer.
- Heat transfer occurs in this viscous layer between the blade and the fluid through both conduction and convection.
- The nature of the boundary layer (laminar or turbulent) plays an important role in the heat transfer process.

Laminar boundary layer (forced convection)

- It can be shown that the heat transfer is related to the Reynolds number and Prandtl number through the Nusselt number.

$$\mathrm{Nu}_x = 0.332(\mathrm{Re}_x)^{1/2}(\mathrm{PR})^{1/3} = \frac{C_f}{2}(\mathrm{PR})^{1/3}\,\mathrm{Re}_x$$

- Heat transfer is a function of $(\mathrm{Re}_x)^{1/2}$ and $\mathrm{PR}^{1/3}$ and C_f.
- A thin boundary layer has a larger heat transfer.
- Therefore maximum heat transfer in a turbine blade occurs near the stagnation point and the leading edge.

Turbulent boundary layer (forced convection)

For a flat plate with a turbulent boundary layer, the following equation is commonly used:

$$Nu_x = 0.029(Re_x)^{4/5} PR^{1/3}$$

A general equation for both laminar and turbulent flow analysis can be written as $Nu_x = A\,Re_x^m\,PR^n$

where, A, m and n are constants for a particular flow. This is called the Nusselt's equation.

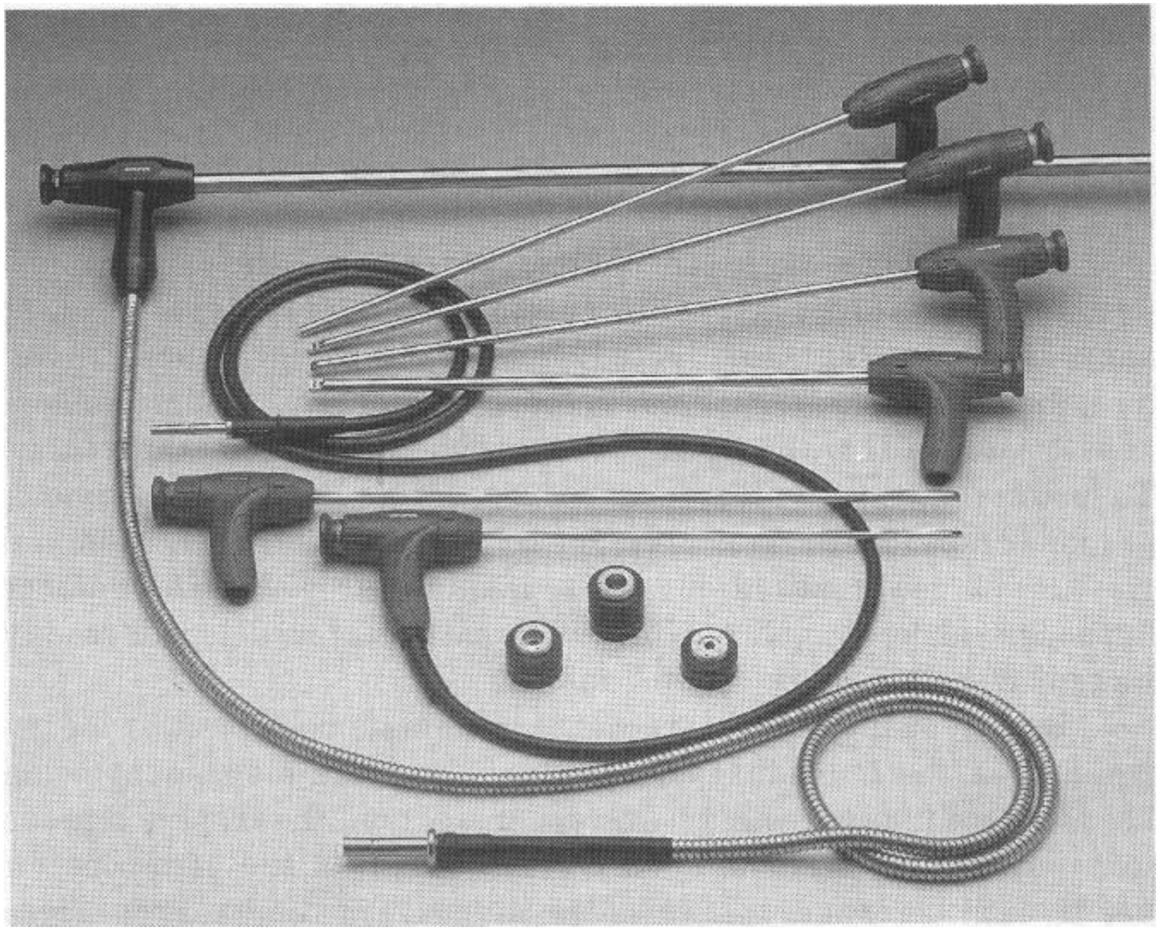
Fundamentals of heat transfer

- Based on our discussion on laminar and turbulent flows:
  - Heat transfer is higher for a thin boundary layer than a thick boundary layer as the temperature gradient is higher for a thin boundary layer.
  - Heat transfer for a turbulent boundary layer is higher than a laminar boundary layer.
  - Heat transfer in thin viscous regions like stagnation point or leading edge, is very high. The velocity and temperature gradients are extremely high in these zones.

Turbine blade cooling

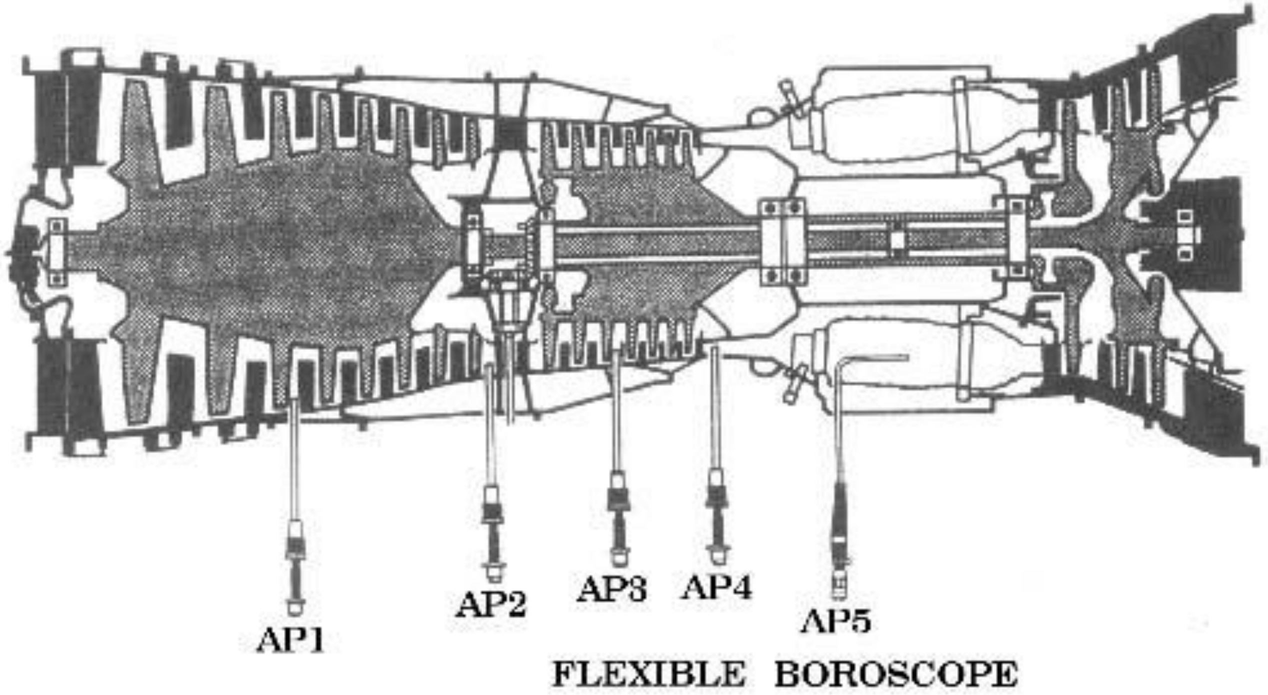
- In order to decide the cooling methodology to be used in a turbine blade, a very strong understanding of the heat transfer mechanisms are essential.
- Turbine blade cooling requires significant amount of compressor air (as high as 20%).
- The cooling air also mixes with the turbine flow leading to losses.
- Due to the above, vigorous analysis is carried out to minimize the amount of cooling as well as the negative aerodynamic effects of cooling.

Inspection and damage assessment



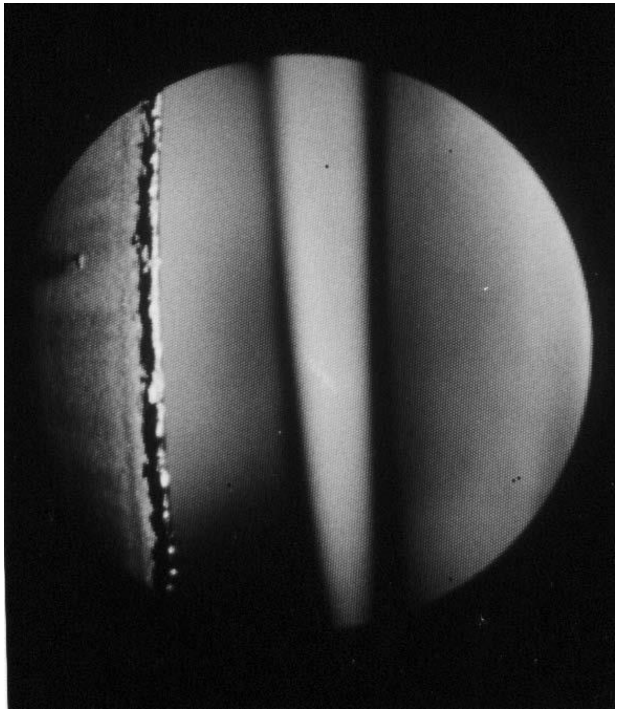
Boroscope for inspection of gas turbine interior

From: Gas Turbine Handbook: Giampaolo, 3rd Ed

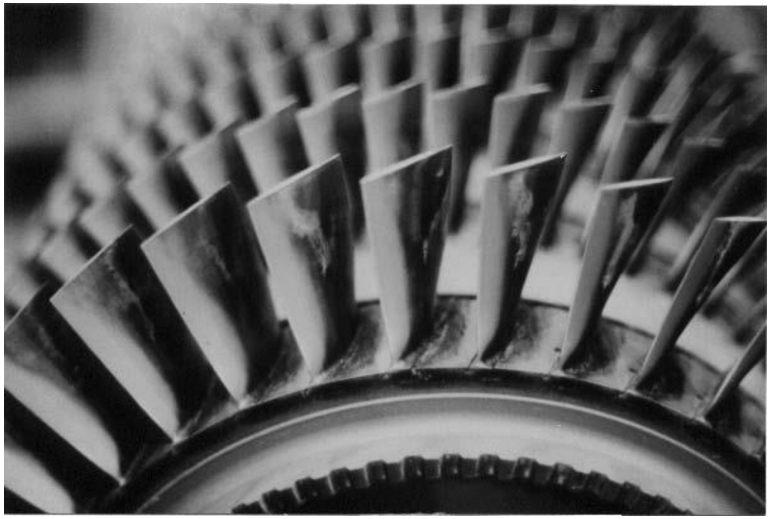


Gas turbine with the location of boroscope ports indicated

From: Gas Turbine Handbook: Giampaolo, 3rd Ed

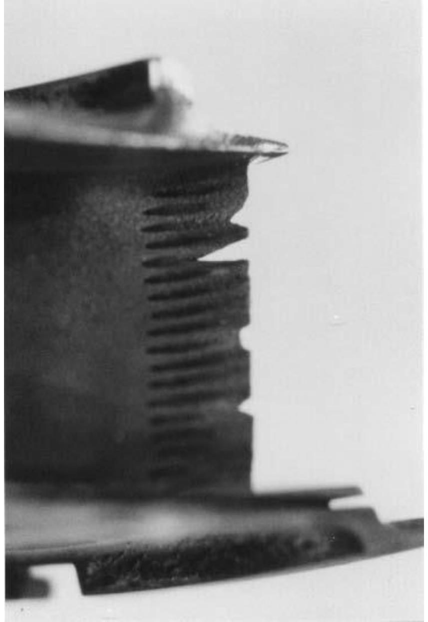


Tar-like deposit on a first stage compressor blade LE after 1,000 hours operation

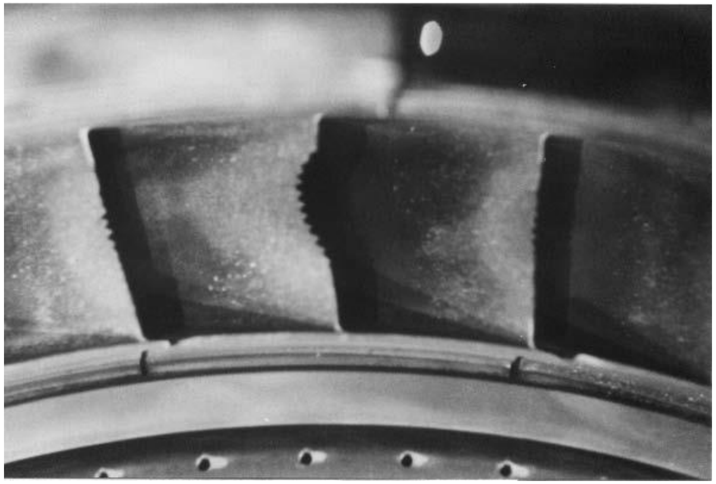


Carbon deposits distributed across the compressor blades after 16000 hours of operation

From: Gas Turbine Handbook: Giampaolo, 3rd Ed

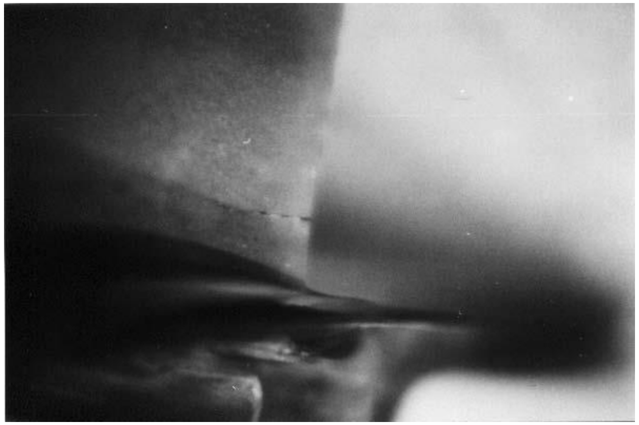


Cracked, burnt, eroded, and corroded first stage turbine nozzle concave trailing edge surface (17000 hrs of operation)



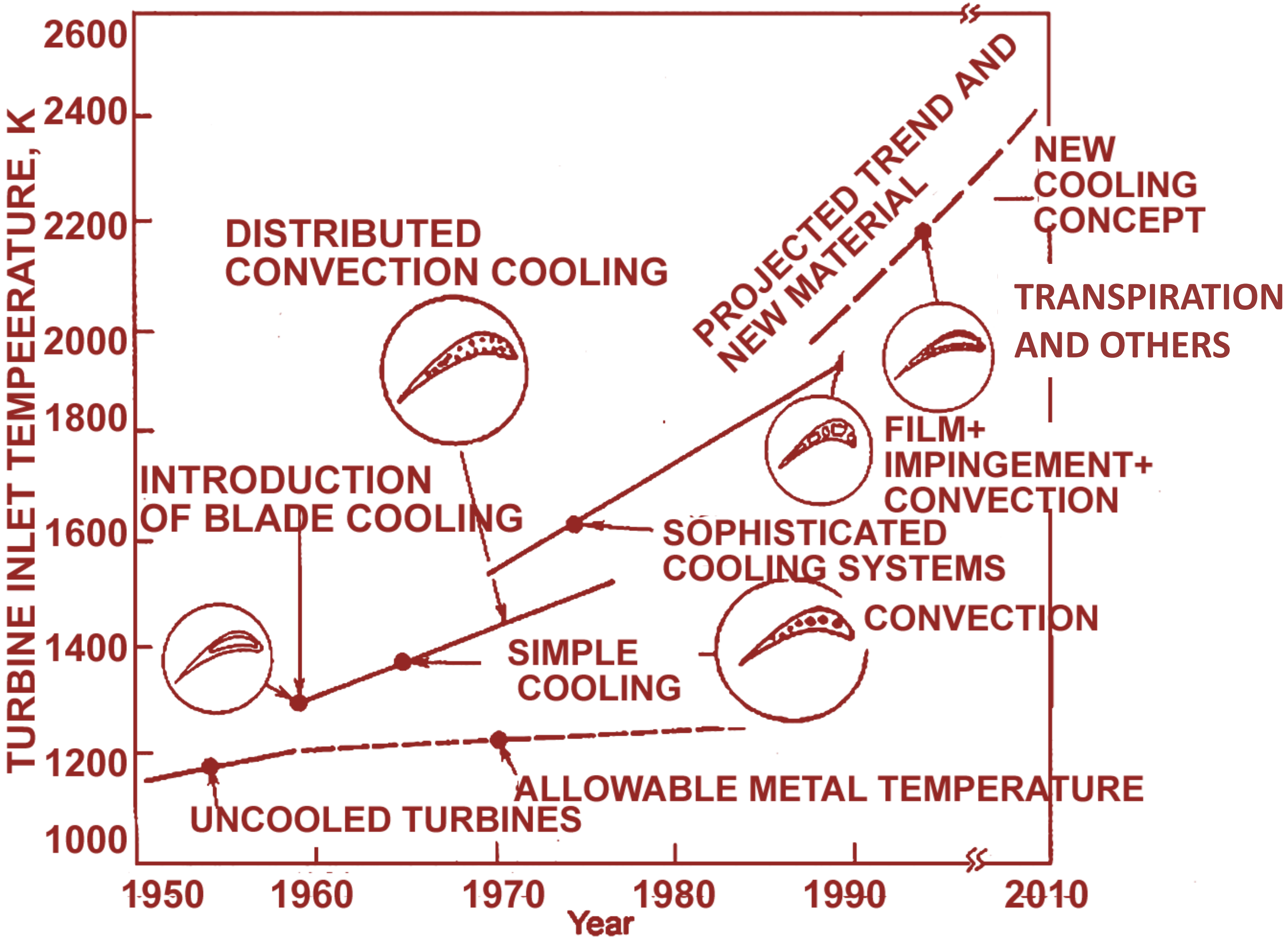
Burnt and eroded trailing edges of first stage turbine nozzles after 44,500 hours operation.

From: Gas Turbine Handbook: Giampaolo, 3rd Ed



Trailing edge crack in the first stage turbine nozzle trailing edge.

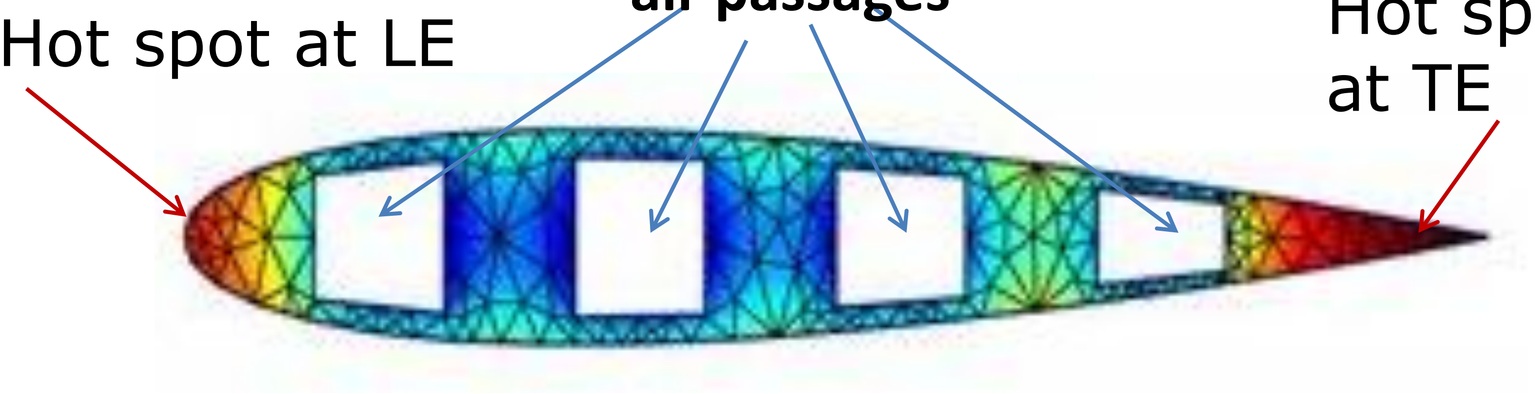
From: Gas Turbine Handbook: Giampaolo, 3rd Ed


TURBINE INLET TEMPEERATURE, K
2600
2400
2200
2000
1800
1600
1400
1200
1000
1950
1960
1970
1980
1990
2010
Year
DISTRIBUTED CONVECTION COOLING
PROJECTED TREND AND NEW MATERIAL
NEW COOLING CONCEPT
TRANSPIRATION AND OTHERS
FILM+ IMPINGEMENT+ CONVECTION
INTRODUCTION OF BLADE COOLING
SOPHISTICATED COOLING SYSTEMS
CONVECTION
SIMPLE COOLING
ALLOWABLE METAL TEMPERATURE
UNCOOLED TURBINES

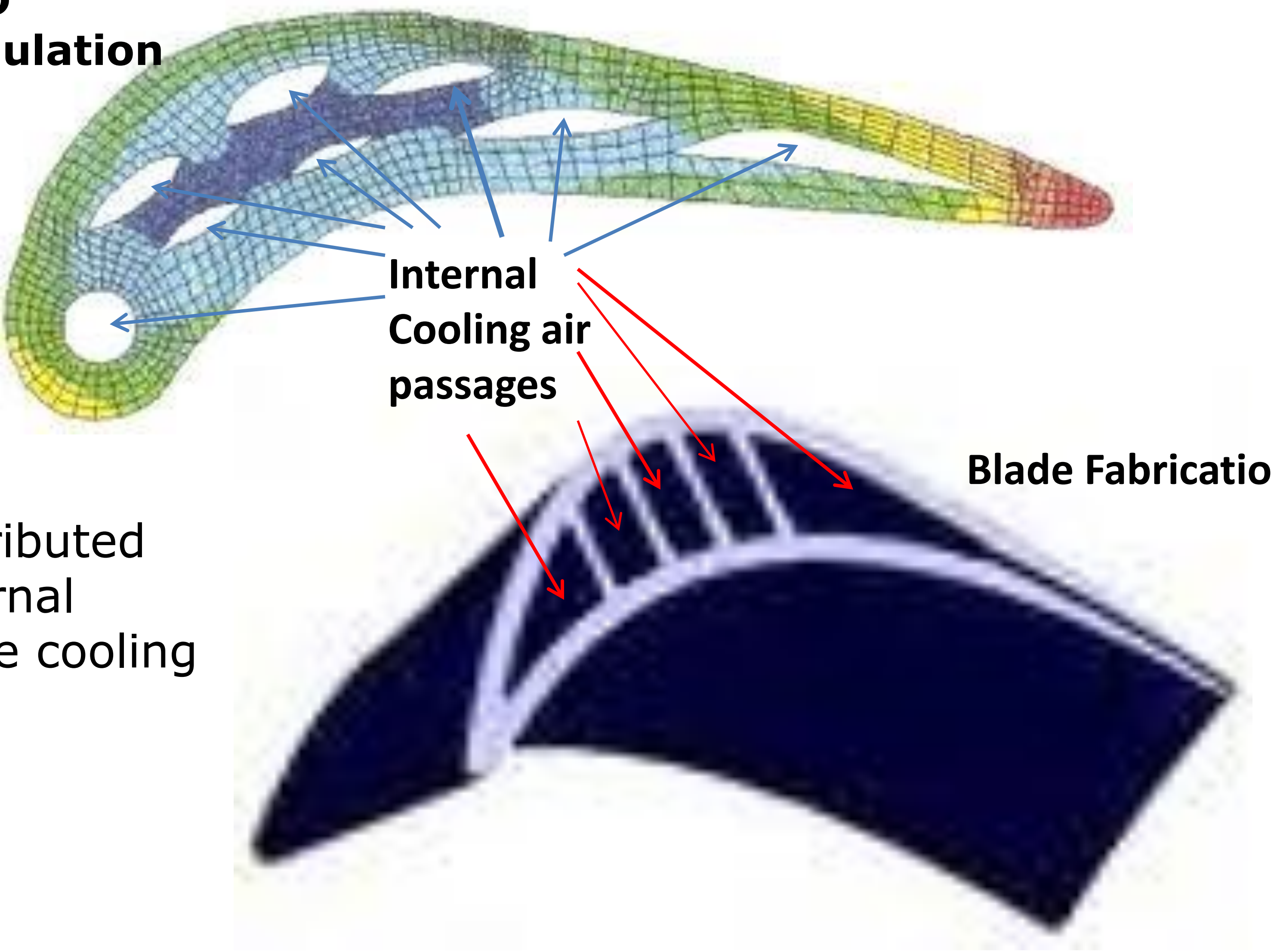
Internal Cooling air passages

Hot spot at LE

Hot spot at TE



Large temperature gradient along the chord



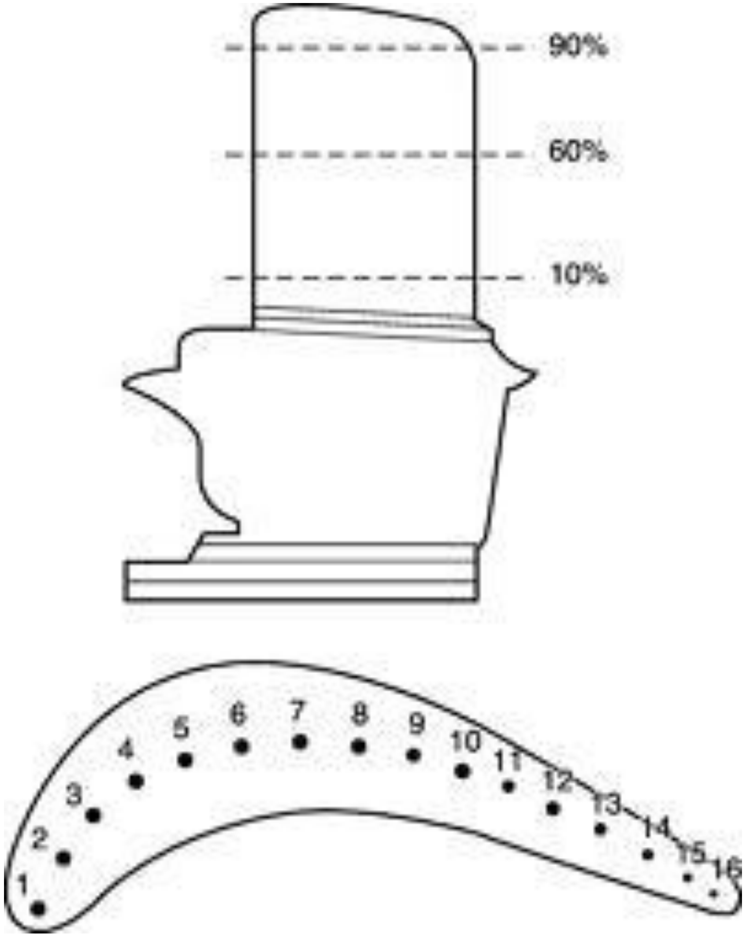
CFD simulation

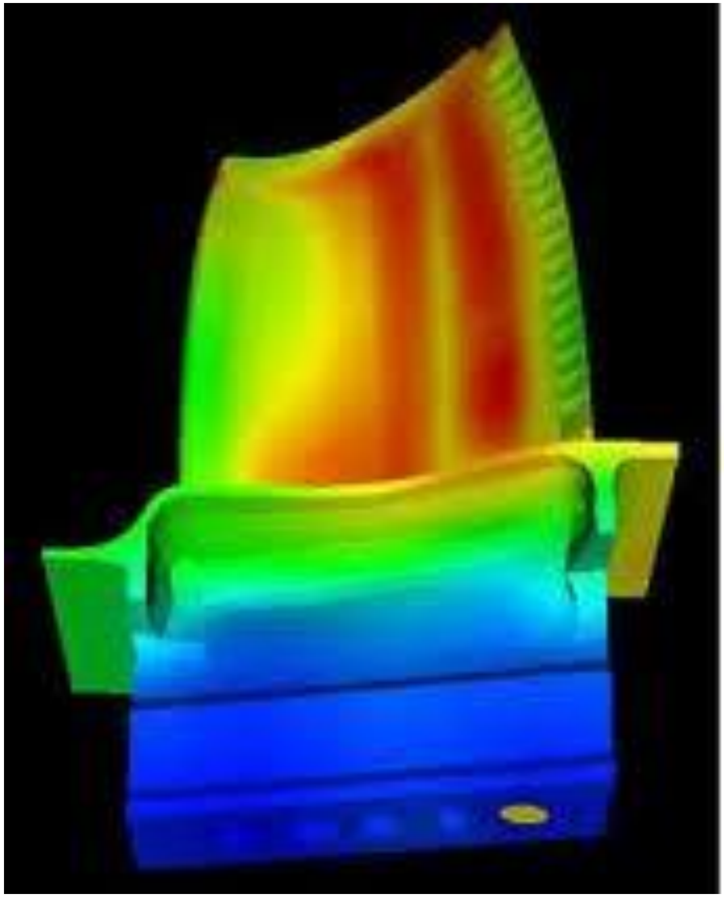
Internal Cooling air passages

Blade Fabrication

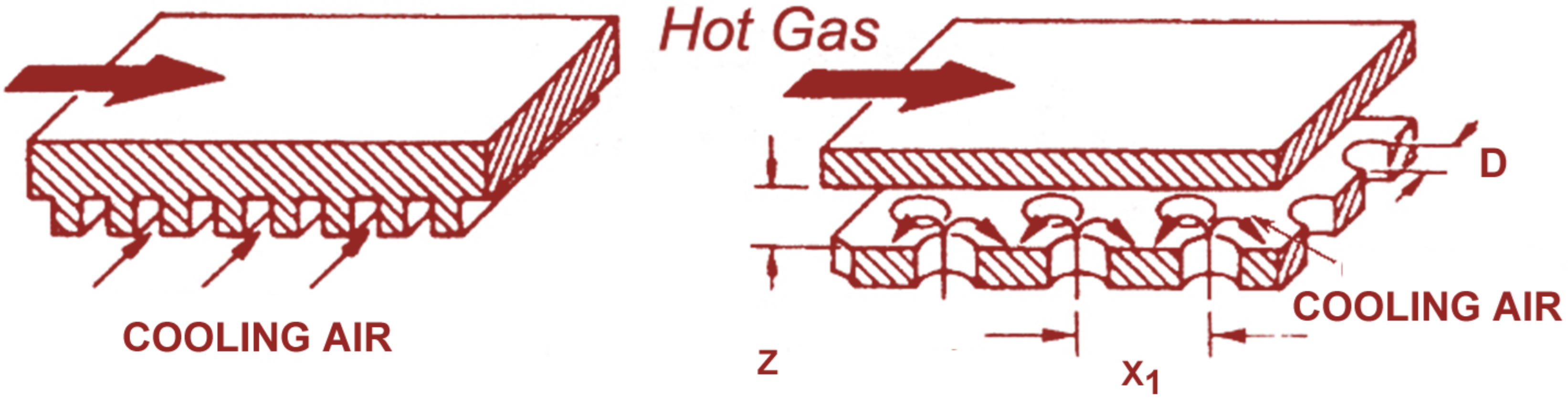
Distributed Internal Blade cooling

- Blade temperature may vary along the blade surface from LE to TE by 200 to 300 K
- Blade temperature may also vary from the root to the tip of a rotor
- Maximum blade temperature is felt at the LE of the first stator – as the flow comes from the combustor.
- HP turbine blades have maximum temperature and maximum temperature gradient across both the rotor and the stator
- Blades are thermally loaded in cycles of operation
- Turbine failure occurs mostly in creep (thermal fatigue)

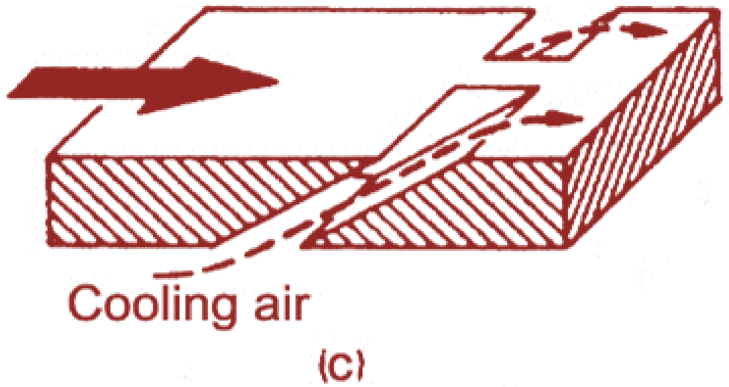




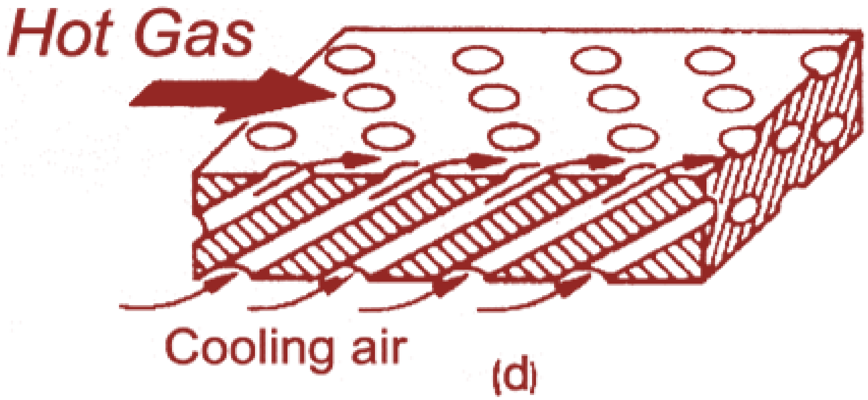
Turbine blade internal temperatures captured : ref : ONERA, France



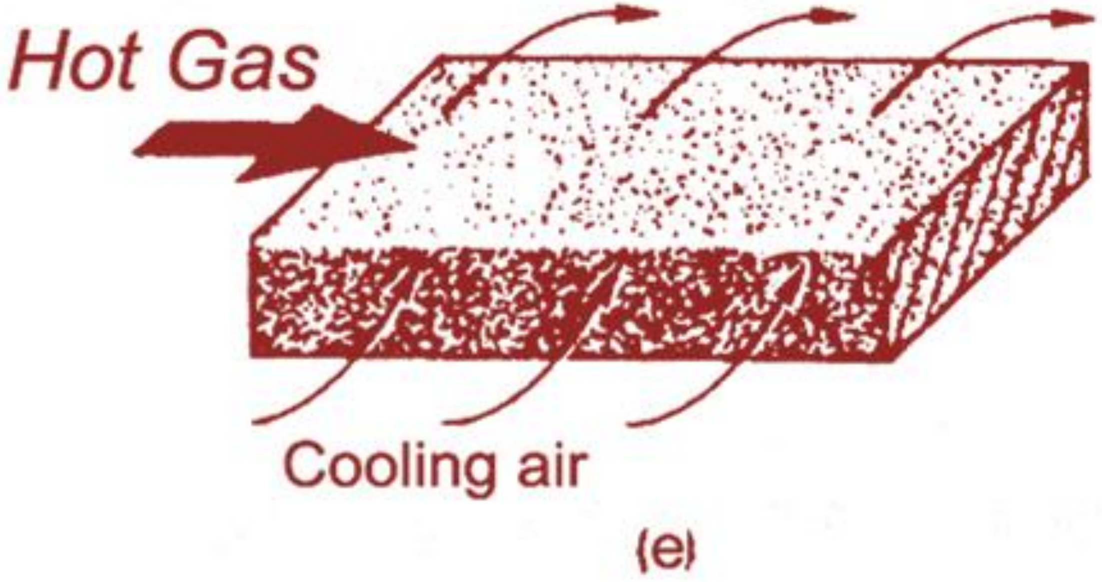
(a) Internal convection cooling (b) Internal impingement cooling



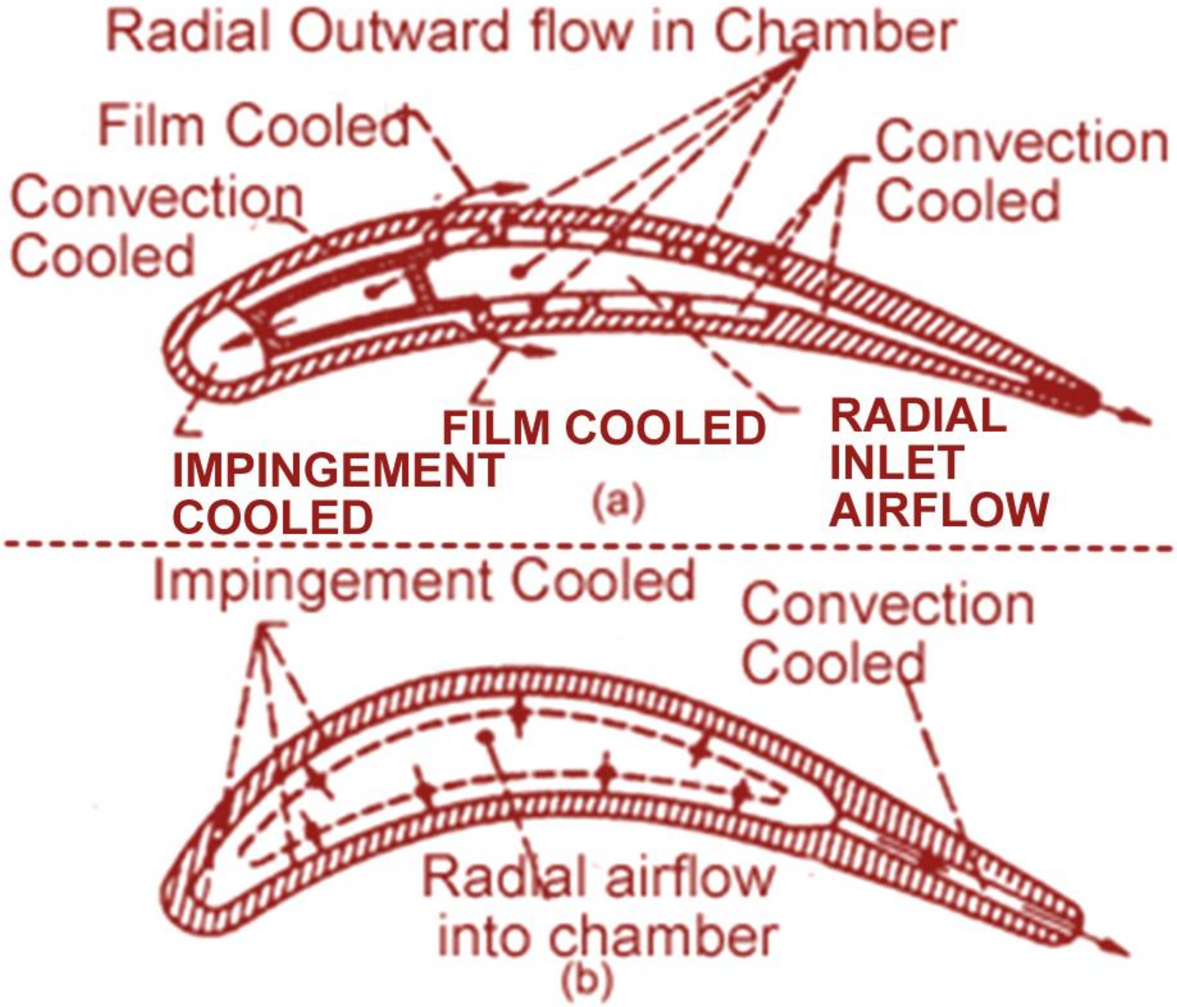
(c) Discrete film cooling



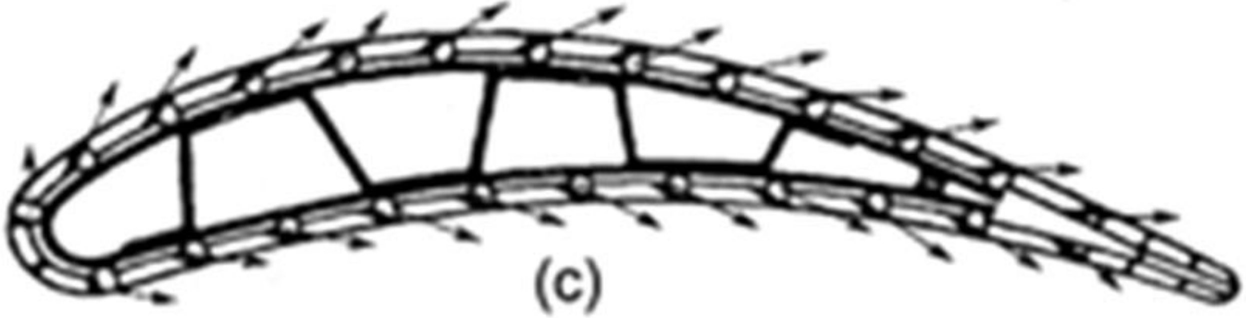
(d) Full blade film cooling



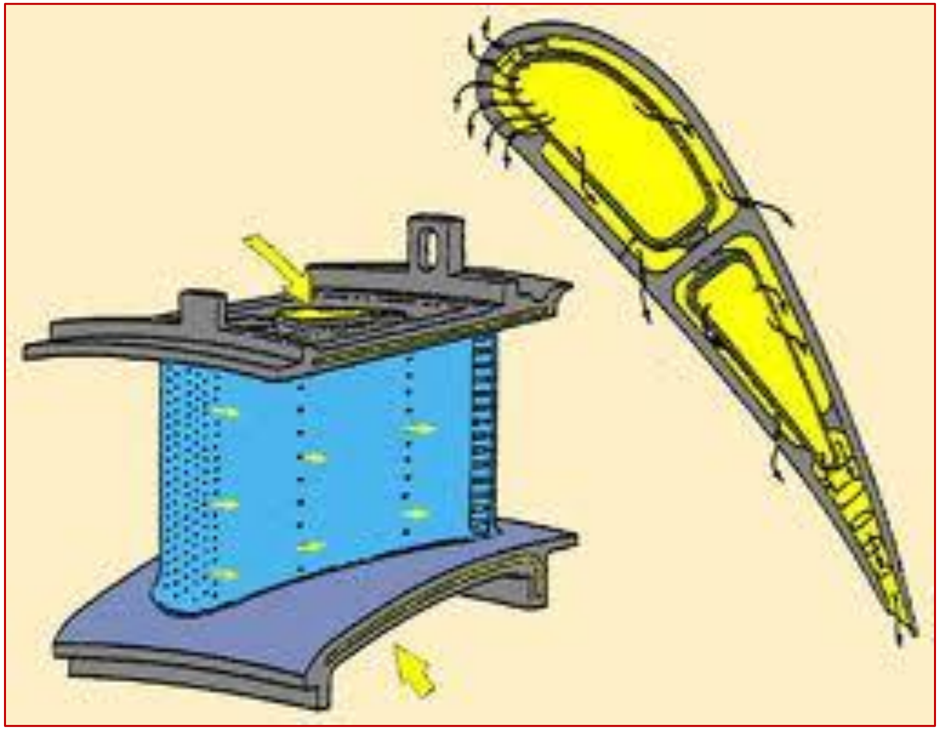
(e) Full blade transpiration cooling (porous blade)

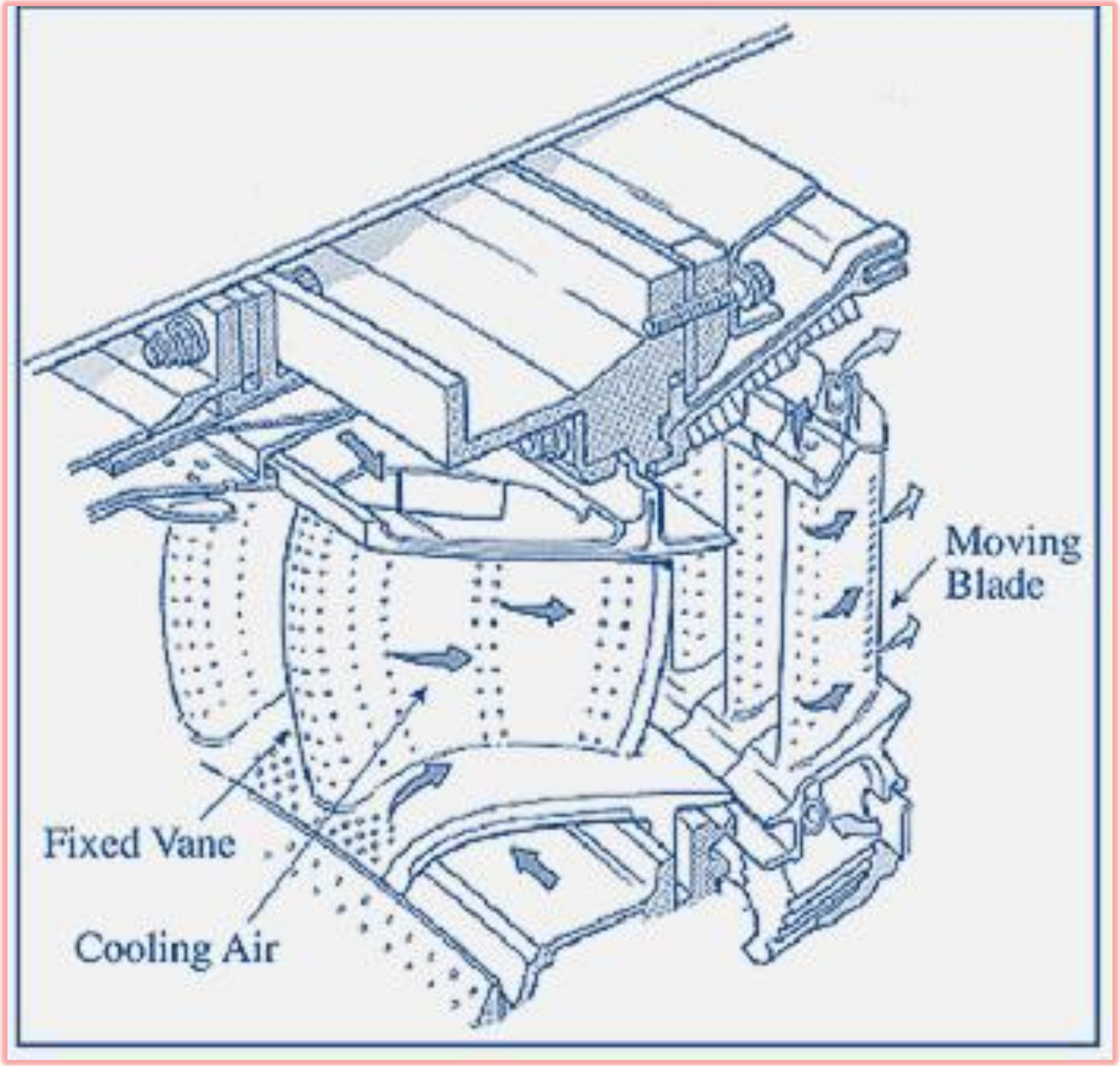

Radial Outward flow in Chamber
Film Cooled
Convection Cooled
Convection Cooled
FILM COOLED
IMPINGEMENT COOLED
RADIAL INLET AIRFLOW
(a)
Impingement Cooled
Convection Cooled
Radial airflow into chamber
(b)

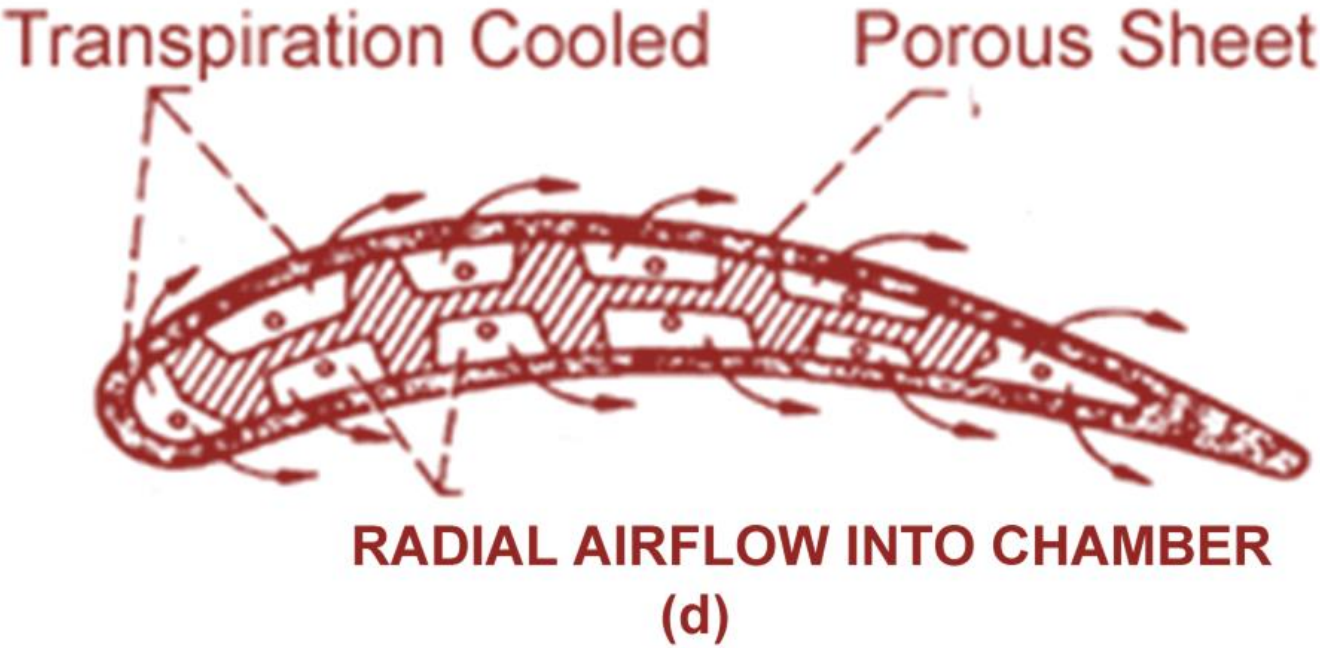
c) Full blade film cooled



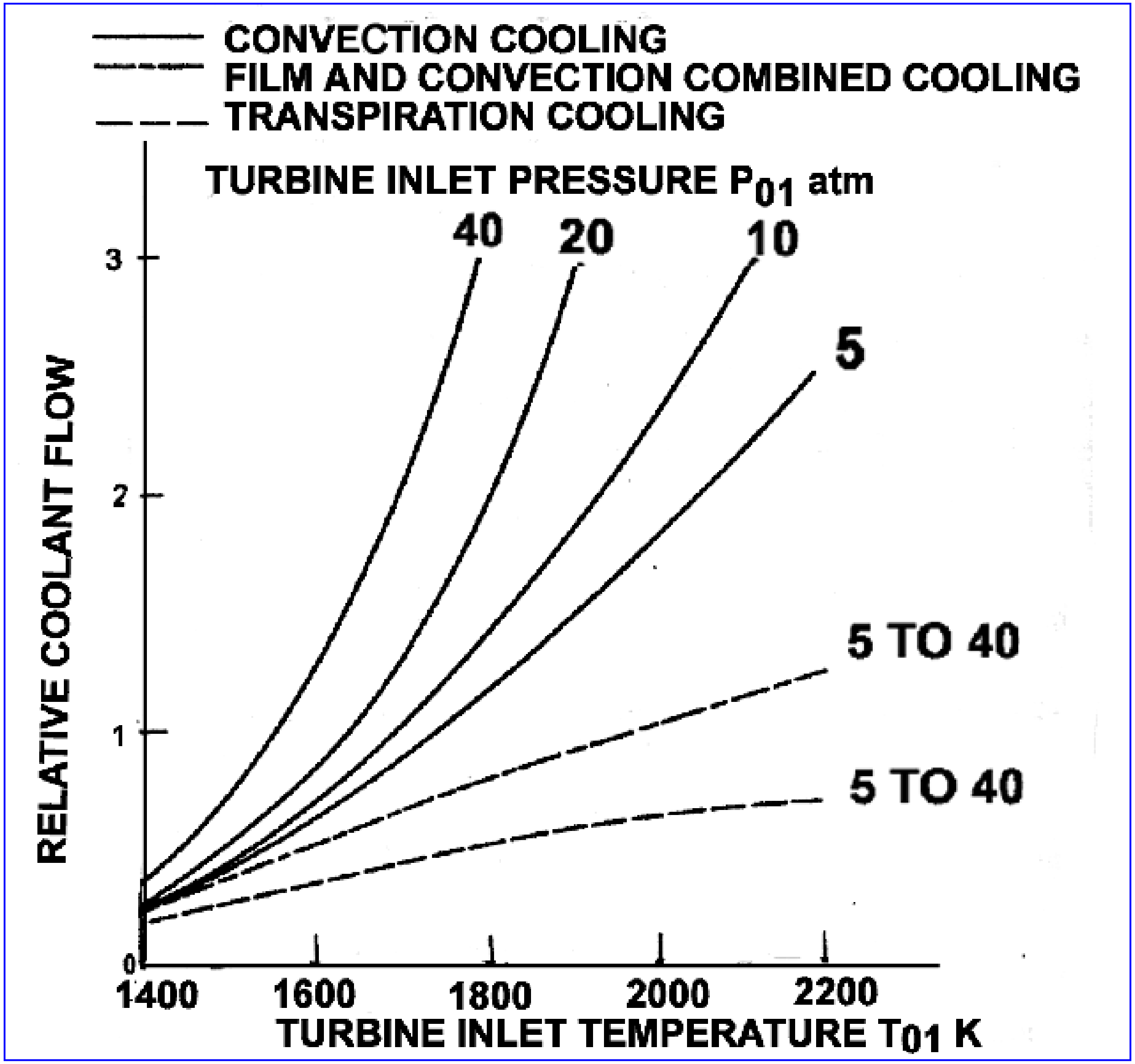
(c)



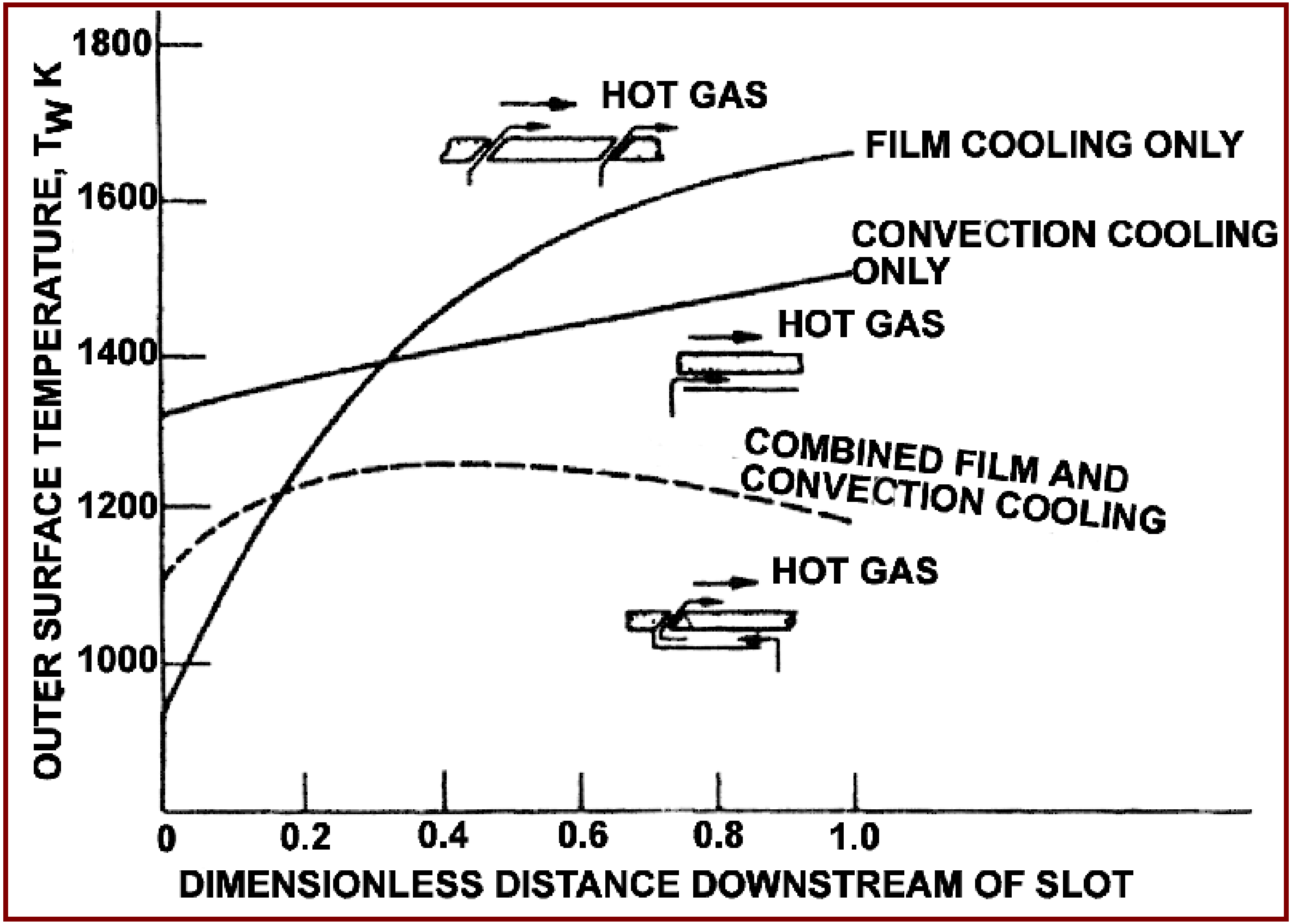

Moving
Blade
Fixed Vane
Cooling Air

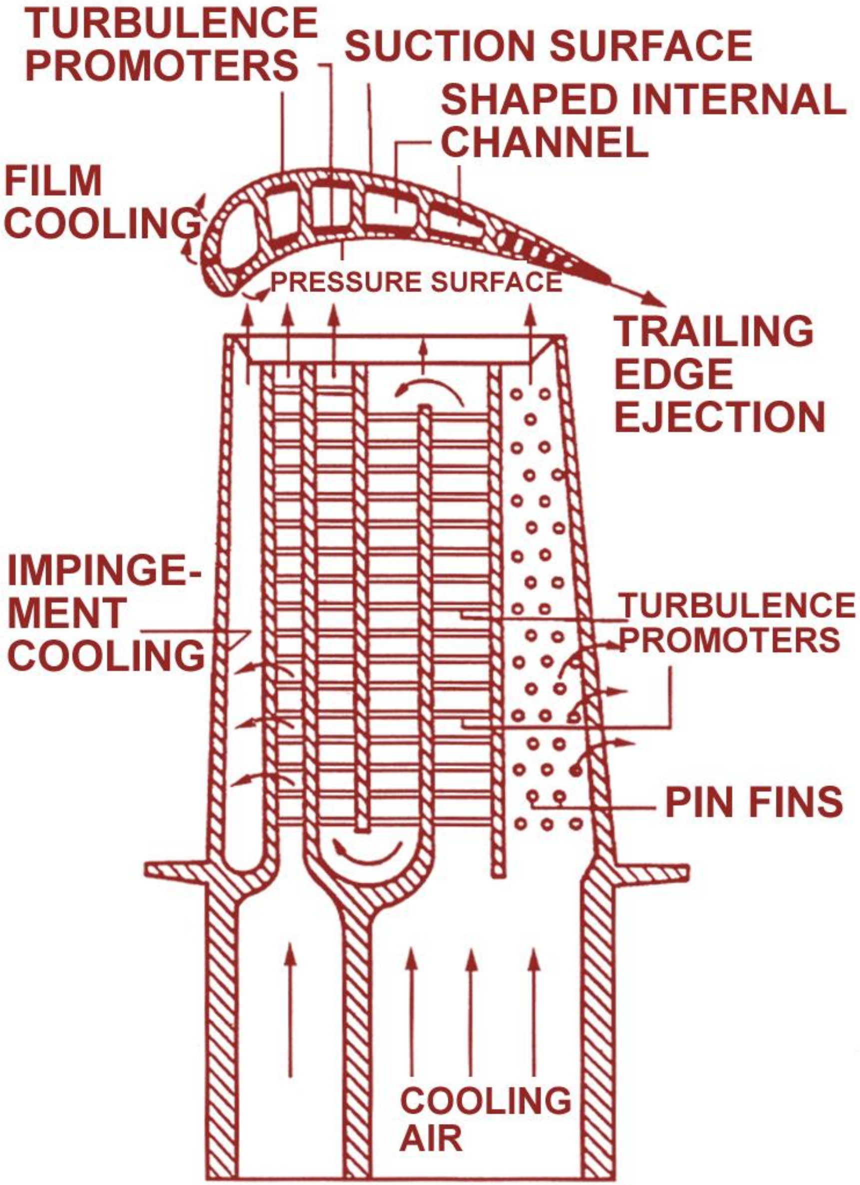


d) Transpiration cooled

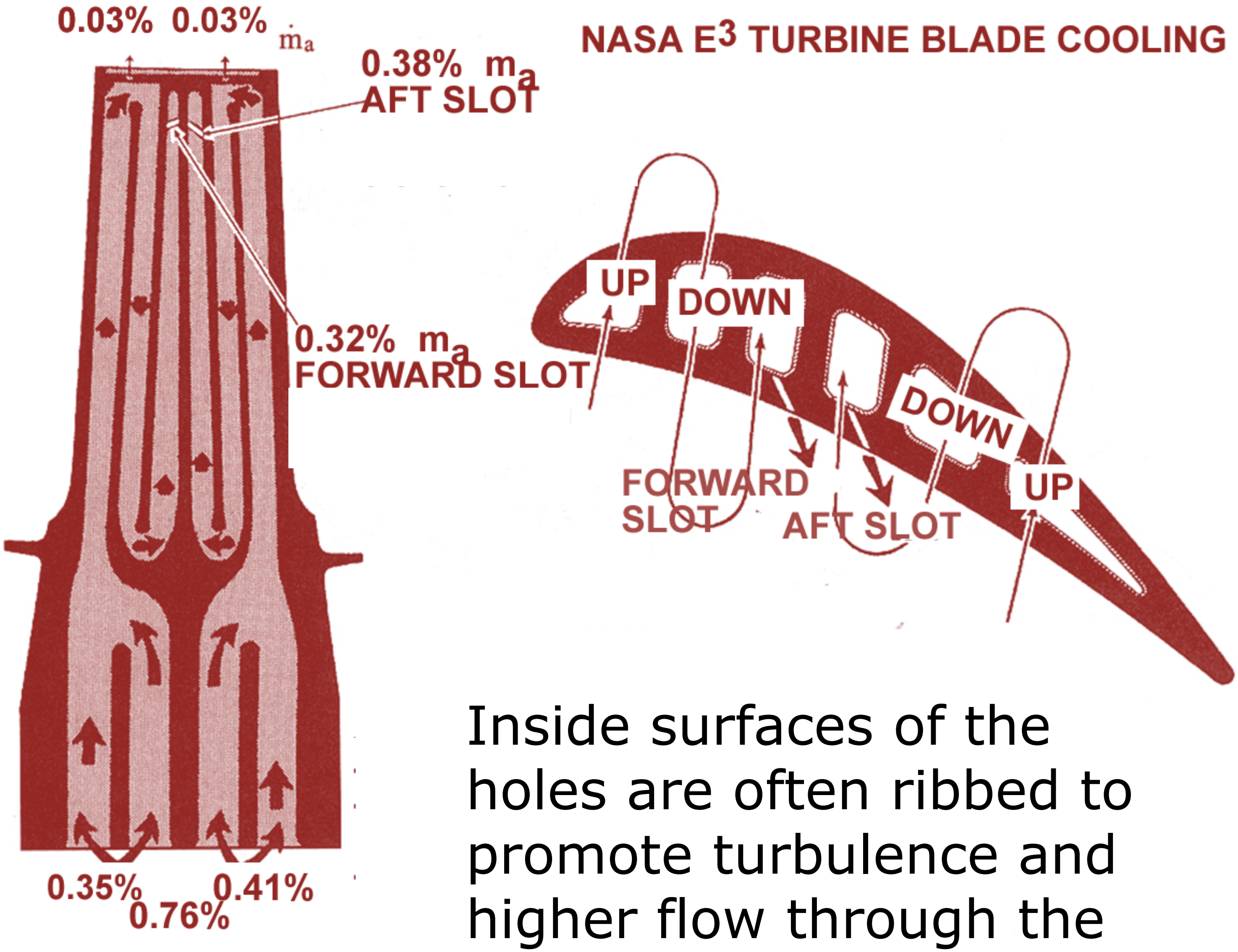


Advanced cooling has extended both TIT and Compression ratio

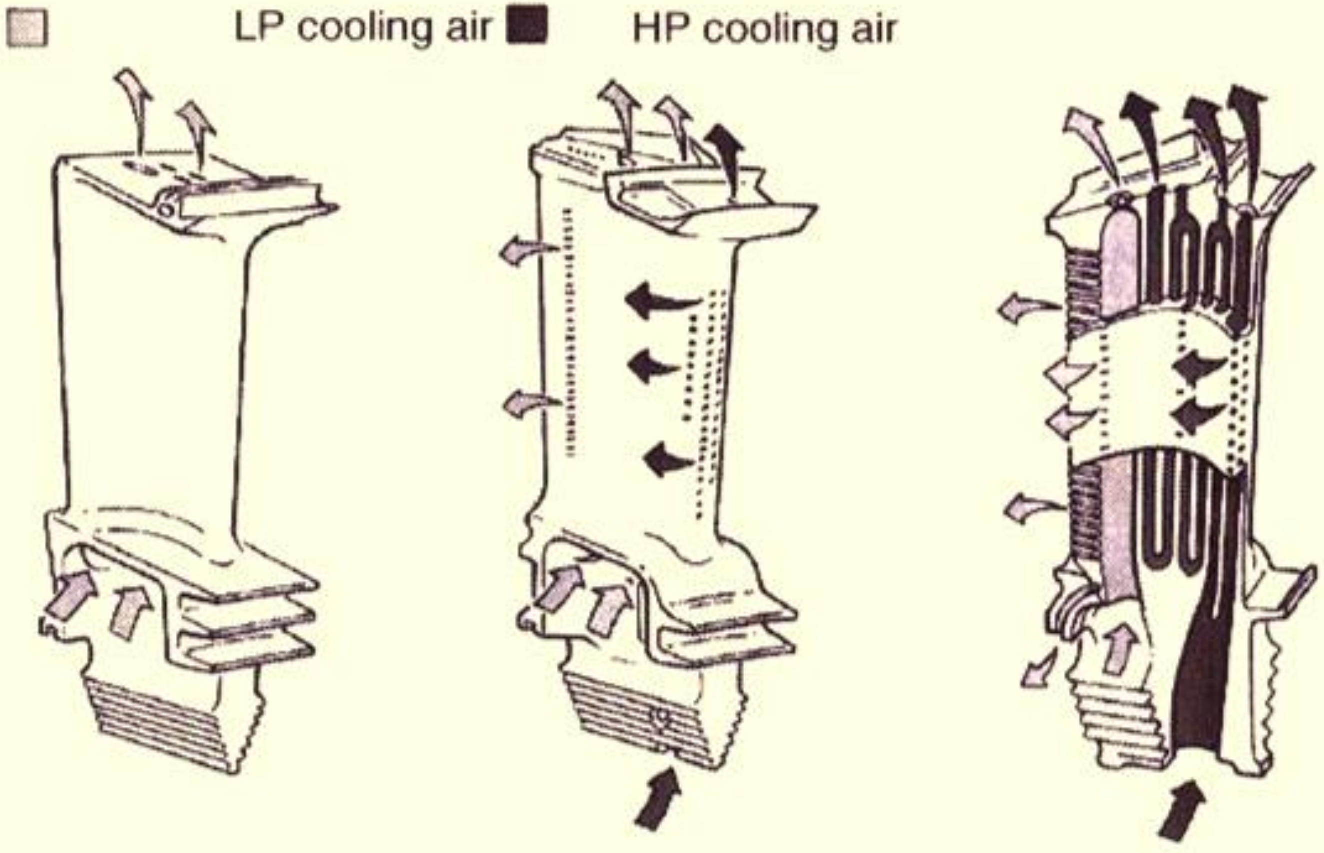

1800
1600
1400
1200
1000
OUTER SURFACE TEMPERATURE, T_W K
HOT GAS
FILM COOLING ONLY
CONVECTION COOLING ONLY
HOT GAS
COMBINED FILM AND CONVECTION COOLING
HOT GAS
0
0.2
0.4
0.6
0.8
1.0
DIMENSIONLESS DISTANCE DOWNSTREAM OF SLOT


TURBULENCE PROMOTERS
SUCTION SURFACE
SHAPED INTERNAL CHANNEL
FILM COOLING
PRESSURE SURFACE
TRAILING EDGE EJECTION
IMPINGE-MENT COOLING
TURBULENCE PROMOTERS
PIN FINS
COOLING AIR

NASA E^3 TURBINE BLADE COOLING



Inside surfaces of the holes are often ribbed to promote turbulence and higher flow through the internal holes

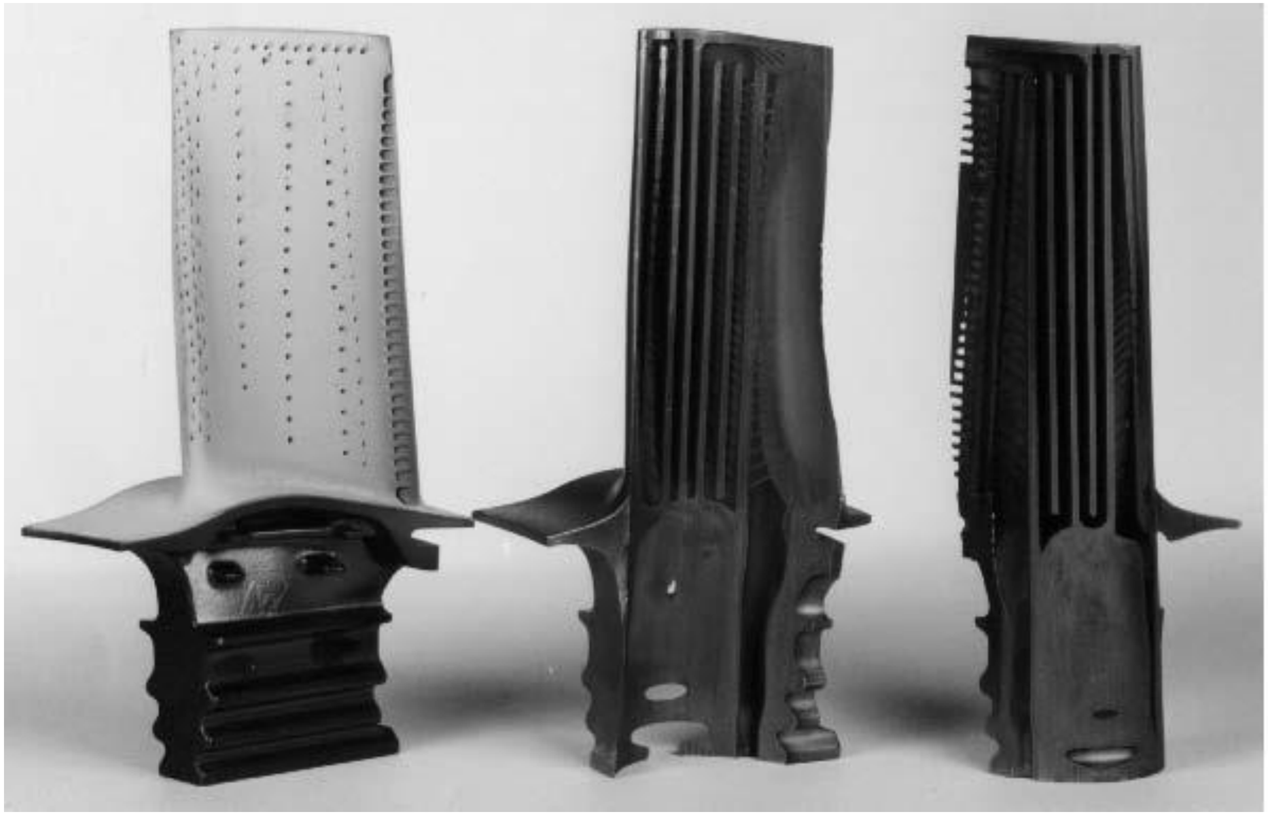


Convection
Single pass
(1960)

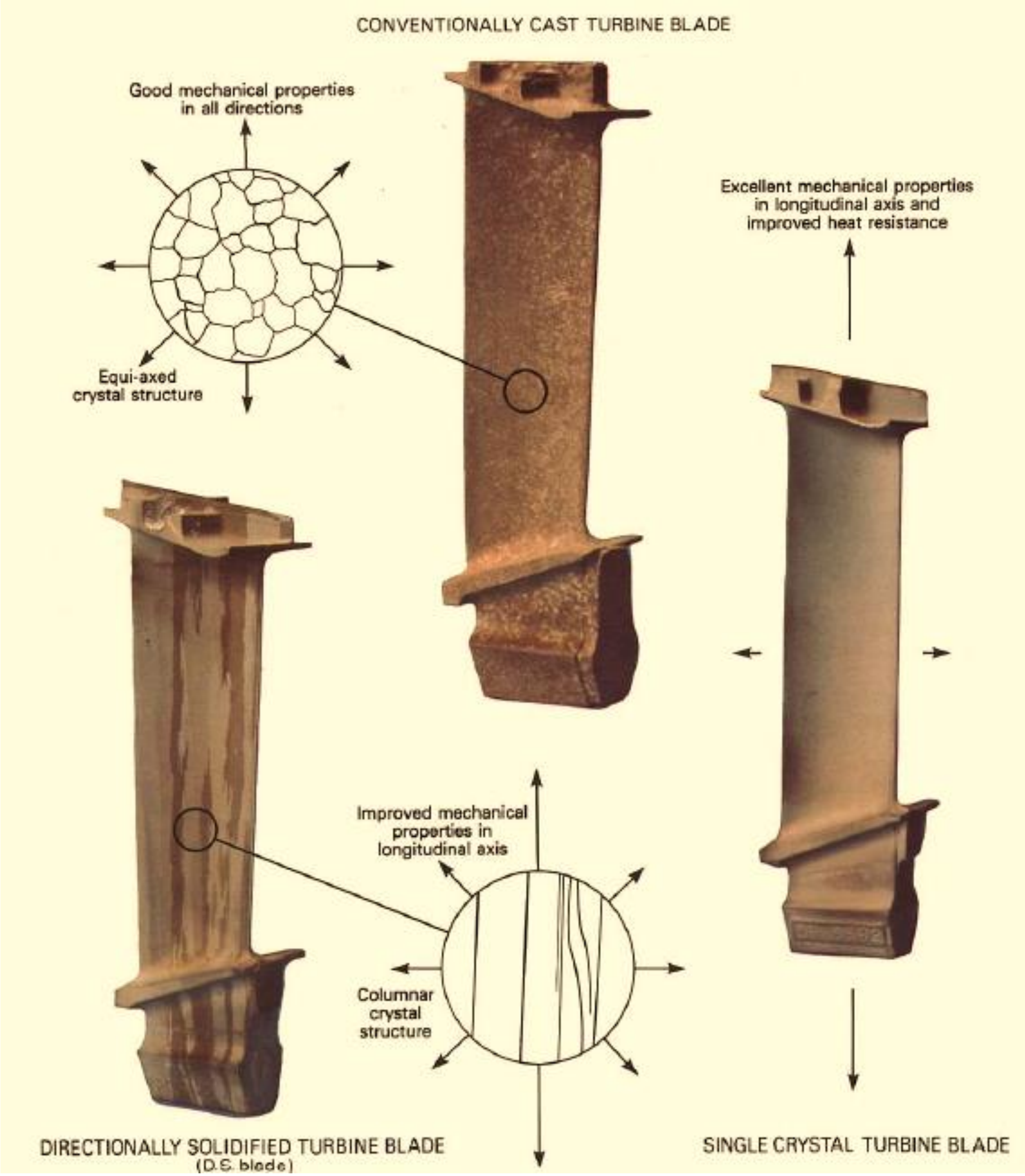
Convection (single pass-
multiple feed) and film
(1970)

Convection (Quintuple pass-
multifeed) and film cooling

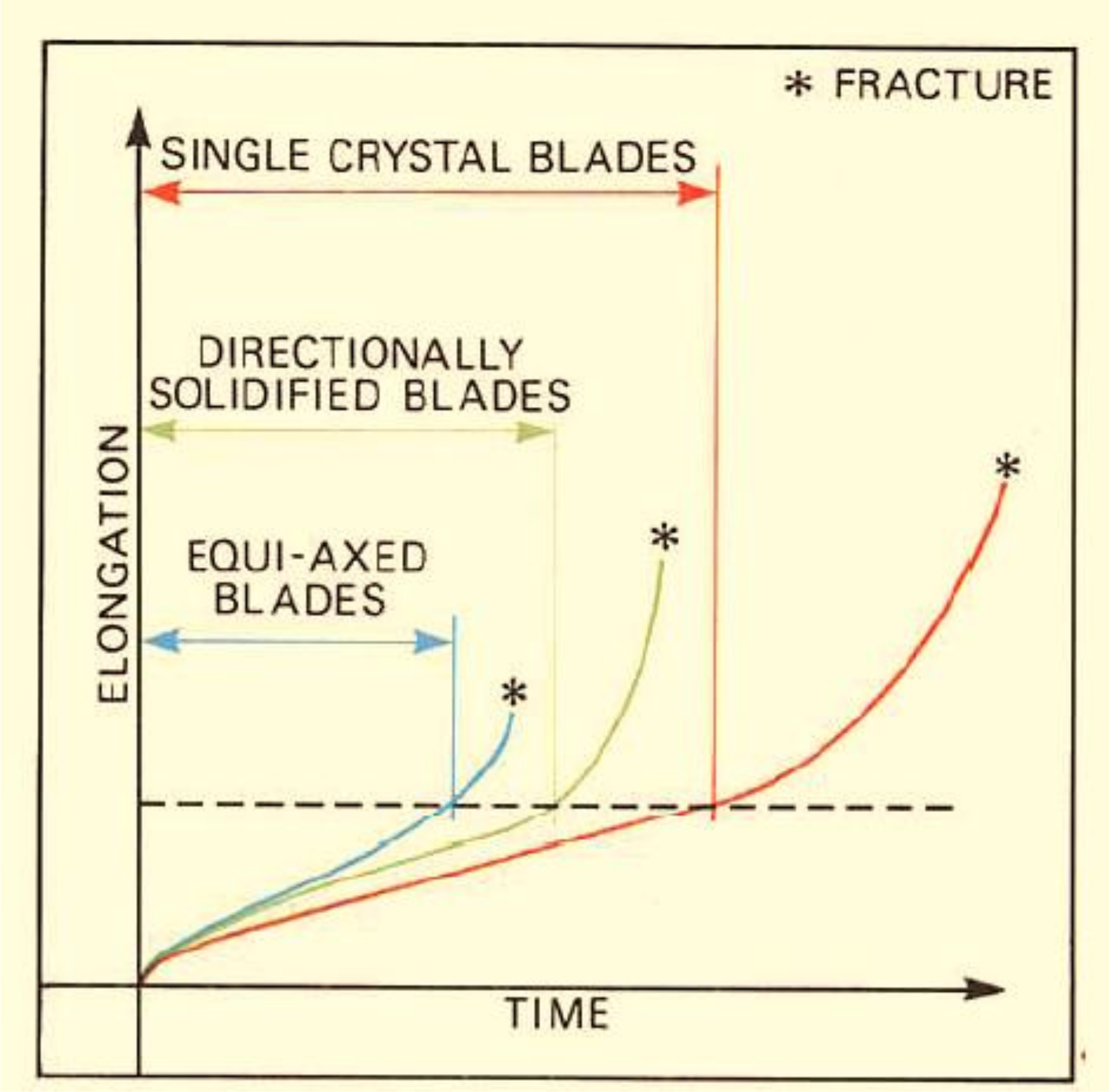
HP turbine blade cooling



HP turbine blade cooling



Source: The Jet Engine, Rolls Royce, 1994



Comparison of blade life

Source: The Jet Engine, Rolls Royce, 1994