)8th Israeli Symposium on Jet Engine and Gas Turbine

Technion, Haifa, November 19, 2009

“Turbine Cooling and Transient Tip Clearance Control: Development Experience”

Boris Glezer, Optimized Turbine Solutions, San Diego, USA

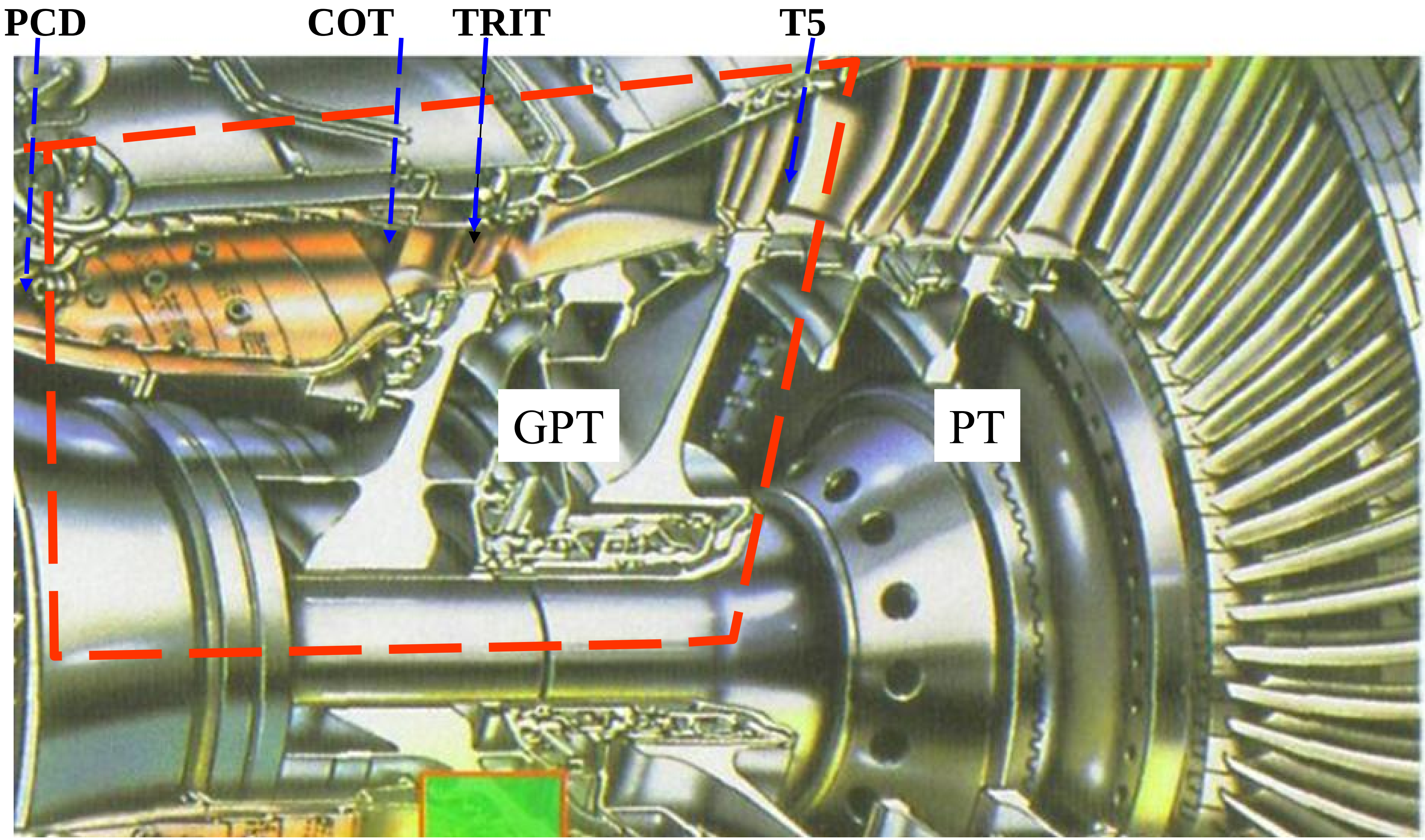
SUBJECTS OF DISCUSSION

Introduction: Design Constraints for Engine Hot Section Components

1. **Engine Cooling Requirements, Cooling Techniques and Means of Reducing Associated Performance Penalties**

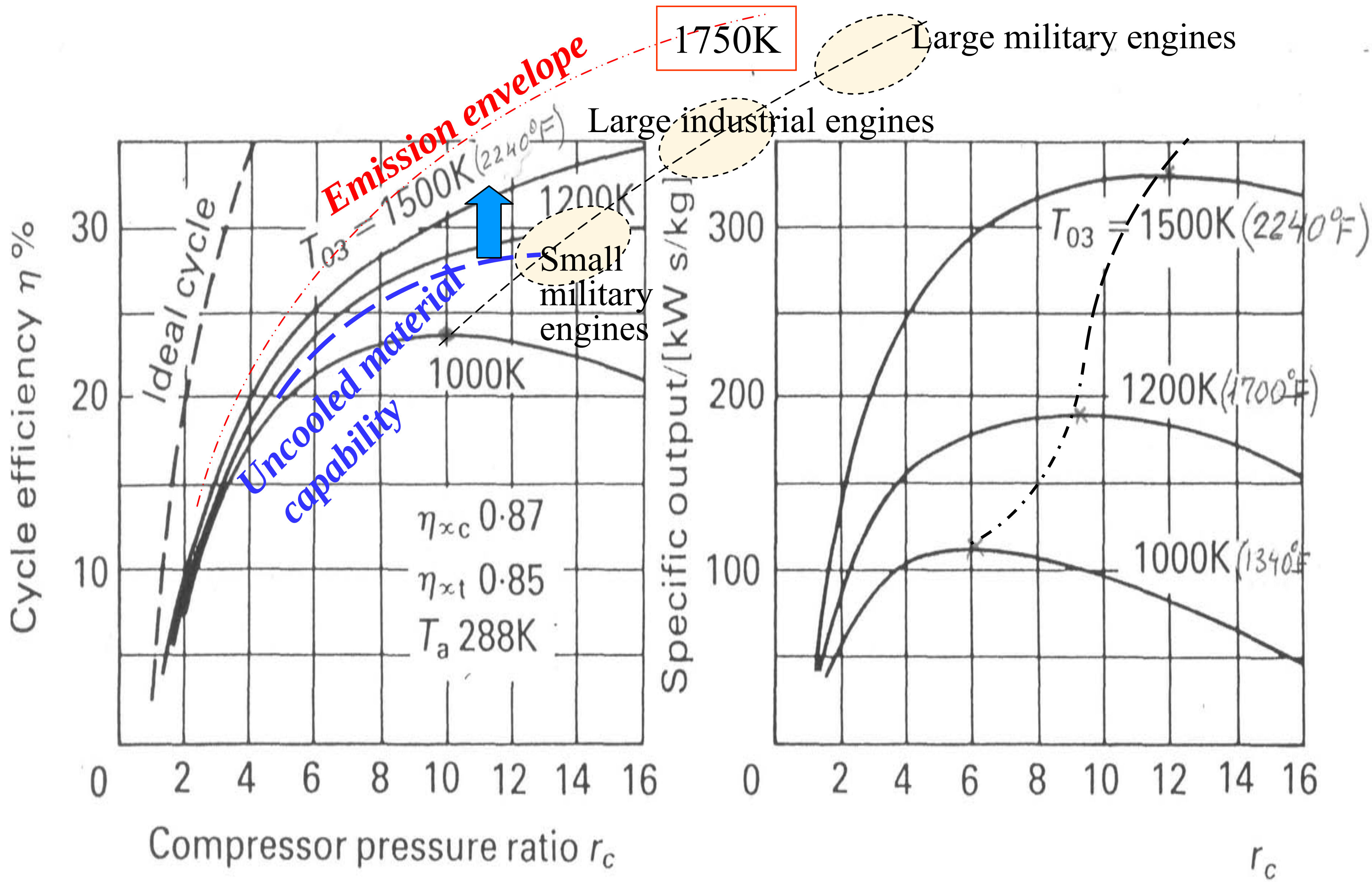
2. **Engine Transient Thermal Behavior and Turbine Blade Tip Clearance Control**

3. **Uncertainty of Numerical Predictions and Experimental Validation Practices**

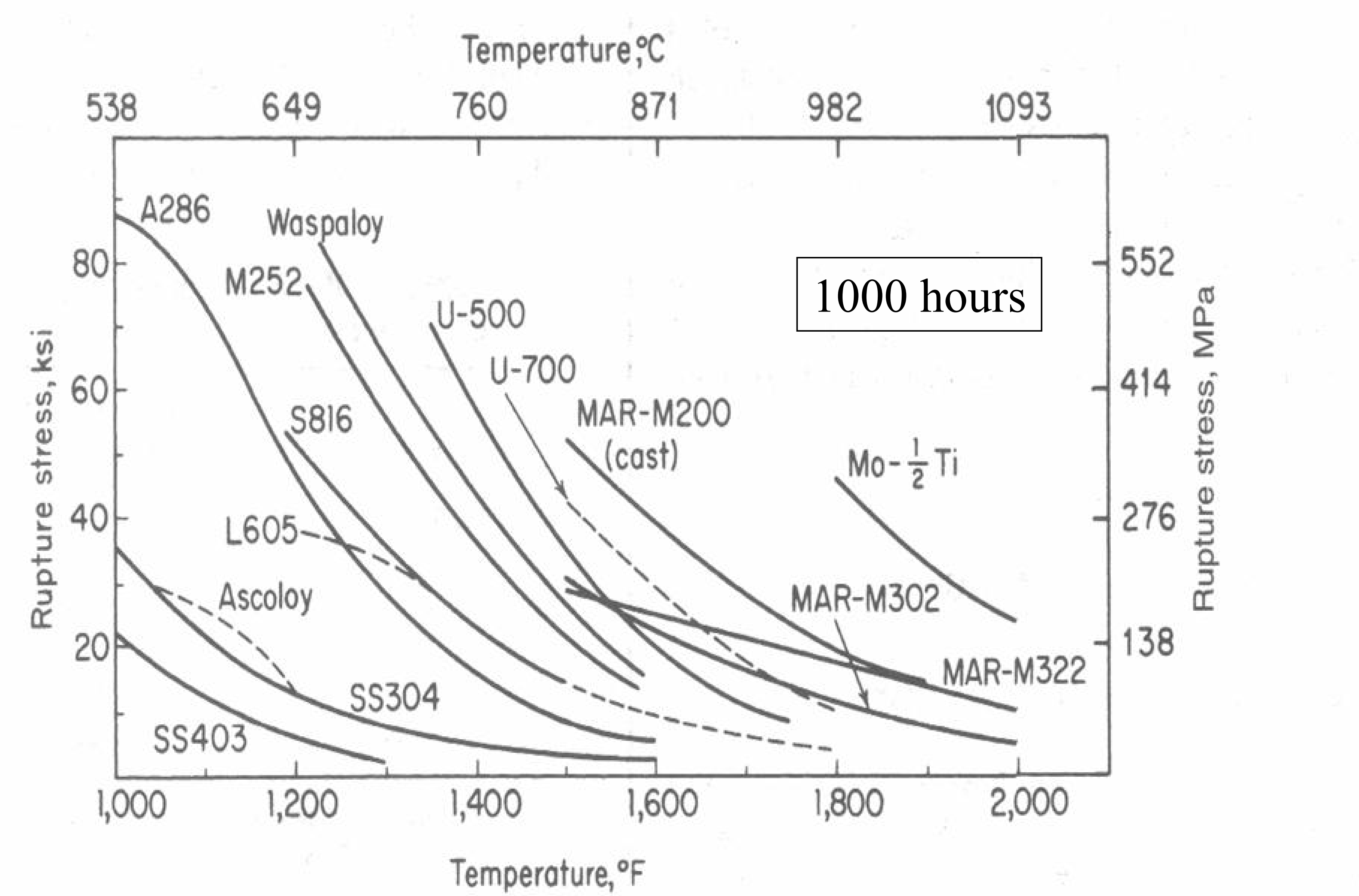


Modern Turbine Hot Section for Aeroengine

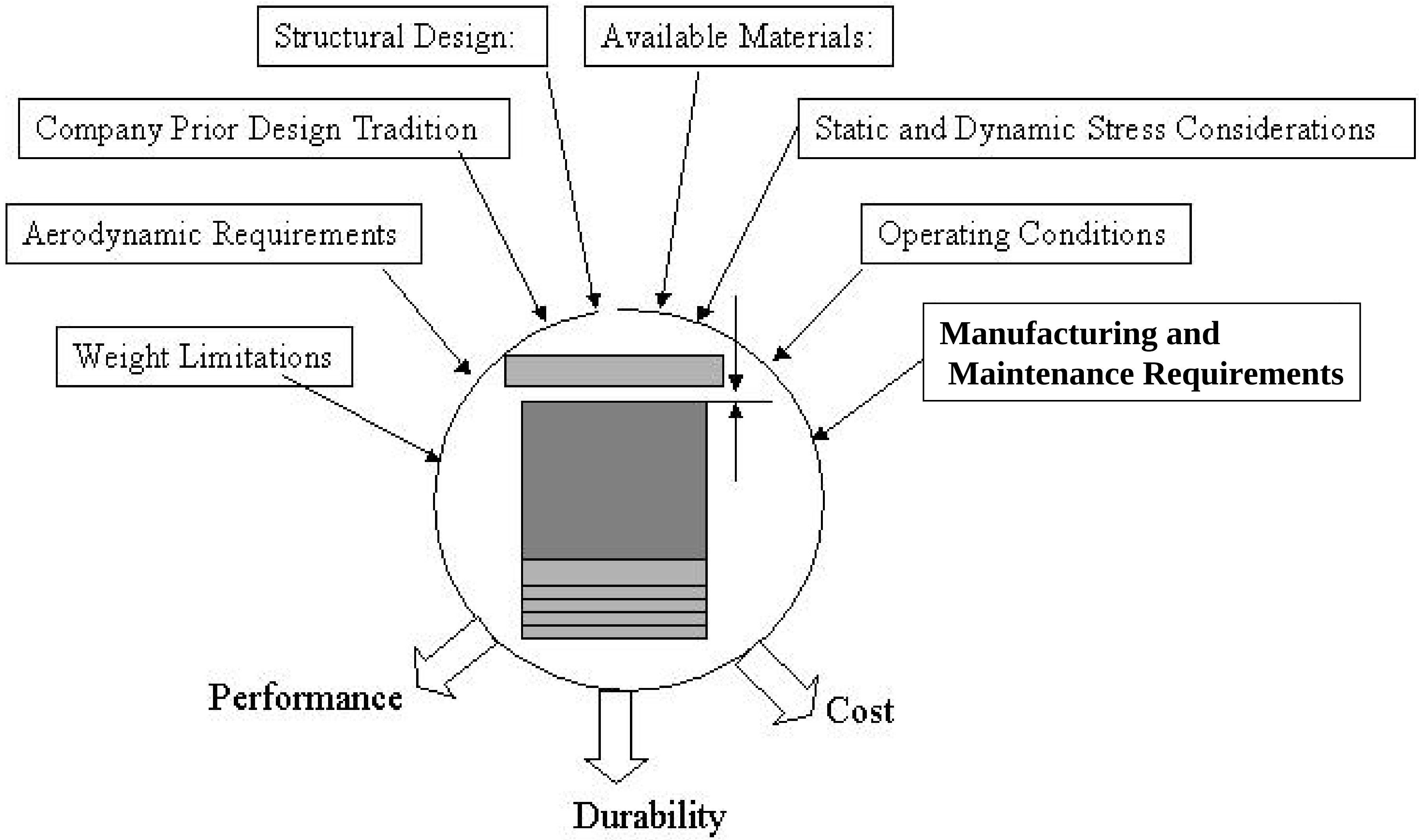
Major Components: Combustor Liner and Transition - Nozzles (Vanes and Endwalls) – Blades (Shrouded versus Unshrouded) -Discs/Preswirlers/ Seals - Turbine Stator Structure



Simple Cycle Efficiency and Specific Power for Aero and Industrial Engines

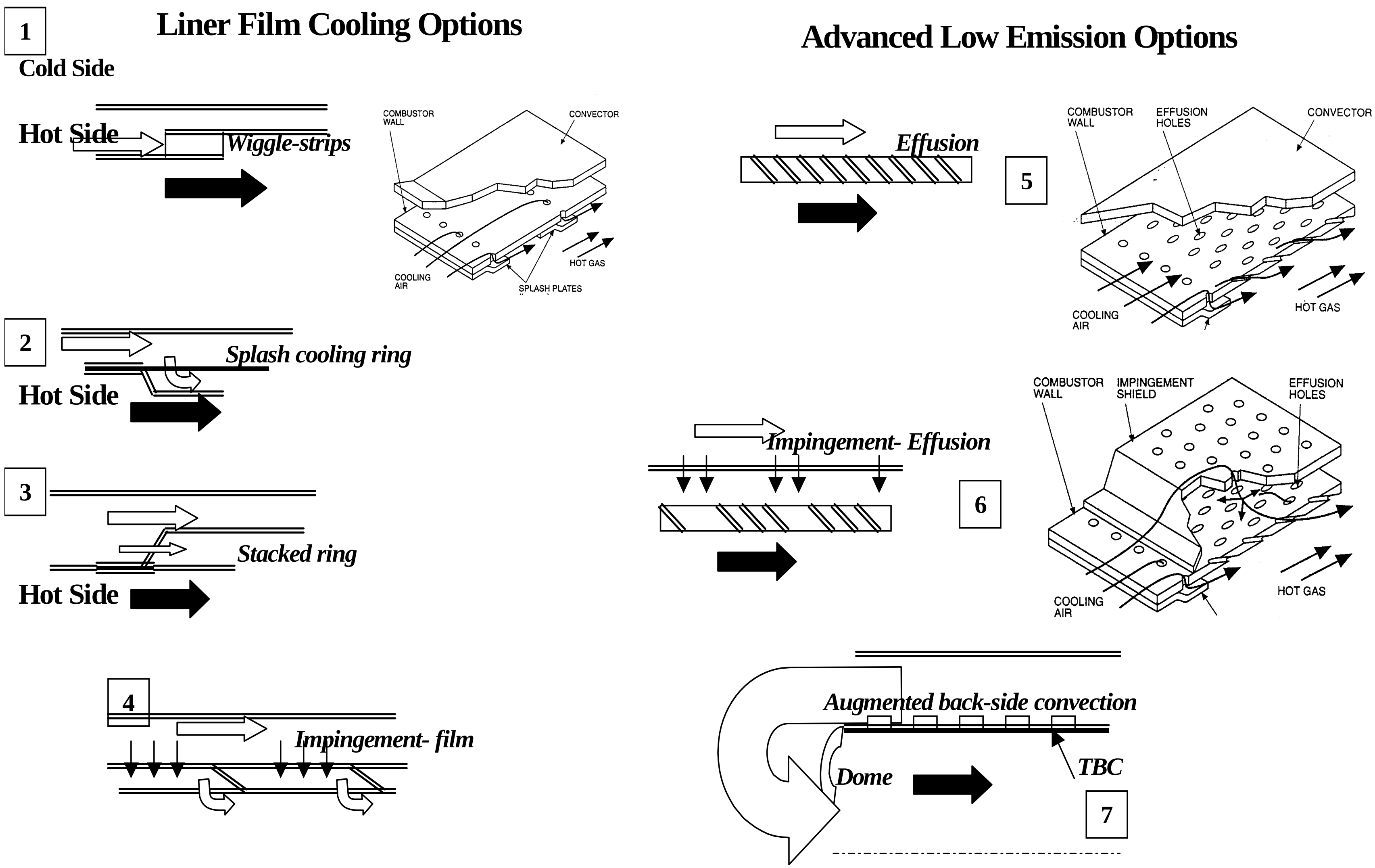


Effect of Temperature on Rupture For Selected Alloys

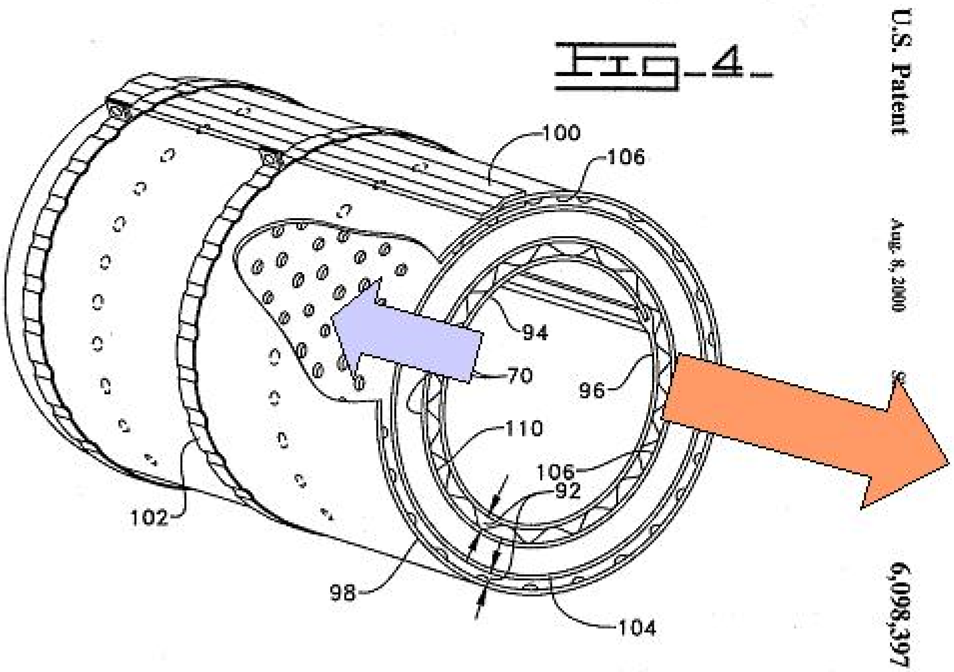


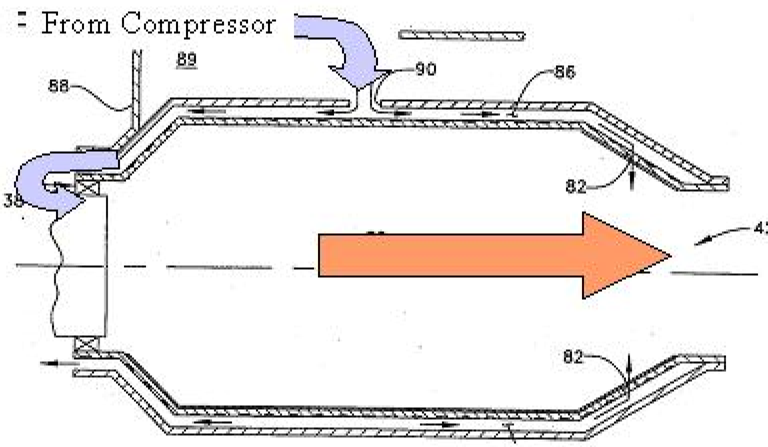
Multidisciplinary Constraints Affecting Selection of Turbine Cooling and Tip Treatment Design

1. ENGINE COOLING REQUIREMENTS, COOLING TECHNIQUES AND MEANS OF REDUCING PERFORMANCE PENALTIES



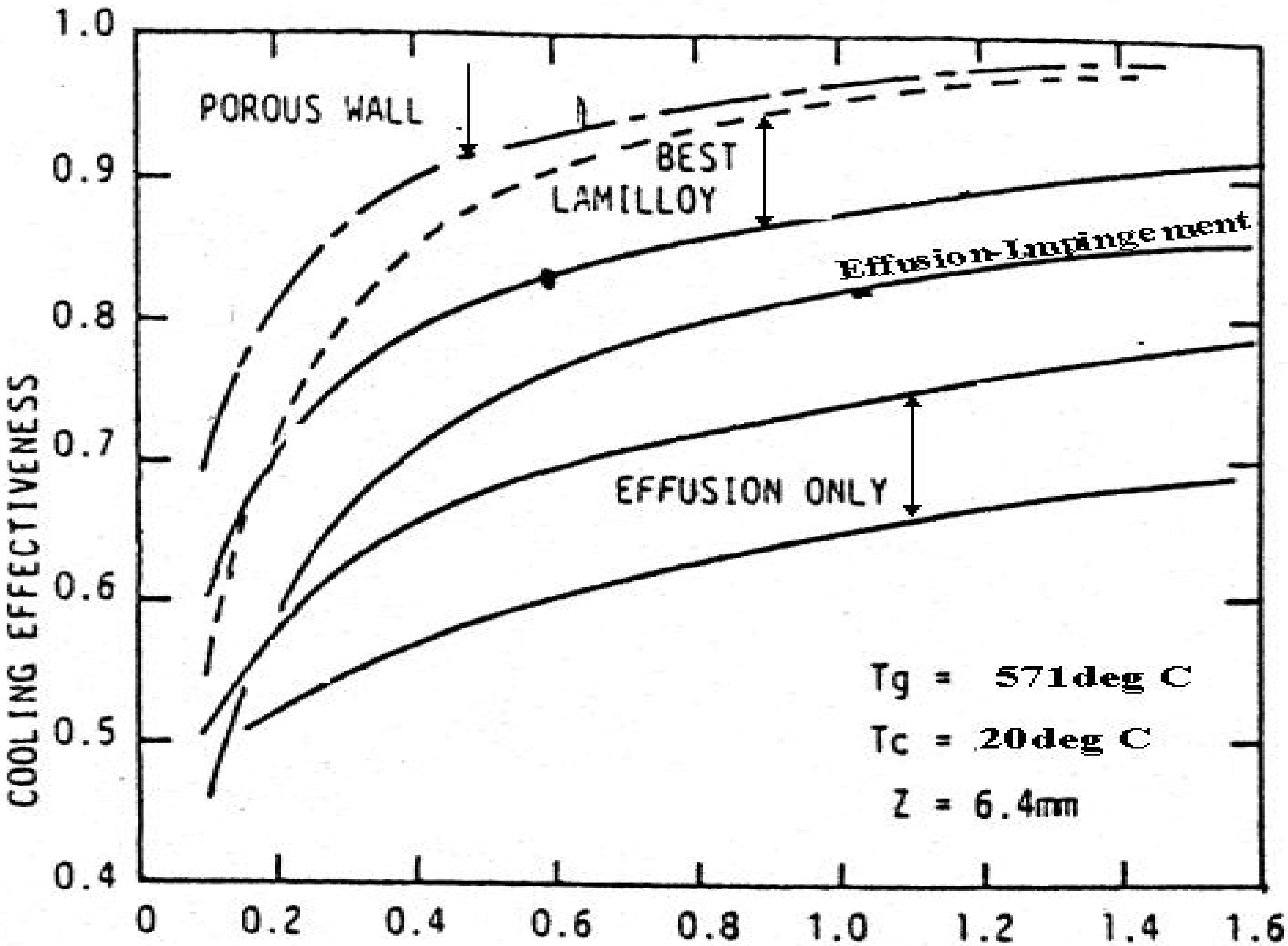
Combustor Liner Cooling Techniques





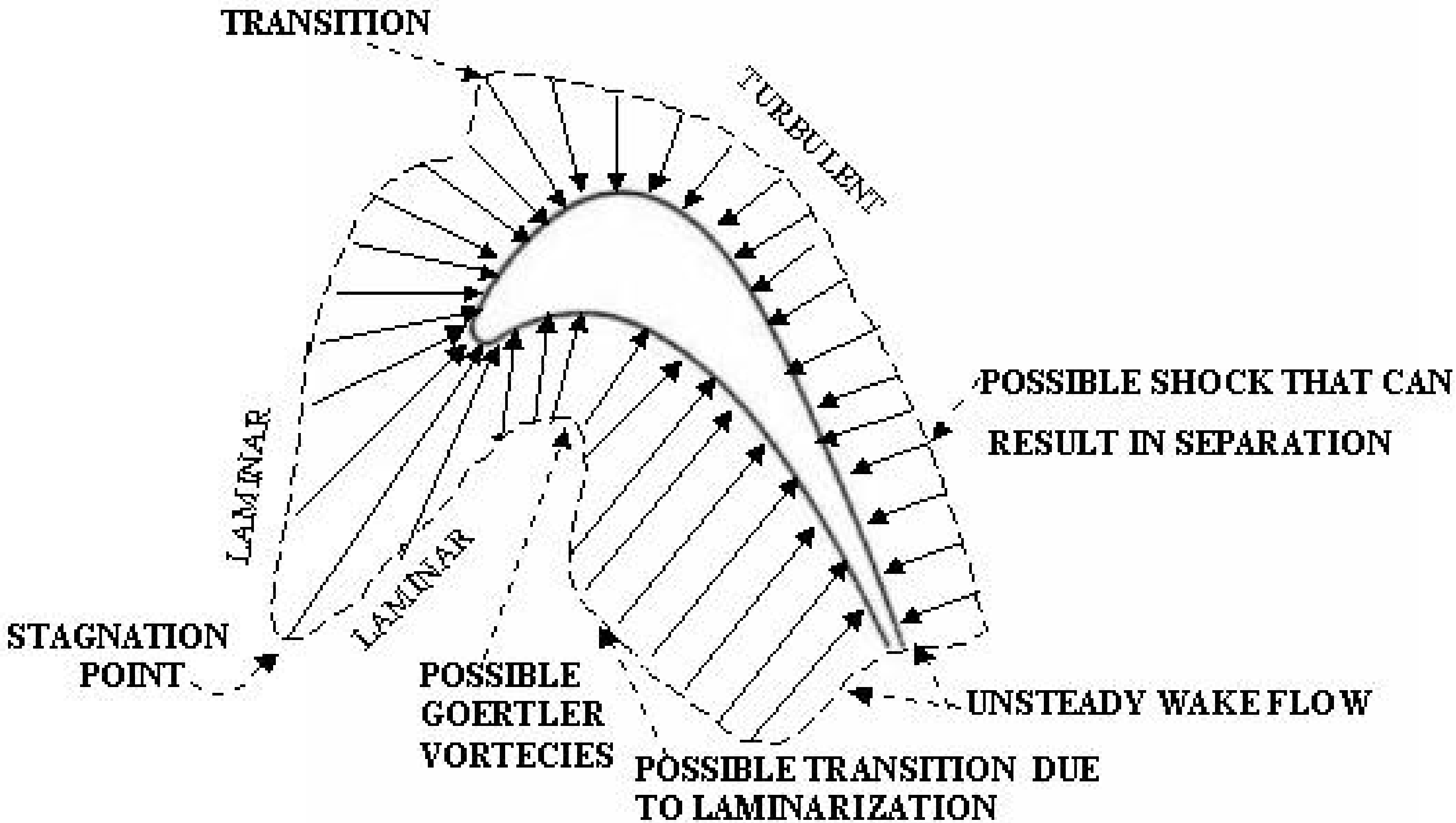
Liner Backside Cooling Using Dimpled Surface

(Tg-Tm)/(Tg-Tc)

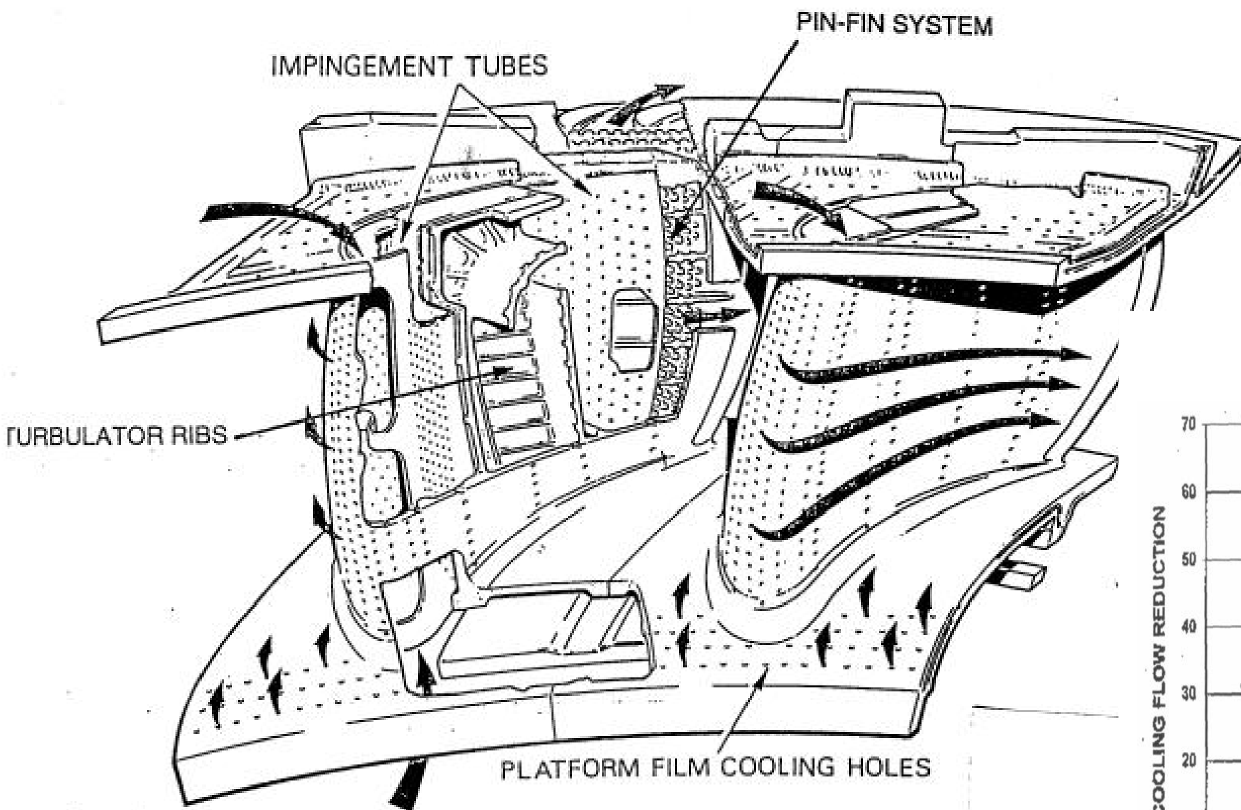


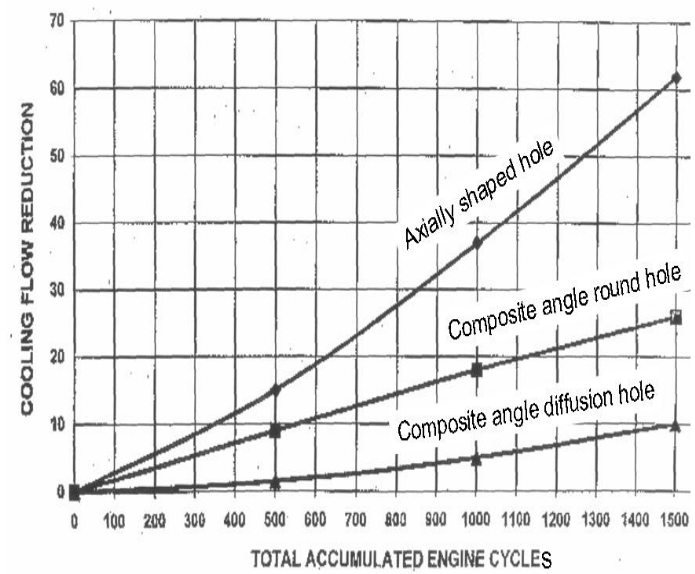
COOLING FLOW PARAMETER mCp/(hA)

Effectiveness of Liner Cooling Methods

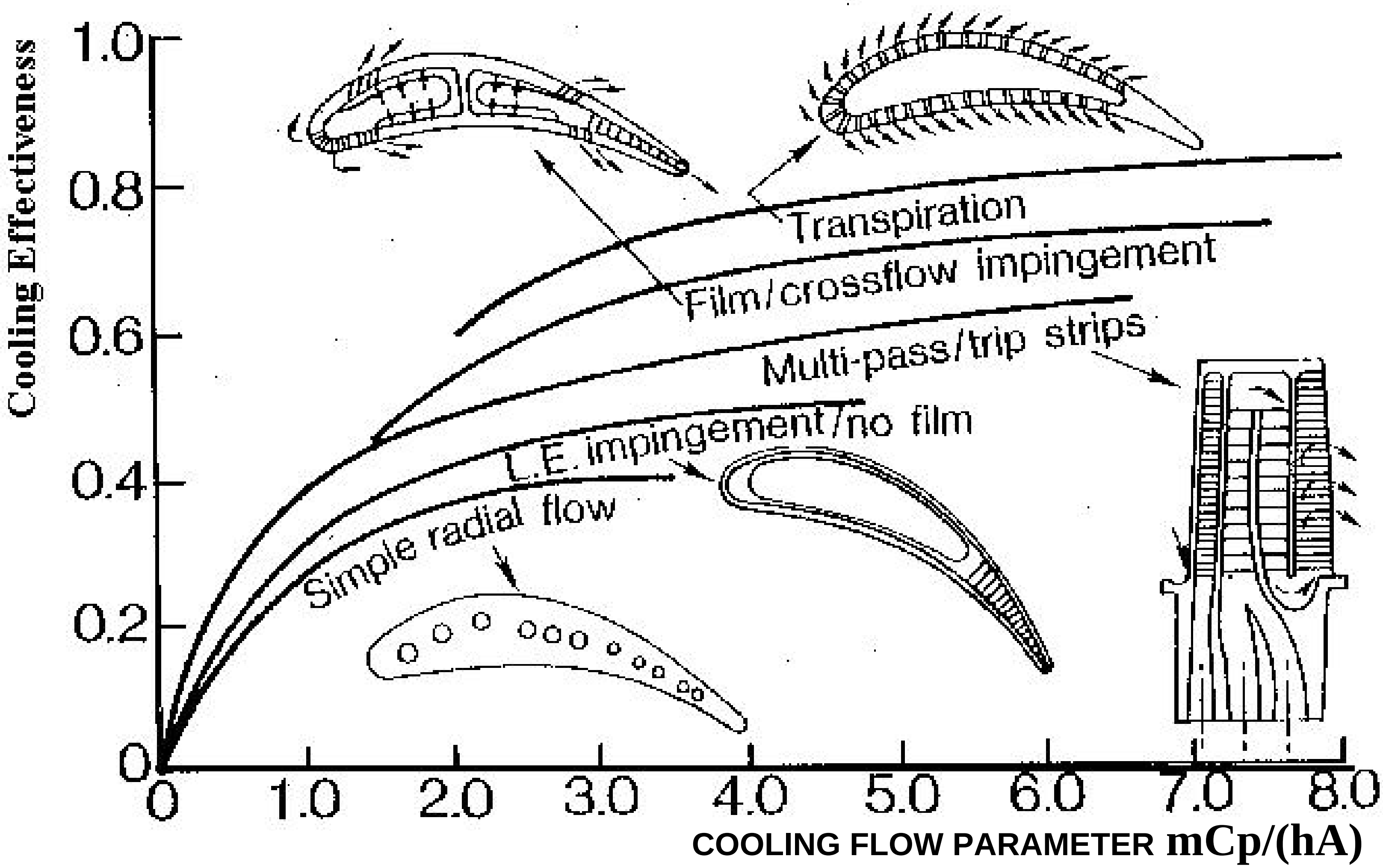


Typical Airfoil External Heat Transfer

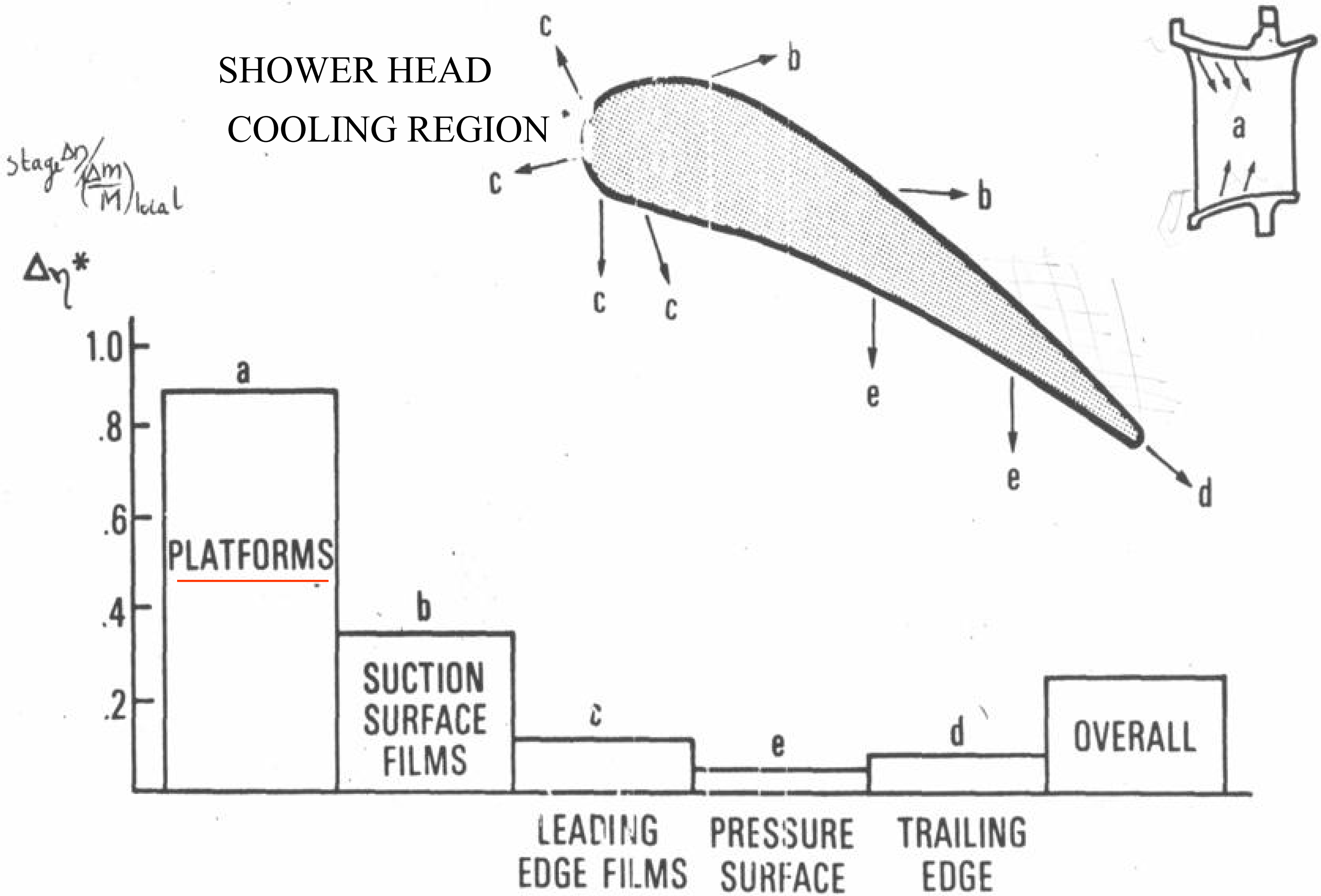




Airfoils –Complexity of Modern Cooling Design and Possible Degradation During Operation



Airfoil Cooling Effectiveness



Nozzle Film Cooling Discharge Penalties

* DISCHARGE COOLING FLOW AS HIGH UPSTREAM OF GAS PATH AS POSSIBLE

* USE SHOWER HEAD COOLING FOR THE LEADING EDGE OF THE FIRST STAGES OF AIRFOILS ONLY IF NECESSARY

* ATTEMPT TO DESIGN THE COOLING SYSTEM DISCHARGING AIR AT A TEMPERATURE APPROACHING ALLOWABLE LOCAL METAL SURFACE TEMPERATURE

* MINIMIZE MIXING LOSSES BY CLOSELY MATCHING VELOCITY VECTORS BETWEEN MAINSTREAM AND DISCHARGED COOLING FLOWS. THIS REQUIRES AS SMALL AS POSSIBLE PRESSURE LOSSES IN THE INTERNAL COOLING PASSAGES

* AVOID AIR DISCHARGE ON SUCTION SIDE OF AIRFOIL ESPECIALLY DOWNSTREAM OF THE THROAT

* REDUCE INTERNAL COOLING FLOWS UTILIZING THERMAL BARRIER COATING (TBC)

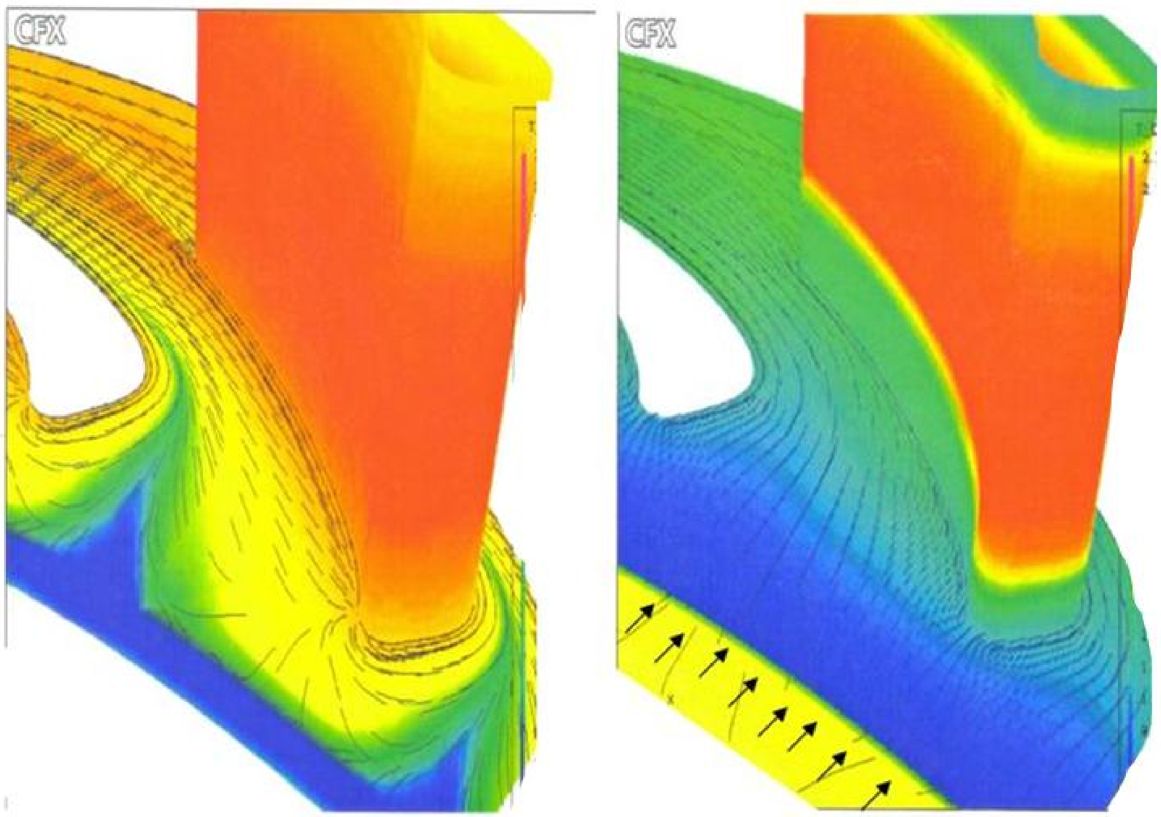
* USE PRE-SWIRLING MECHANISM FOR BLADE COOLING SUPPLY SYSTEM LOWERING THE RELATIVE TEMPERATURE OF THE COOLANT AND REDUCING DISC FRICTION LOSSES

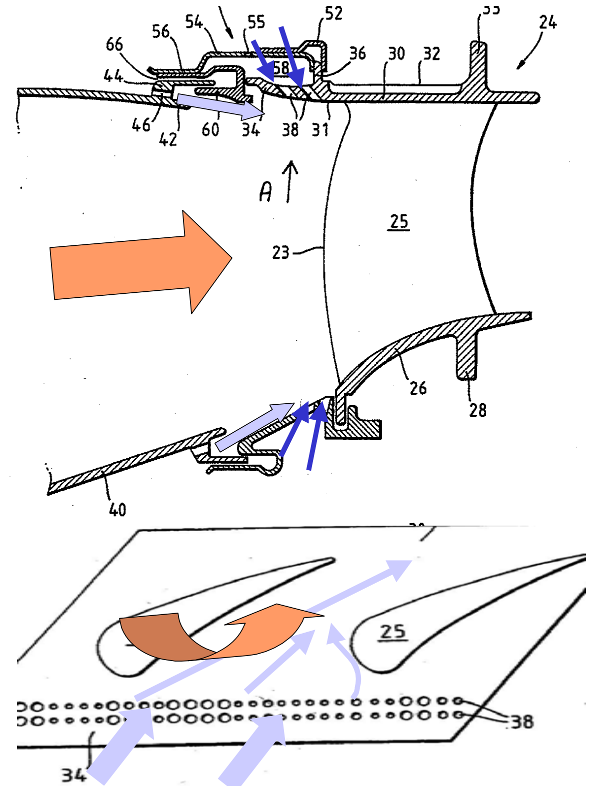
Main Design Rules for Minimizing Cooling Penalties

Suppression of a horseshoe vortex

Endwall 0.8% upstream film flow

Endwall 2% upstream film flow

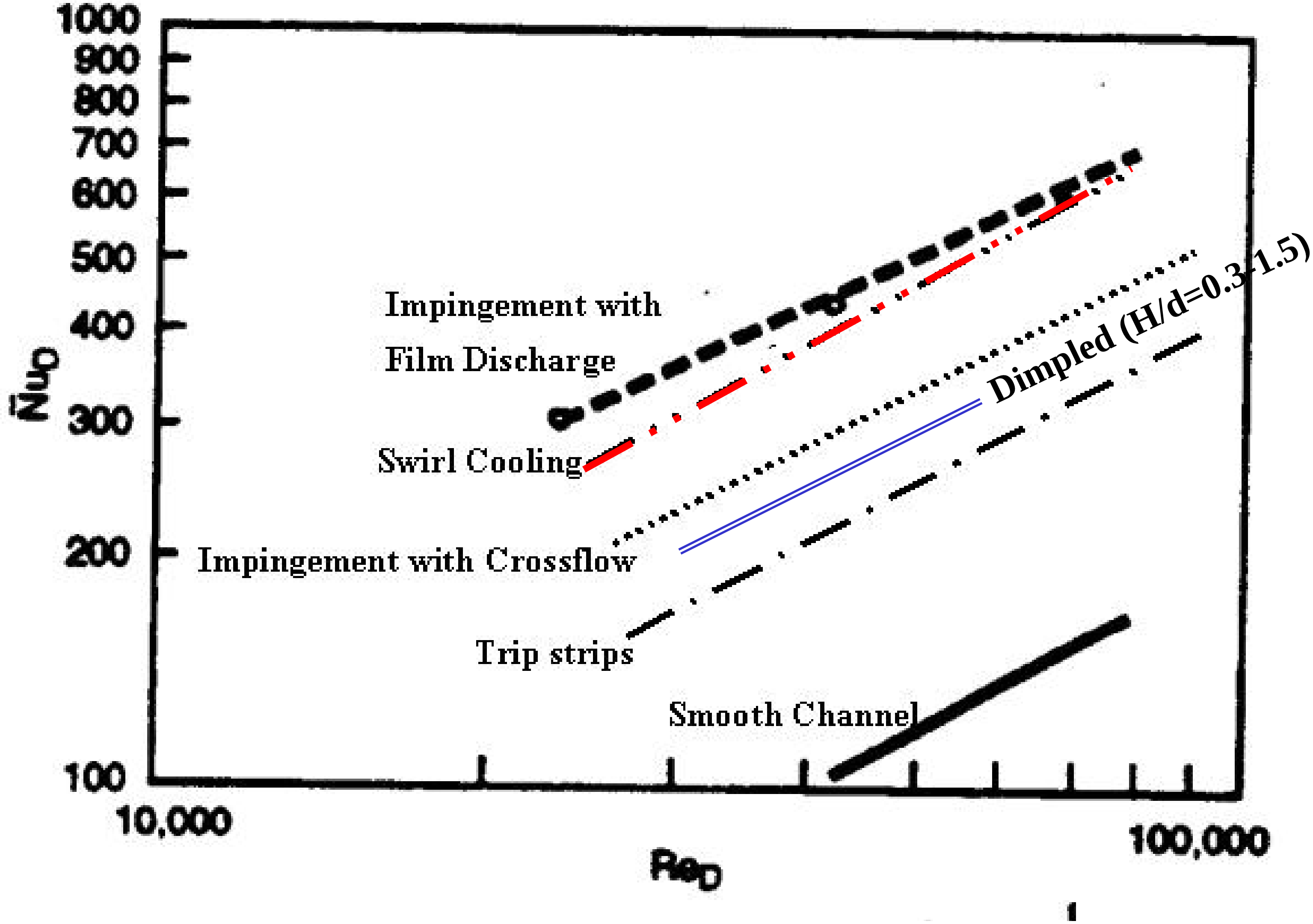




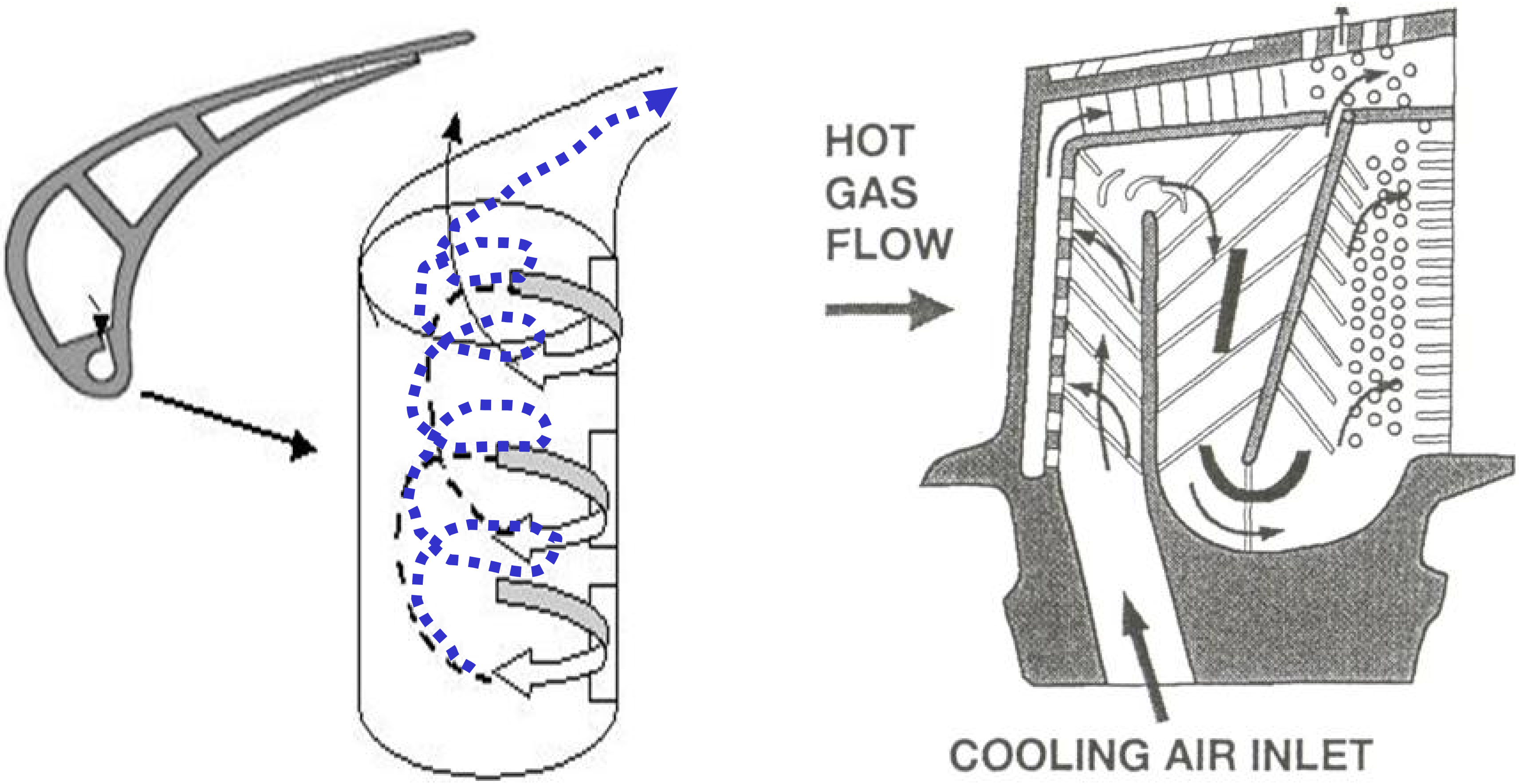
COMBUSTOR TRANSITION – NOZZLE ENDWALL COOLING

RR EPatent 0615055B1, 1995

Effect of Upstream Film on Horseshoe Vortex

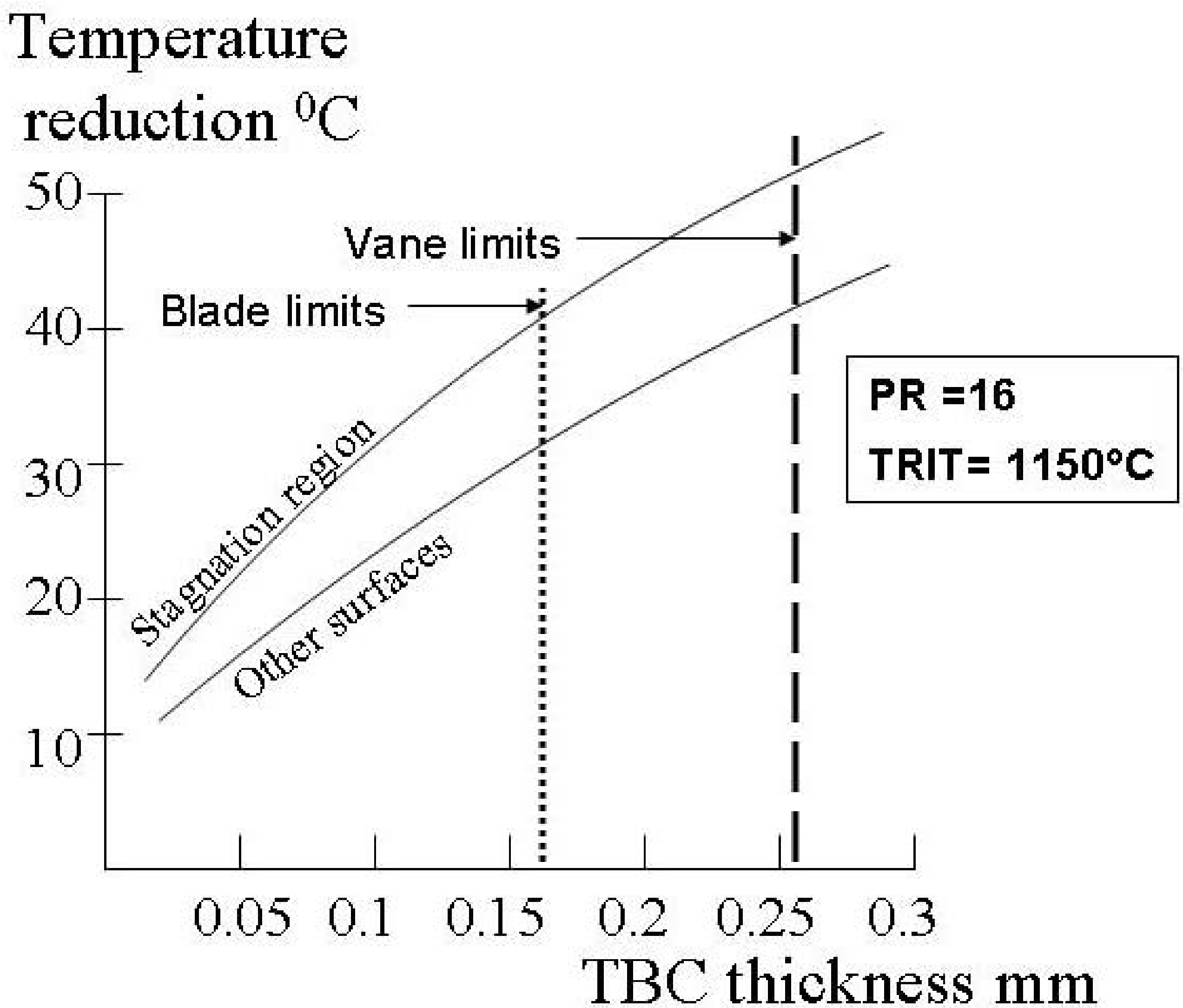


Comparison of HT Performance for Various Blade Cooling Techniques

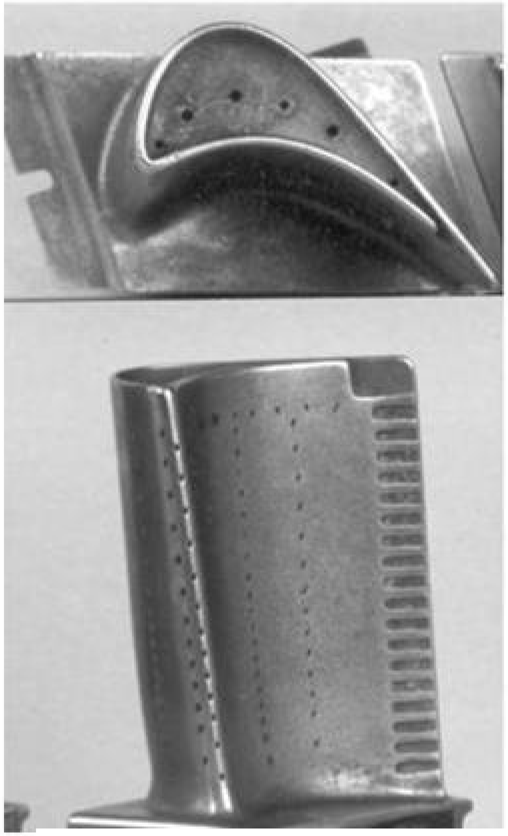


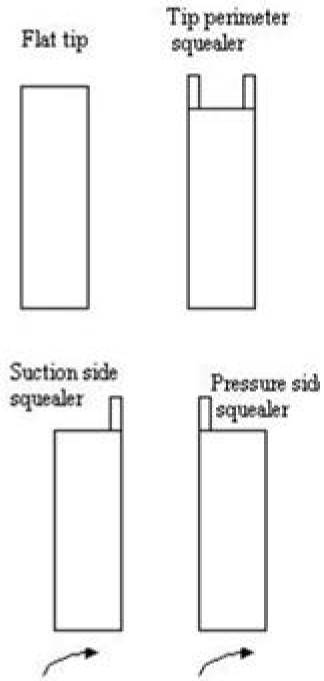
Schematics of Swirl (screw-shaped Vortex) Cooling of Blade Leading Edge

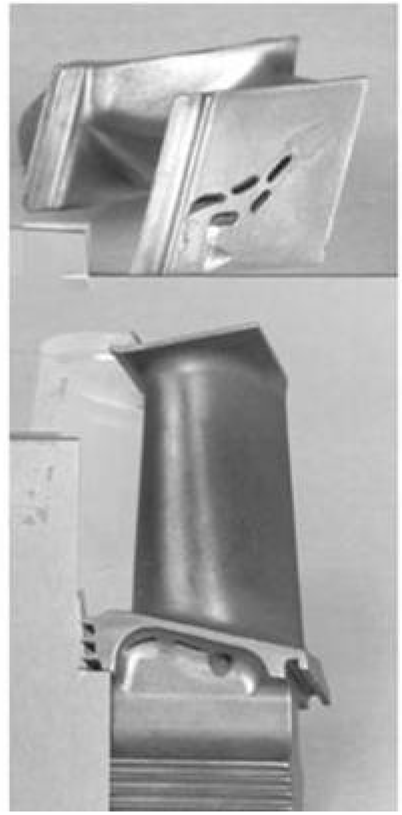
(US patent 5603606, 1997)

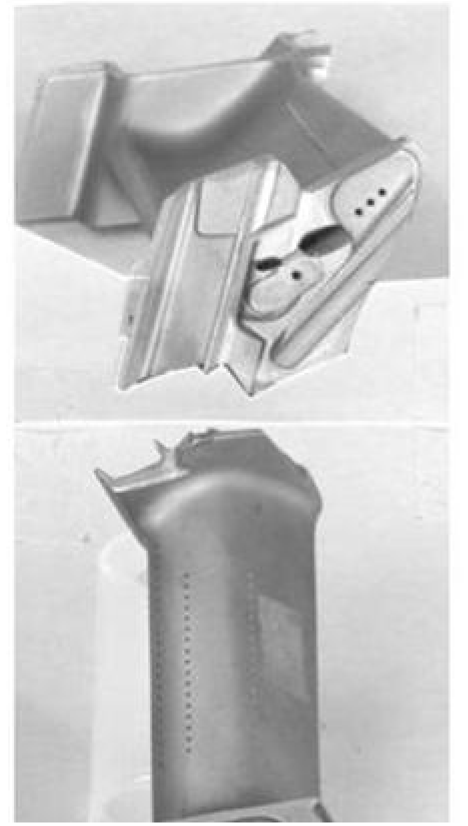


Approximate Effect of TBC on Airfoil Metal Temperature

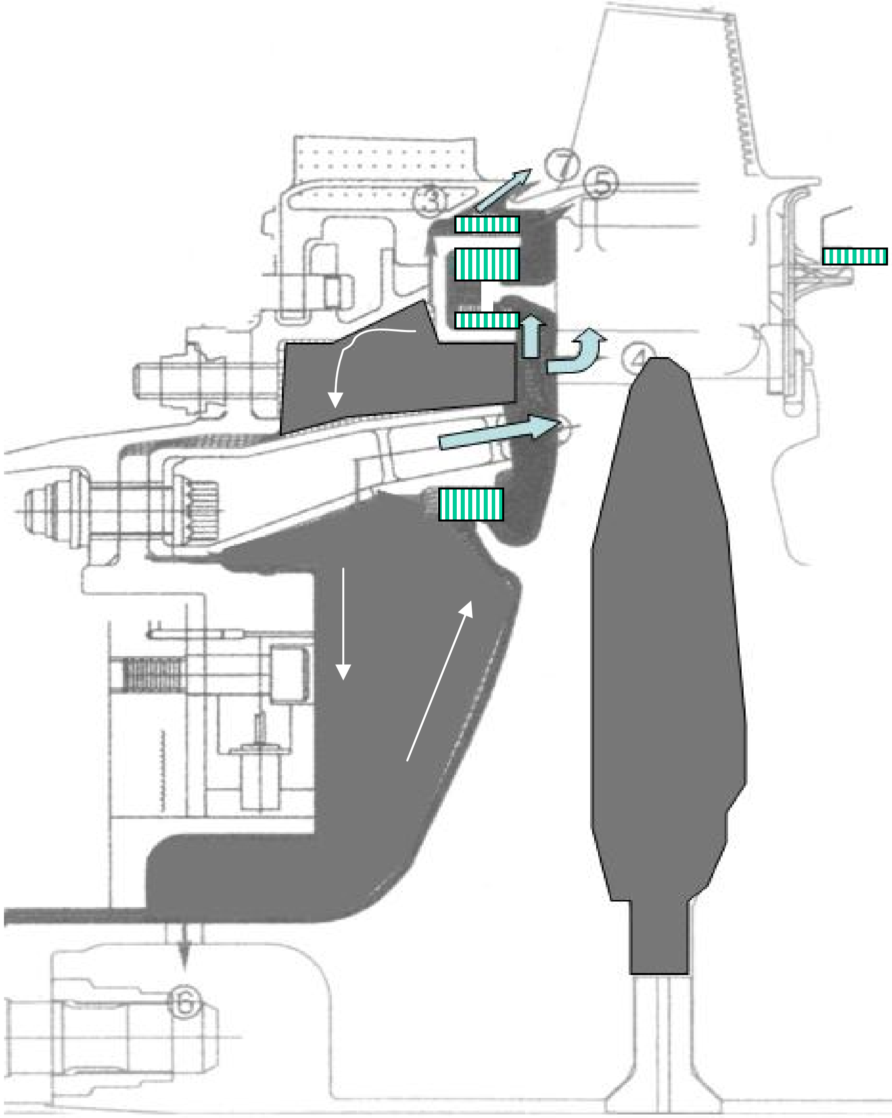


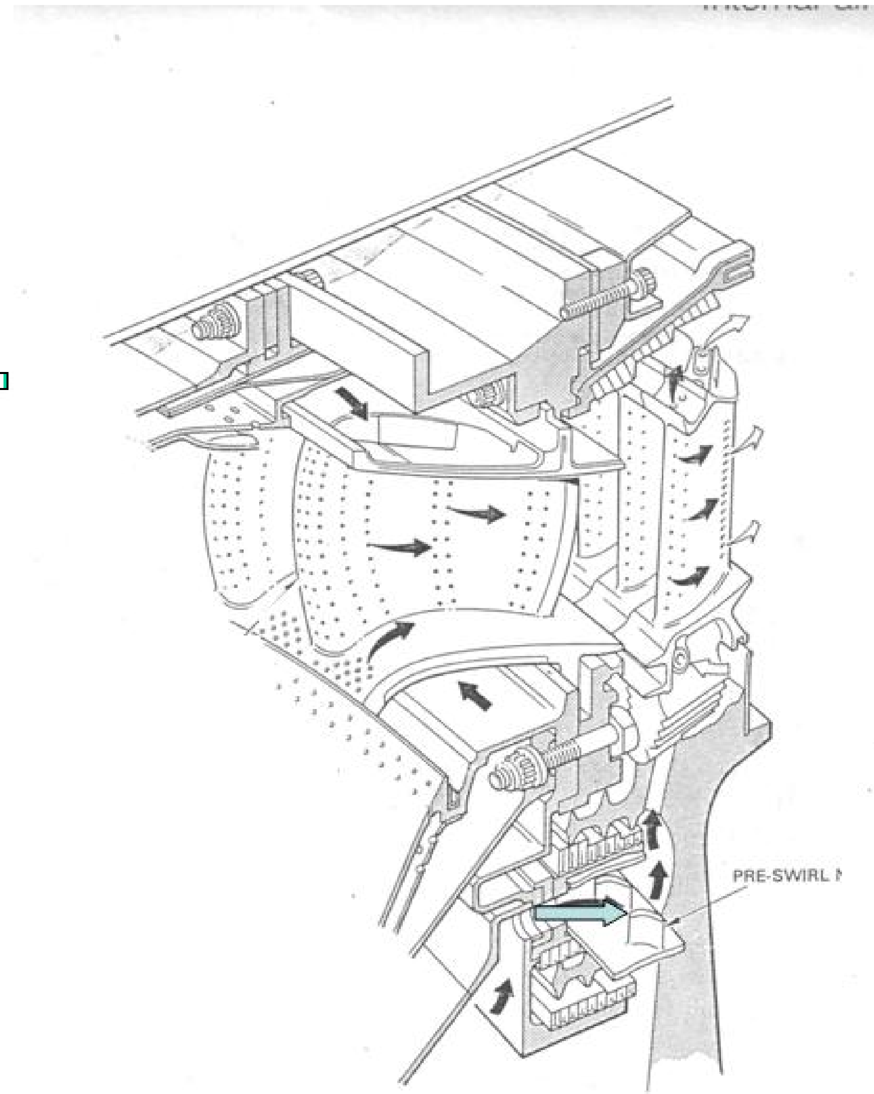




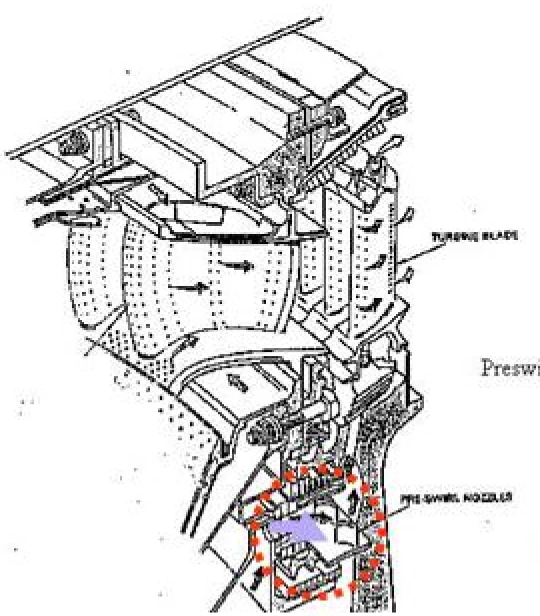


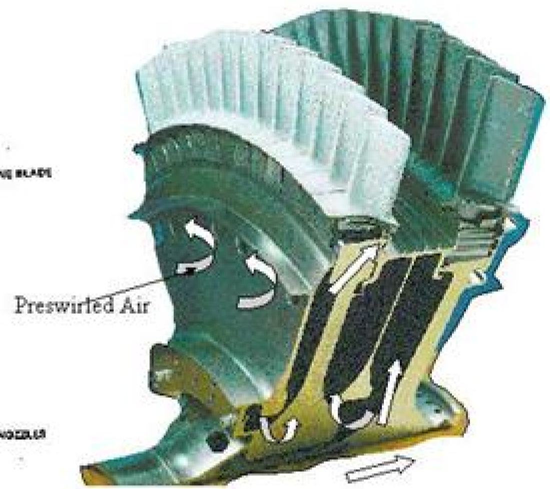
Unshrouded and Shrouded Blades

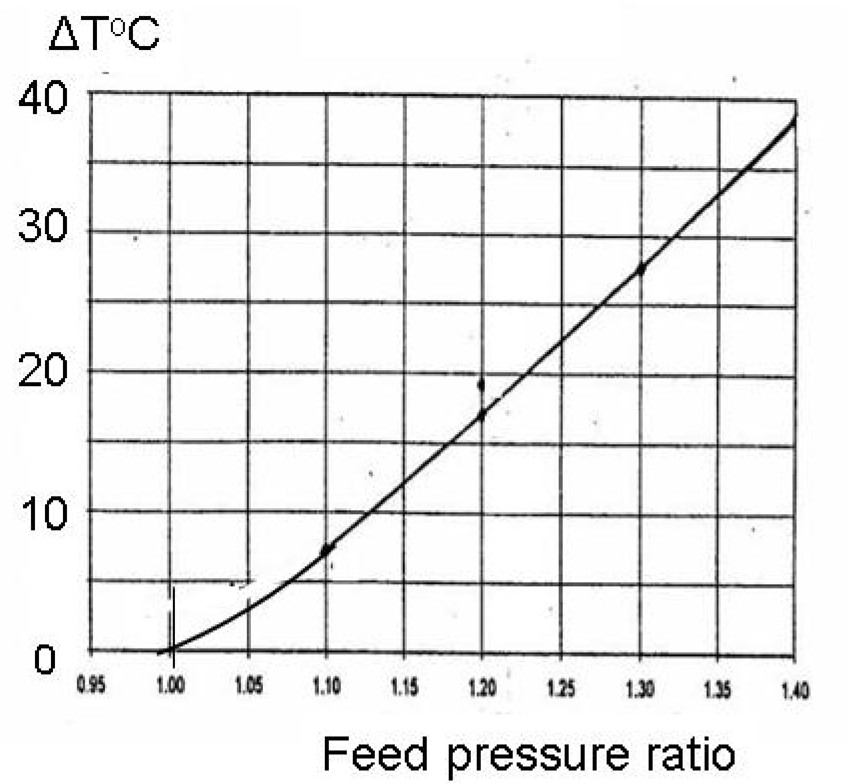




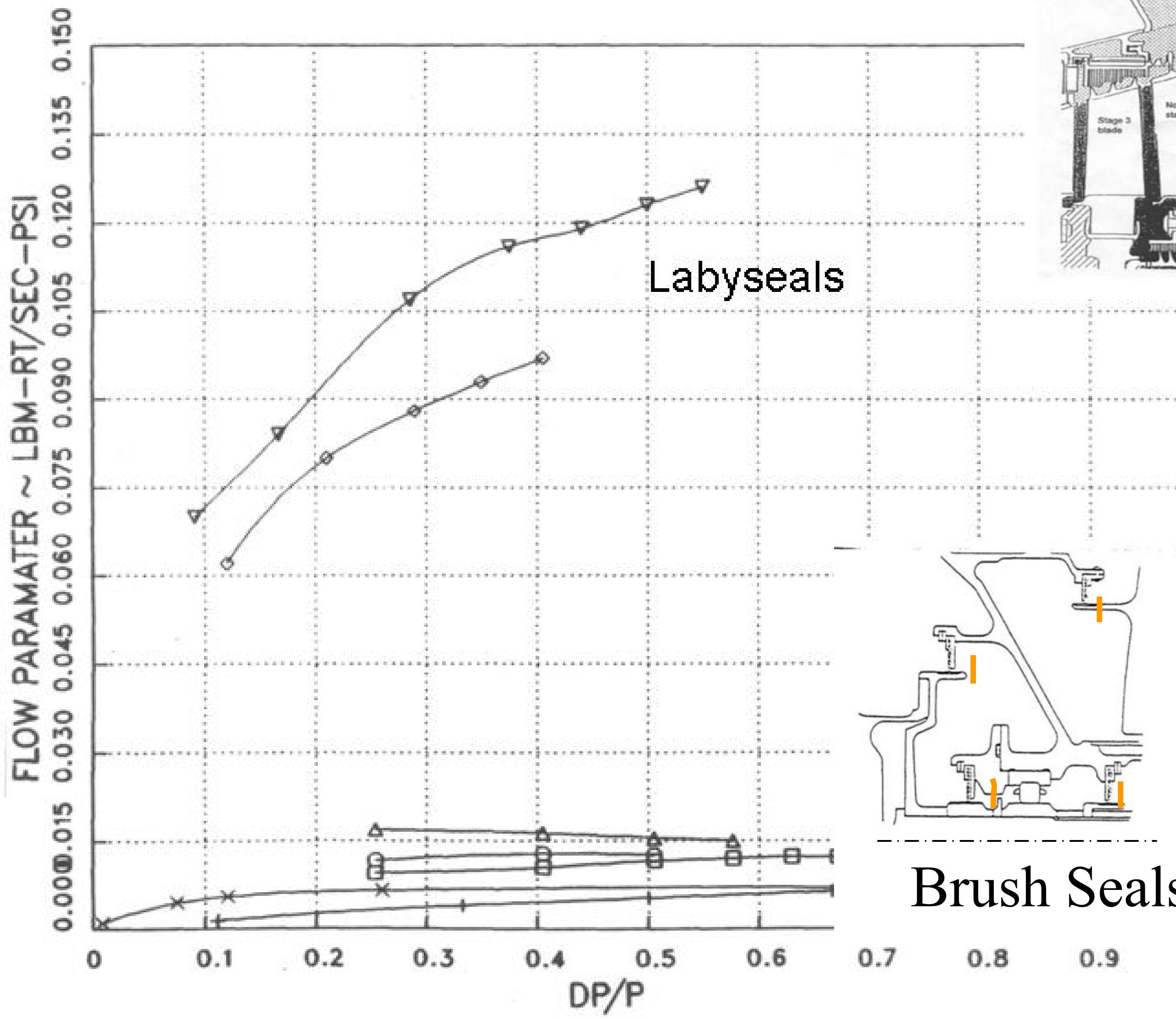
Examples of Modern Disk Rim Seals and Preswirlers

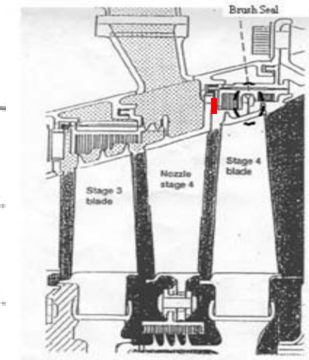






Benefits of Air Preswirler



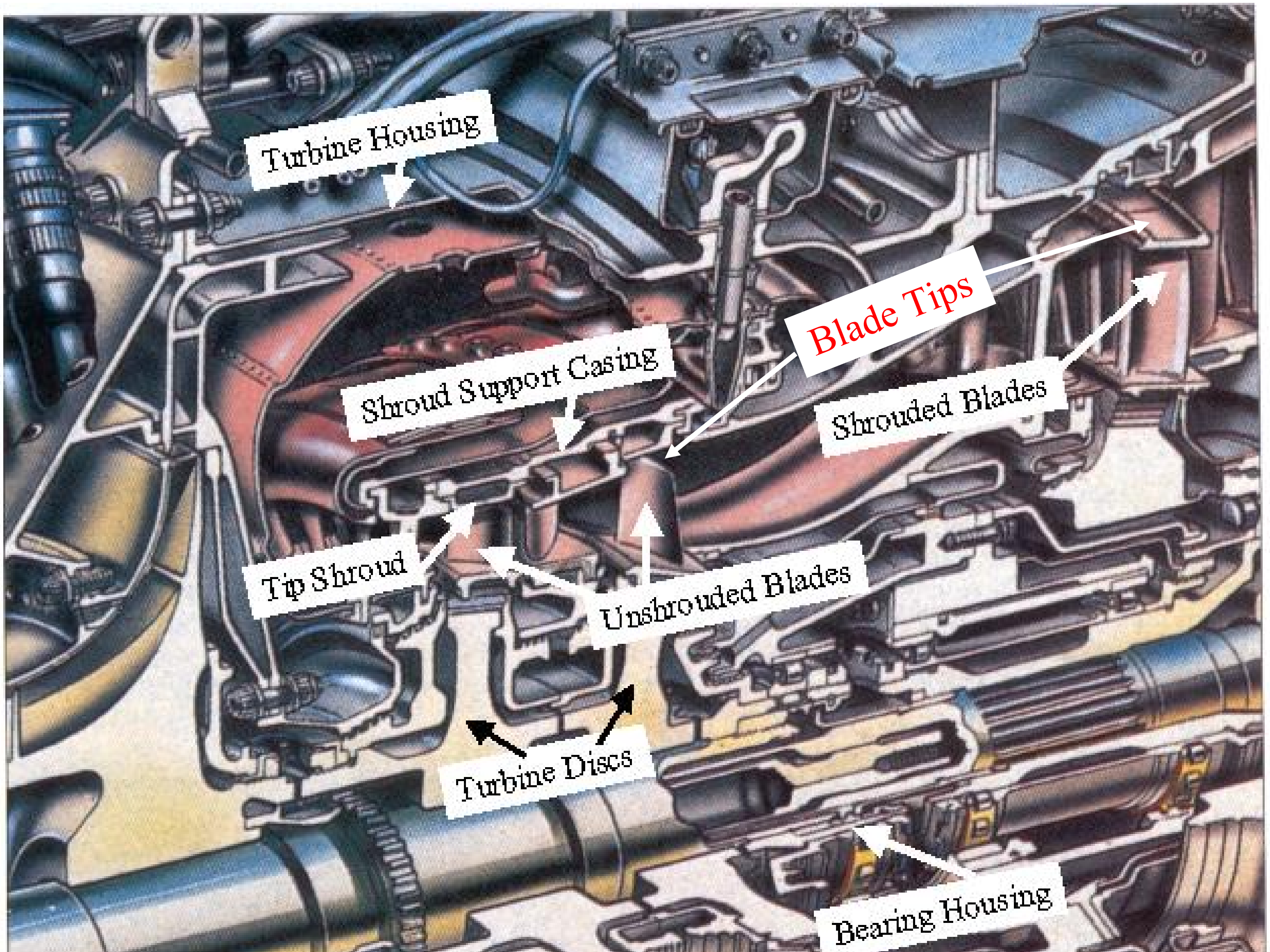


Example of brush seal application on blade tip

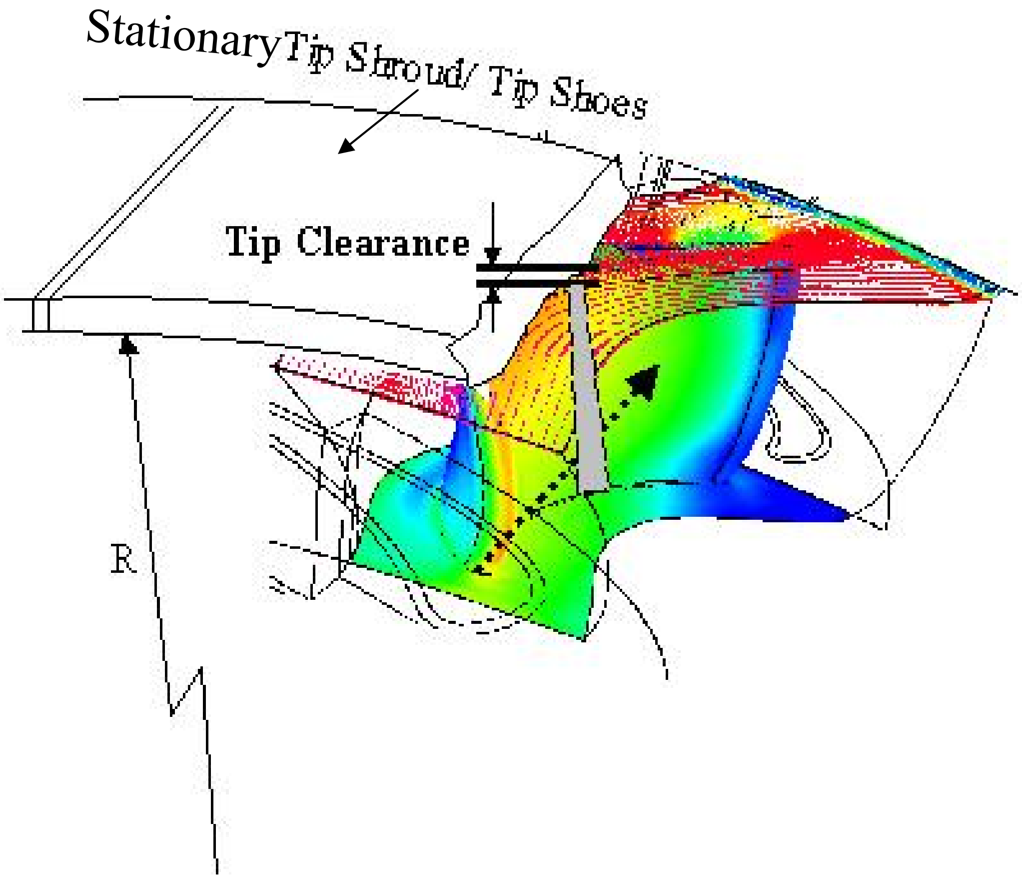
- Diameters 50- 600 mm
- Spans from 8mm to 15mm
- Angles from 45 to 55 deg
- Temperatures up to 870 C
- ΔP= 4-5 kg/cm^2 per seal-stage

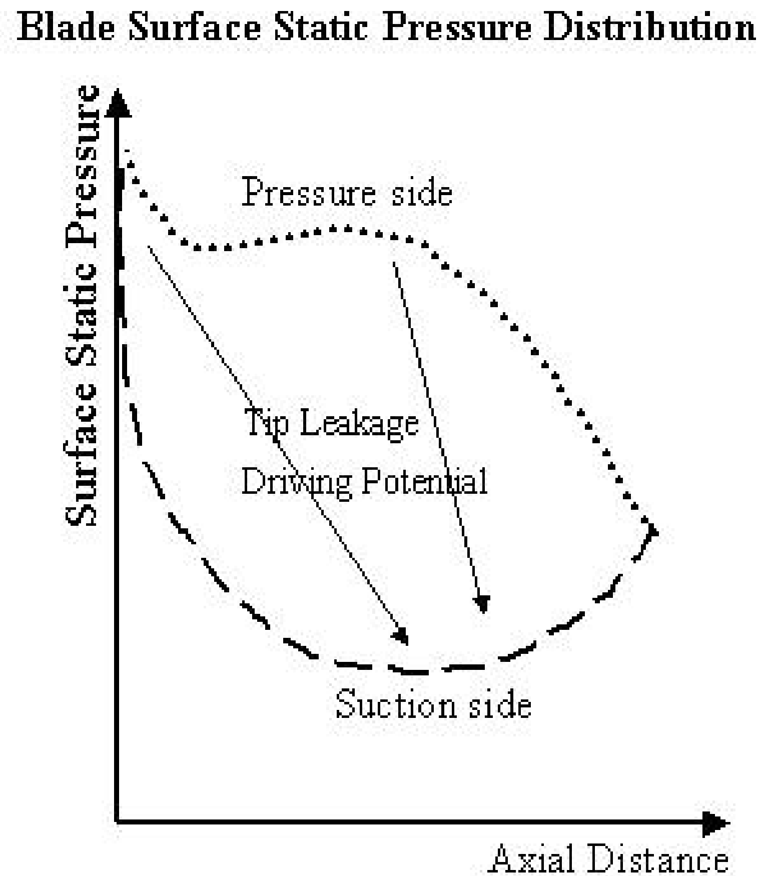
Performance of Brush Seals Versus Labyseals

2. ENGINE TRANSIENT THERMAL BEHAVIOR AND TURBINE BLADE TIP CLEARANCE CONTROL

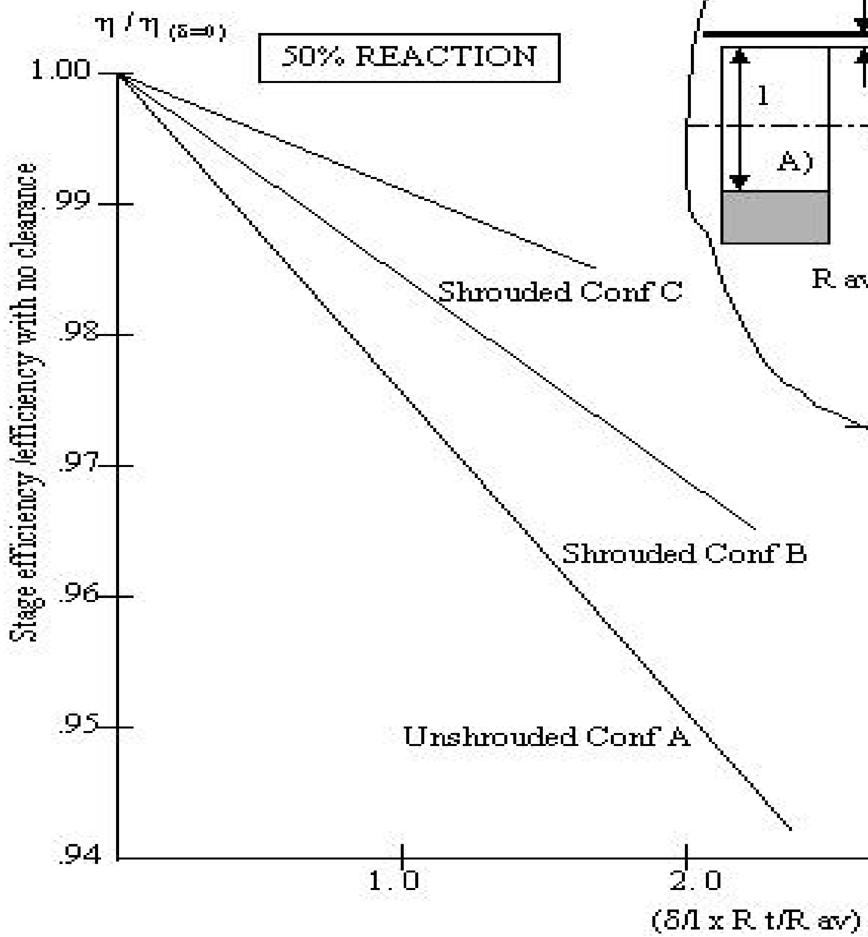


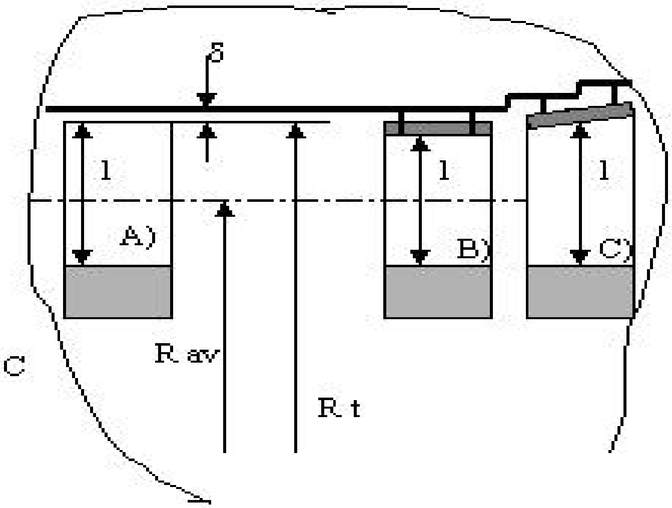
Turbine components influencing TC





Defining Blade Tip Area and Leakage Path





- + Measurable gain in stage efficiency due to reduced tip leakages/ lesser sensitivity to tip clearance variation
- + Improved fatigue strength
- - Difficulty to cool the shroud area
- - Larger cooling flow budget
- - Higher blade and disk centrifugal forces/stresses
- - Significant cost increase particularly for internally cooled blades

Figure 1-12

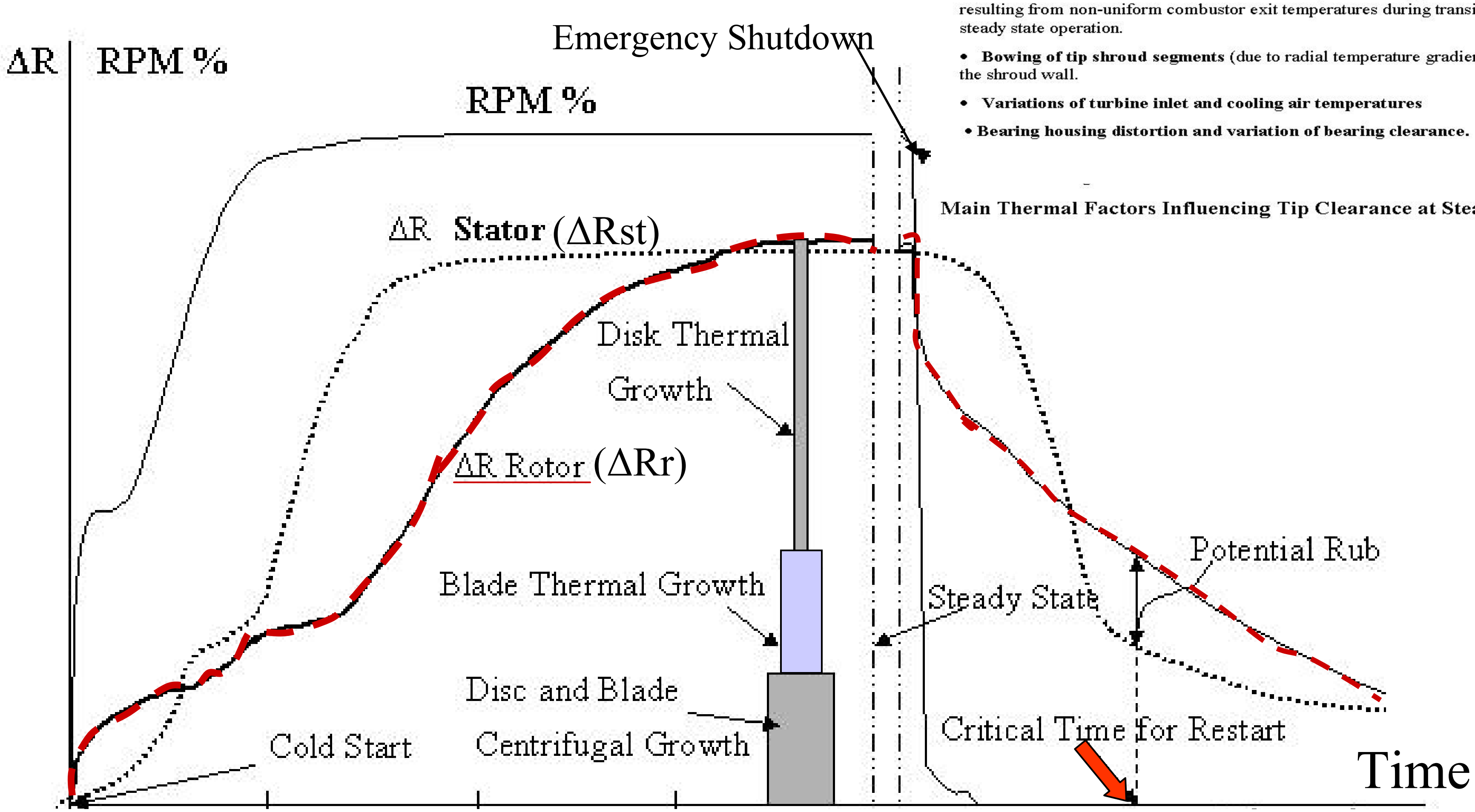
Shrouded Versus Unshrouded Blades –
major benefits (+) and disadvantages(-):

Effect of Tip Clearance on Turbine Efficiency

Transient TC= Build TC + ΔR st - ΔRr

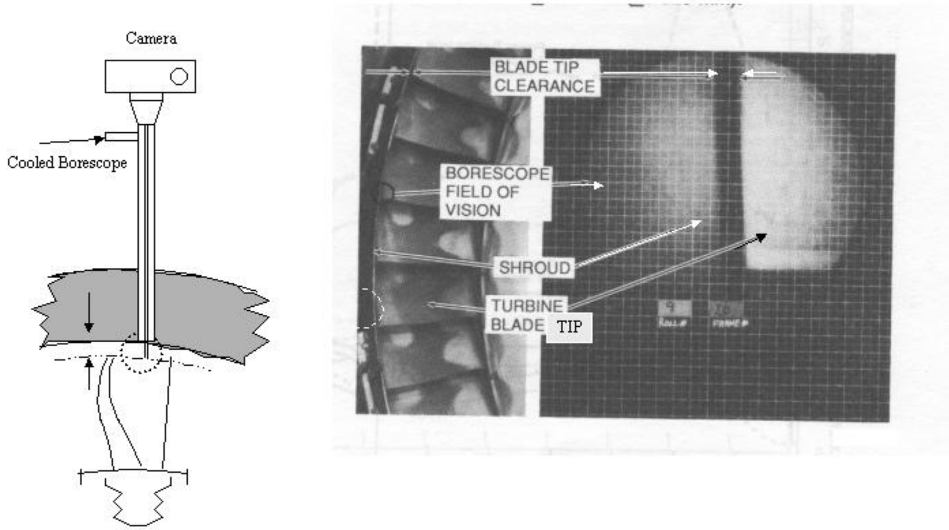
- **Differences in thermal radial growth between the turbine rotor assembly and stator supporting structure** during transients
- **Relative axial rotor-to-stator thermal displacements in the cases when the blade tips are flared.**
- **Circumferential thermal distortion of the tip shroud support structure** resulting from non-uniform combustor exit temperatures during transient or steady state operation.
- **Bowing of tip shroud segments** (due to radial temperature gradients across the shroud wall.
- **Variations of turbine inlet and cooling air temperatures**
- **Bearing housing distortion and variation of bearing clearance.**

Main Thermal Factors Influencing Tip Clearance at Steady State

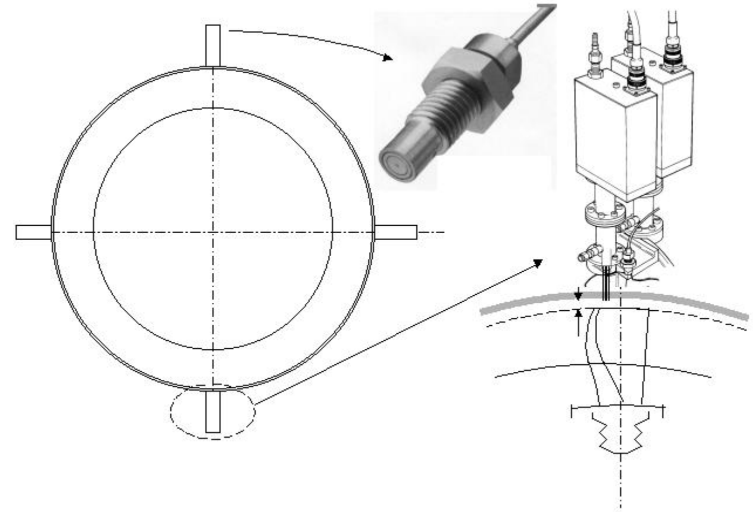


Typical Transient Rotor and Stator Growth

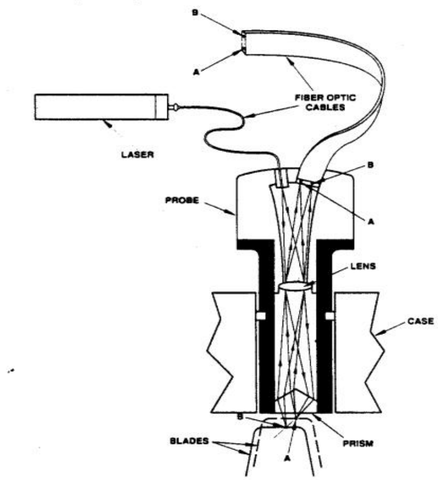
(Midsize Turbine)



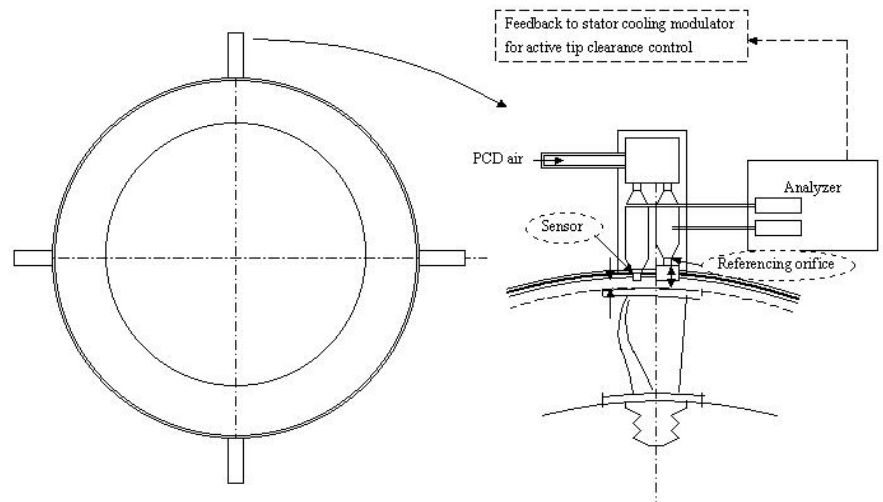
Transient Tip Clearance Photo Recording



Clearance Measuring System Using Capacitance Probes

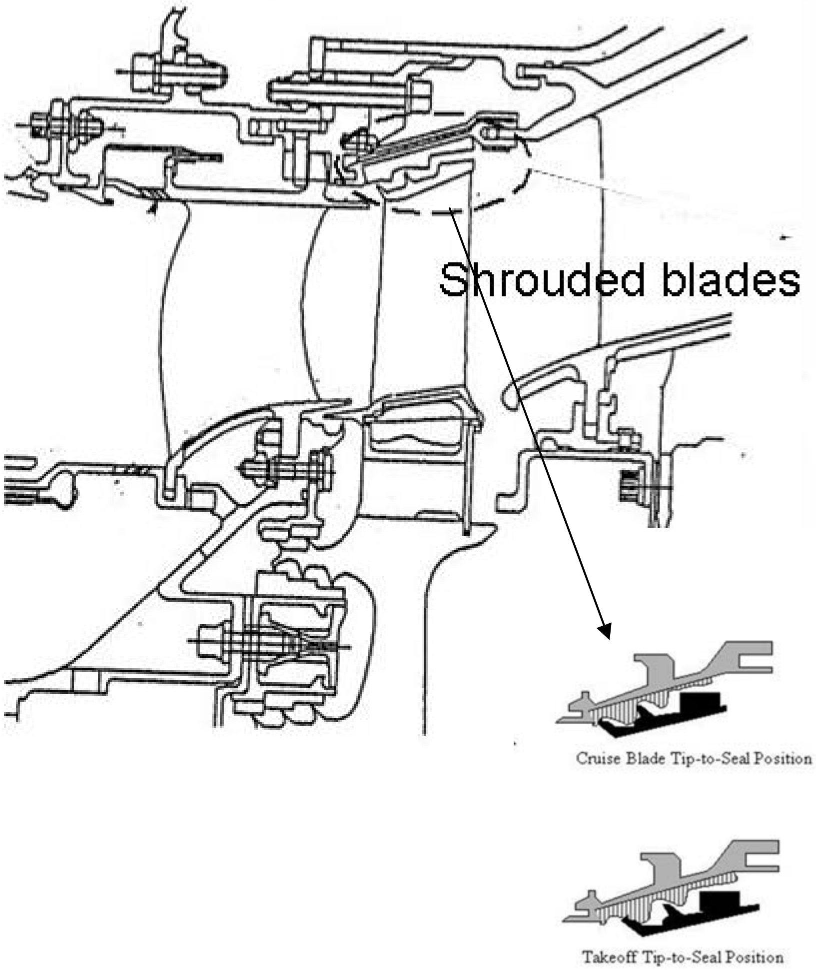


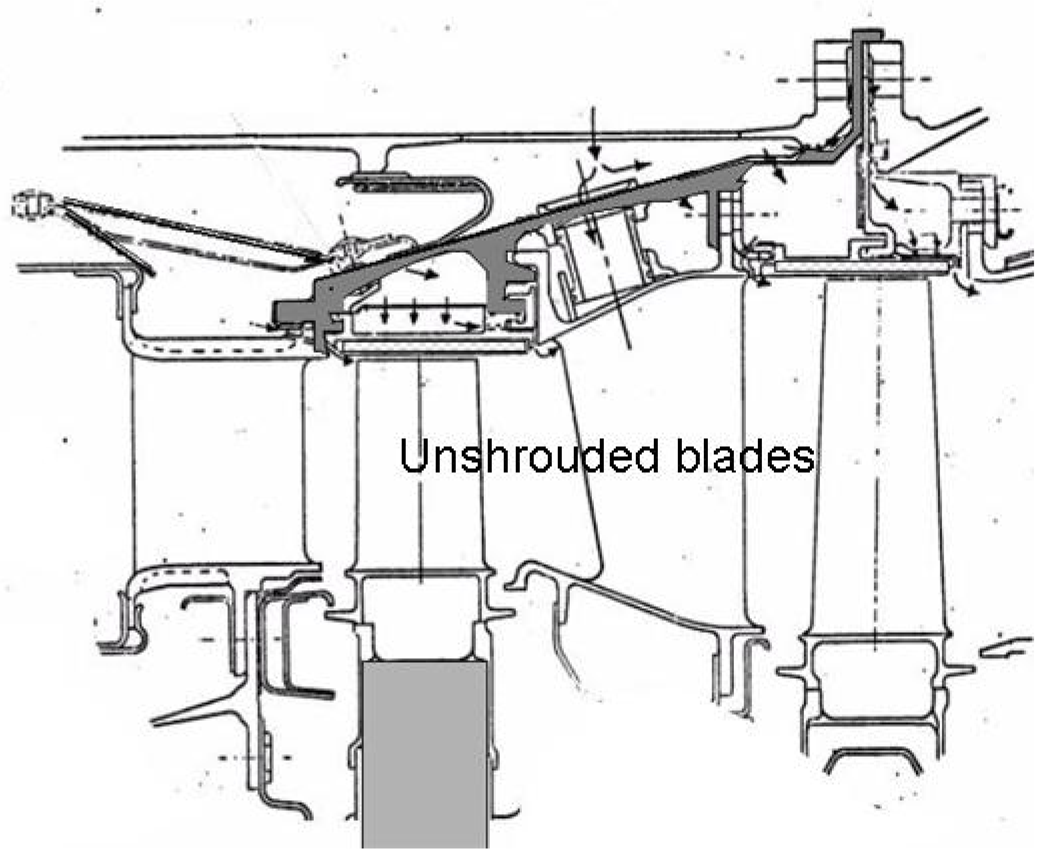
Laser Sensing/ Measuring System Schematics



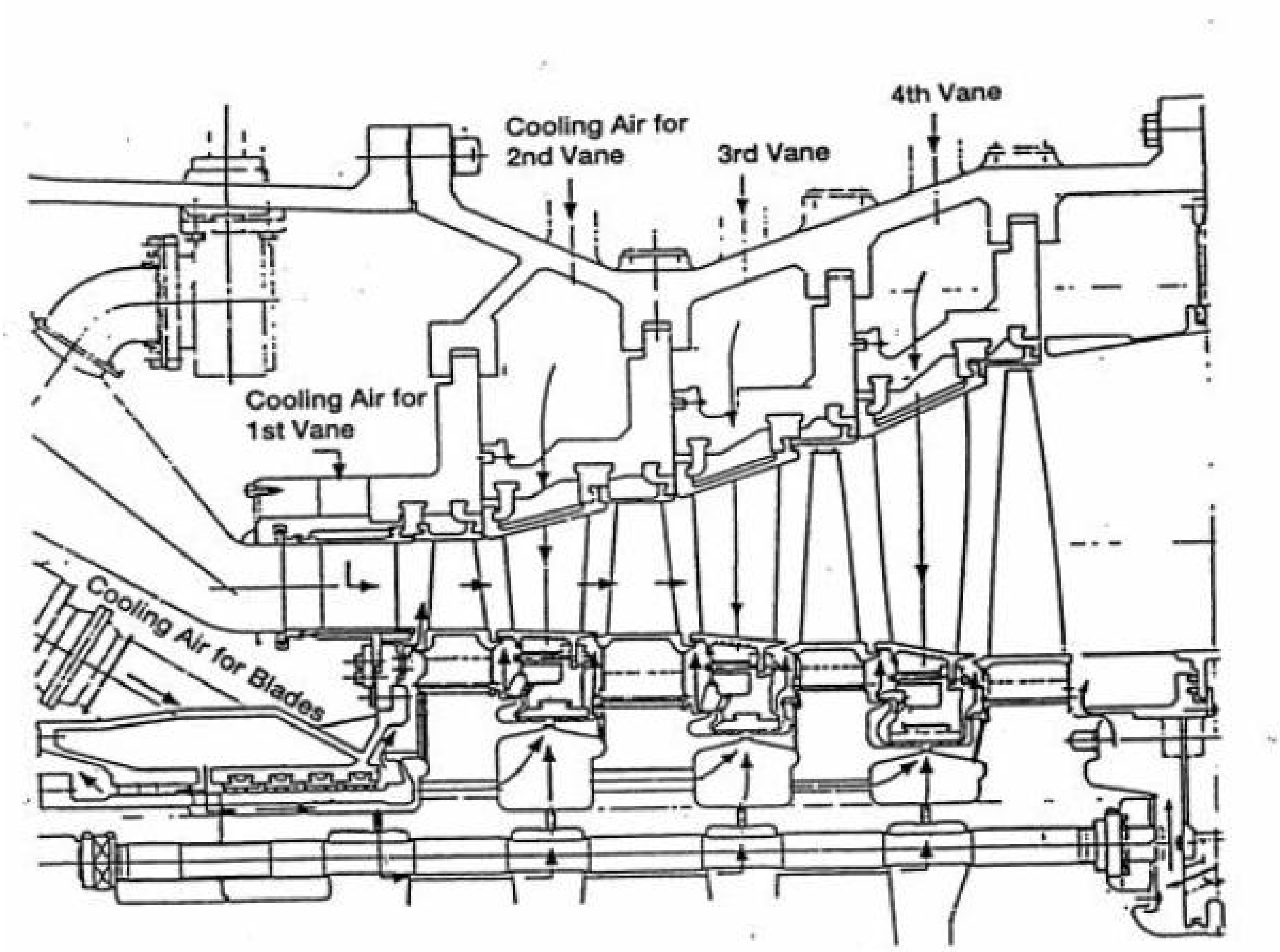
. Pneumatic Clearance Measuring System

Tip Clearance Measurement Techniques

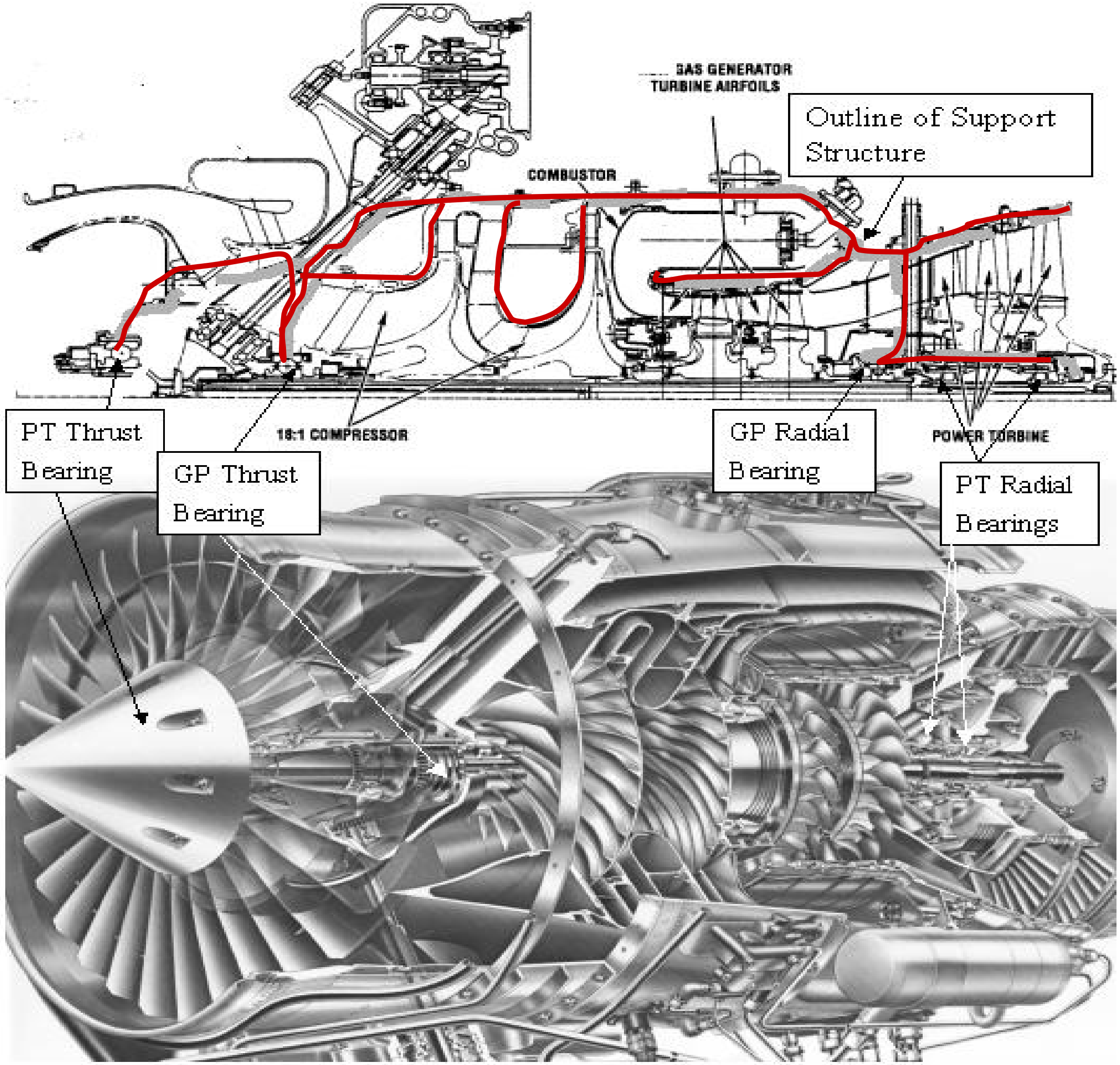




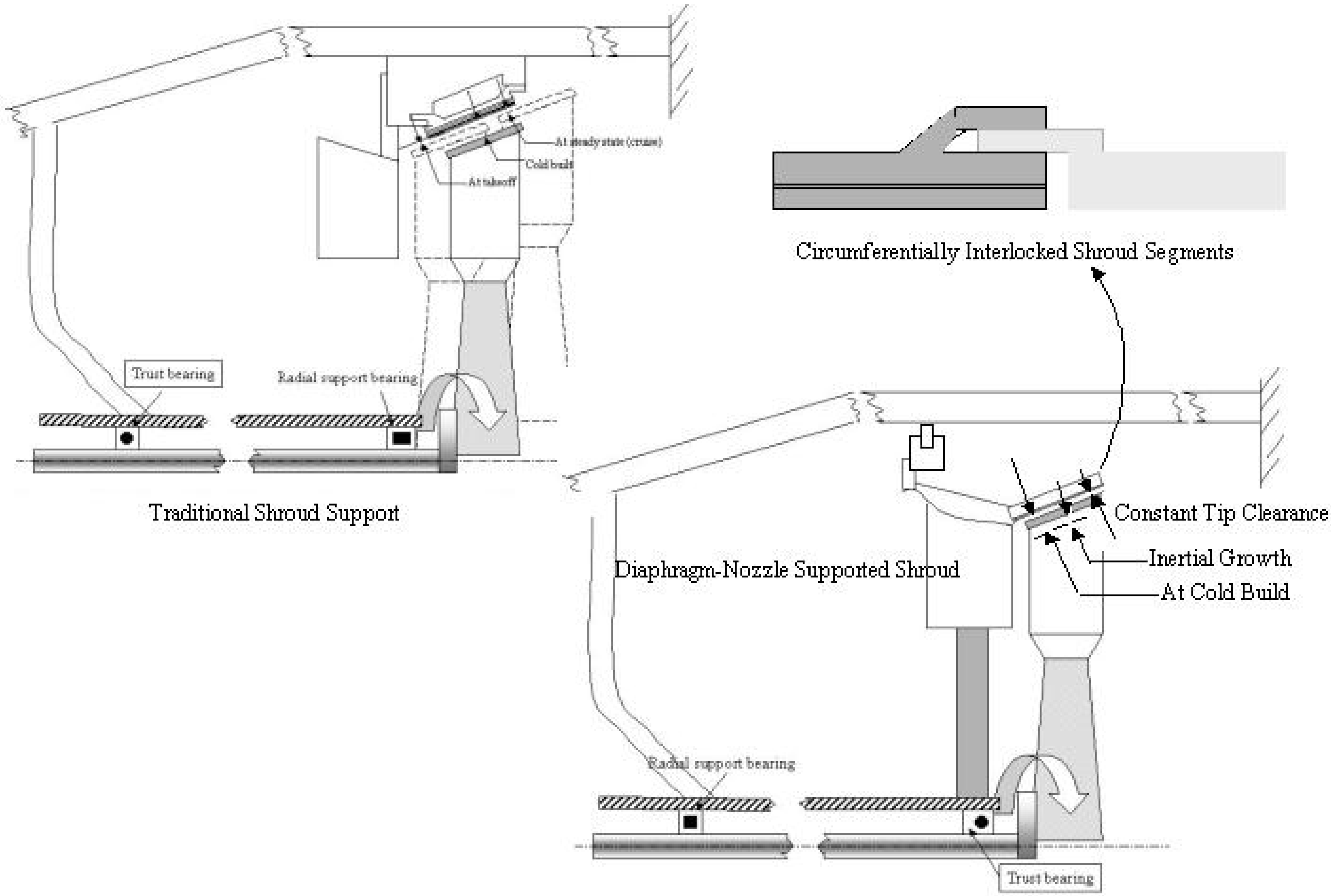
Examples of Light Tip Seal Support and Potential Active Tip Clearance Control



Thermally Matching Stator and Turbine Disks

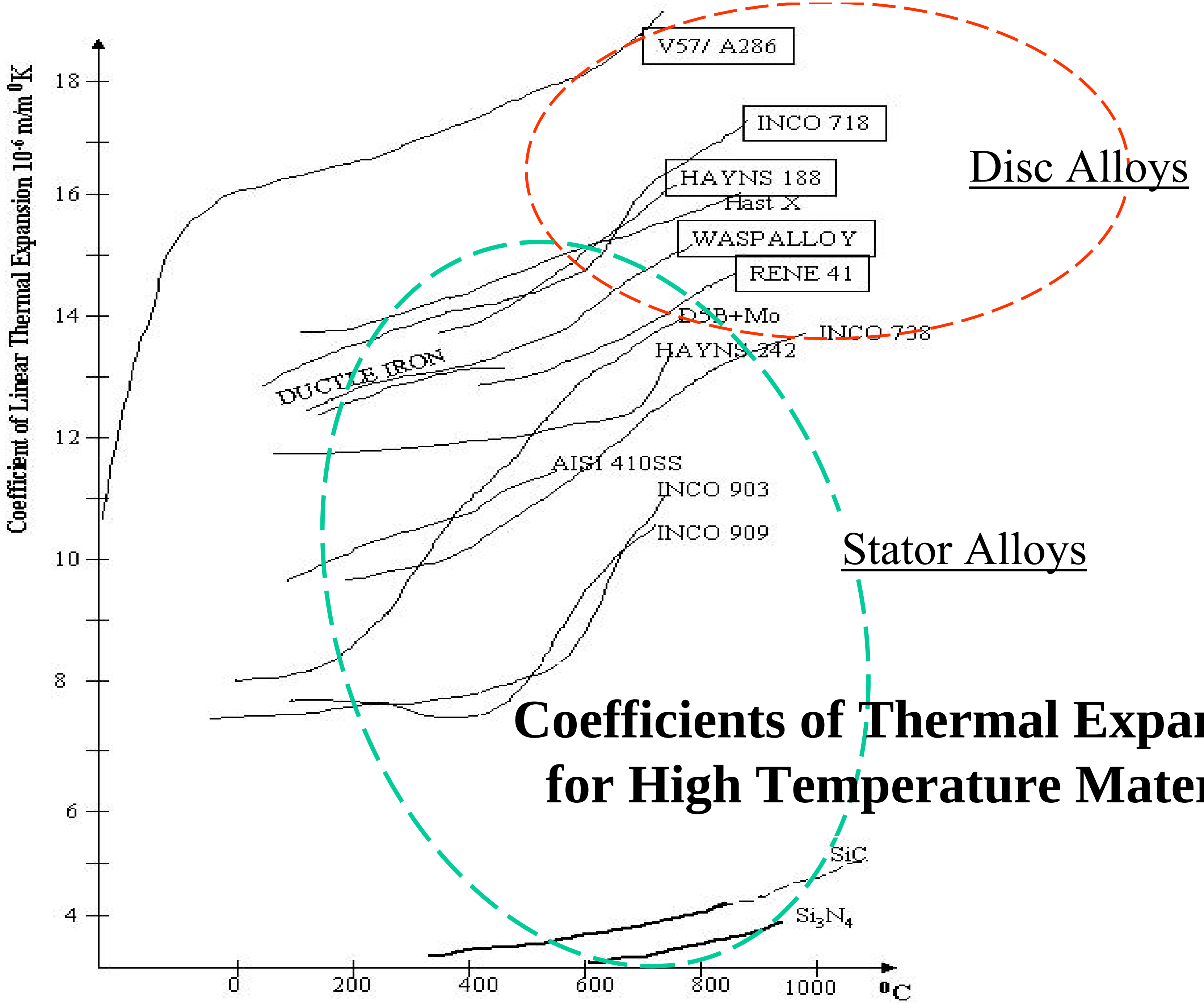


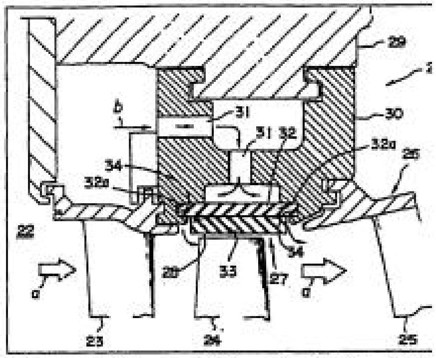
Effect of Thrust Bearing Position on TC Variation



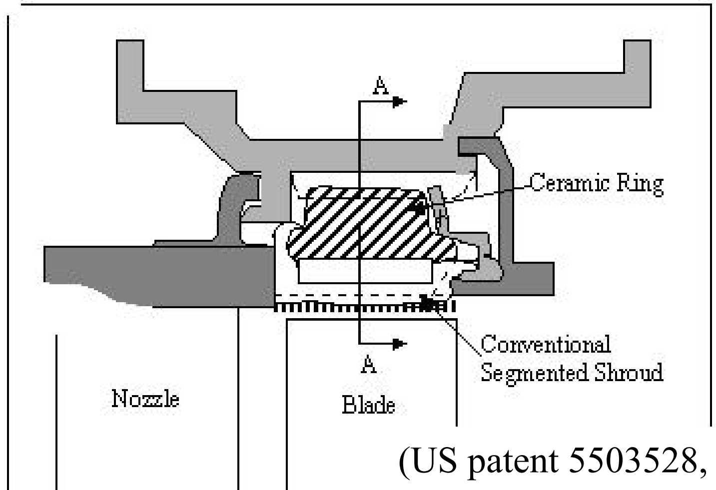
GP Design Providing Nearly Constant Transient TC

Coefficients of Thermal Expansion for High Temperature Materials



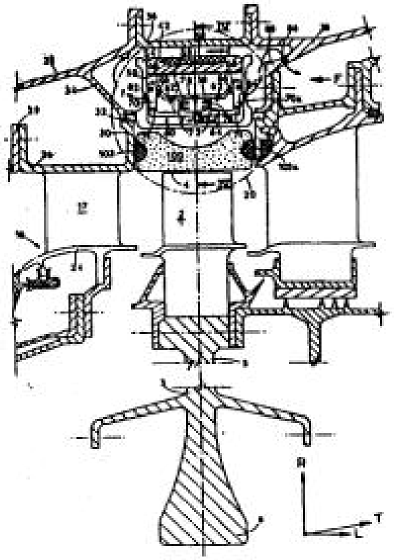


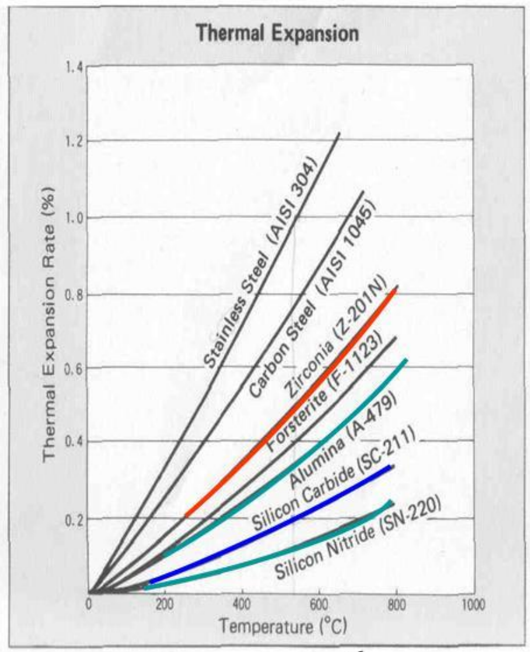
Segmented Ceramic Shrouds (Toshiba Patent, 1996)

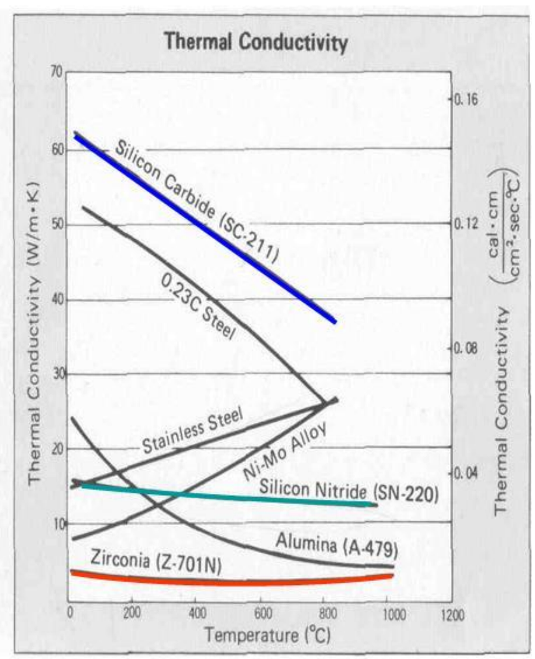


(US patent 5503528, 1996)

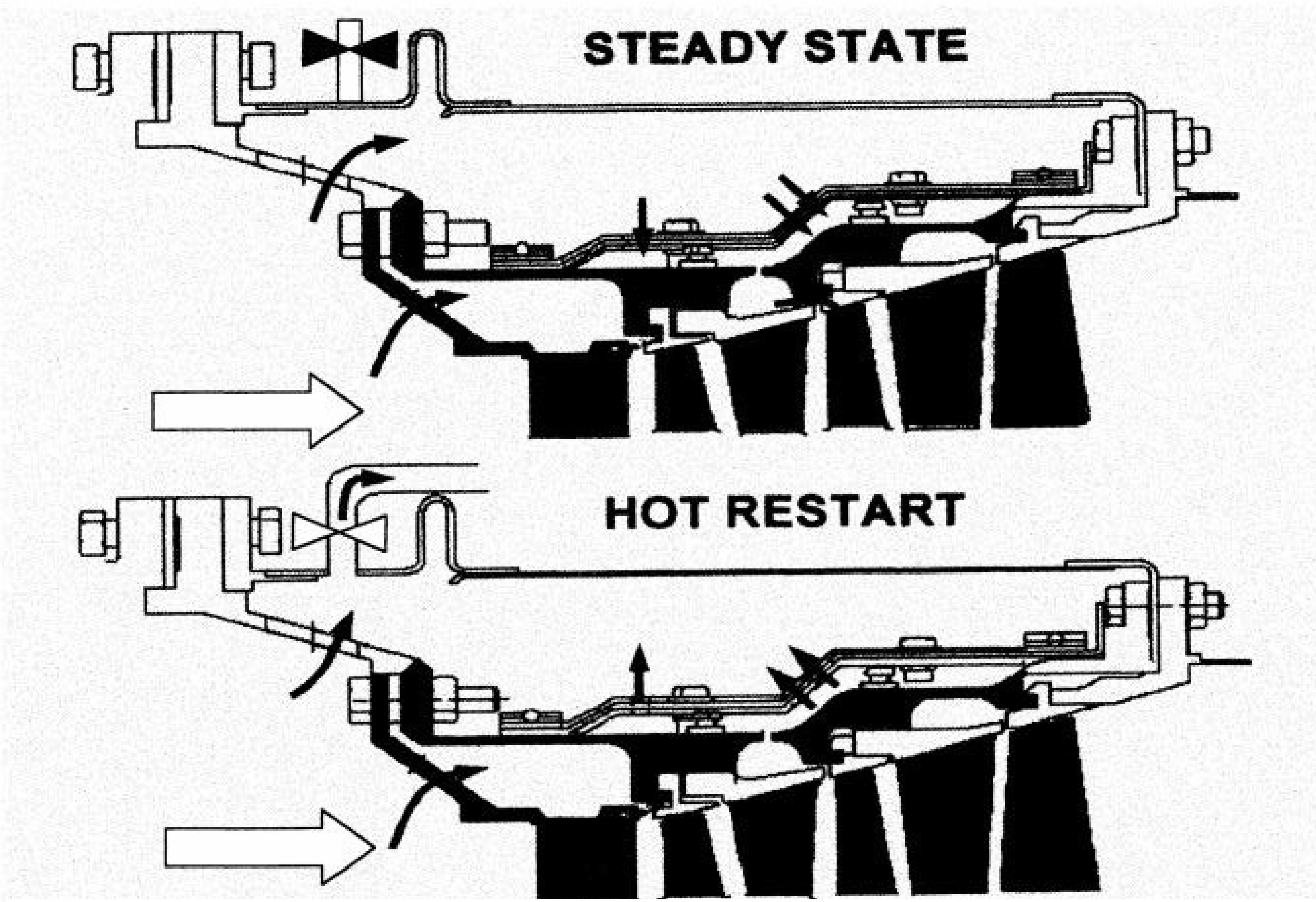
Ceramic Shroud
(SNECMA Patent)



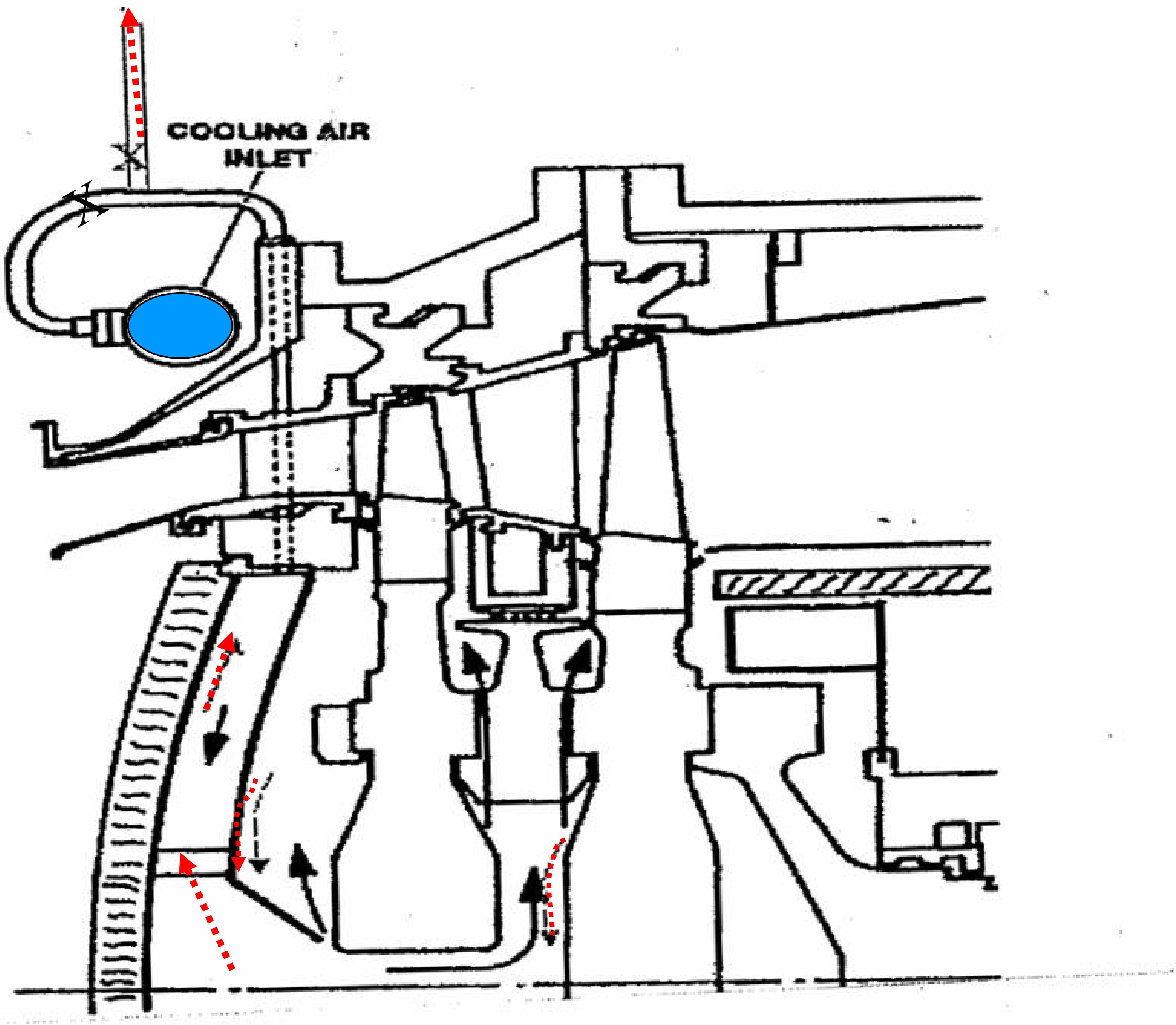




Potential Applications of Ceramics for Tip Clearance Passive Control

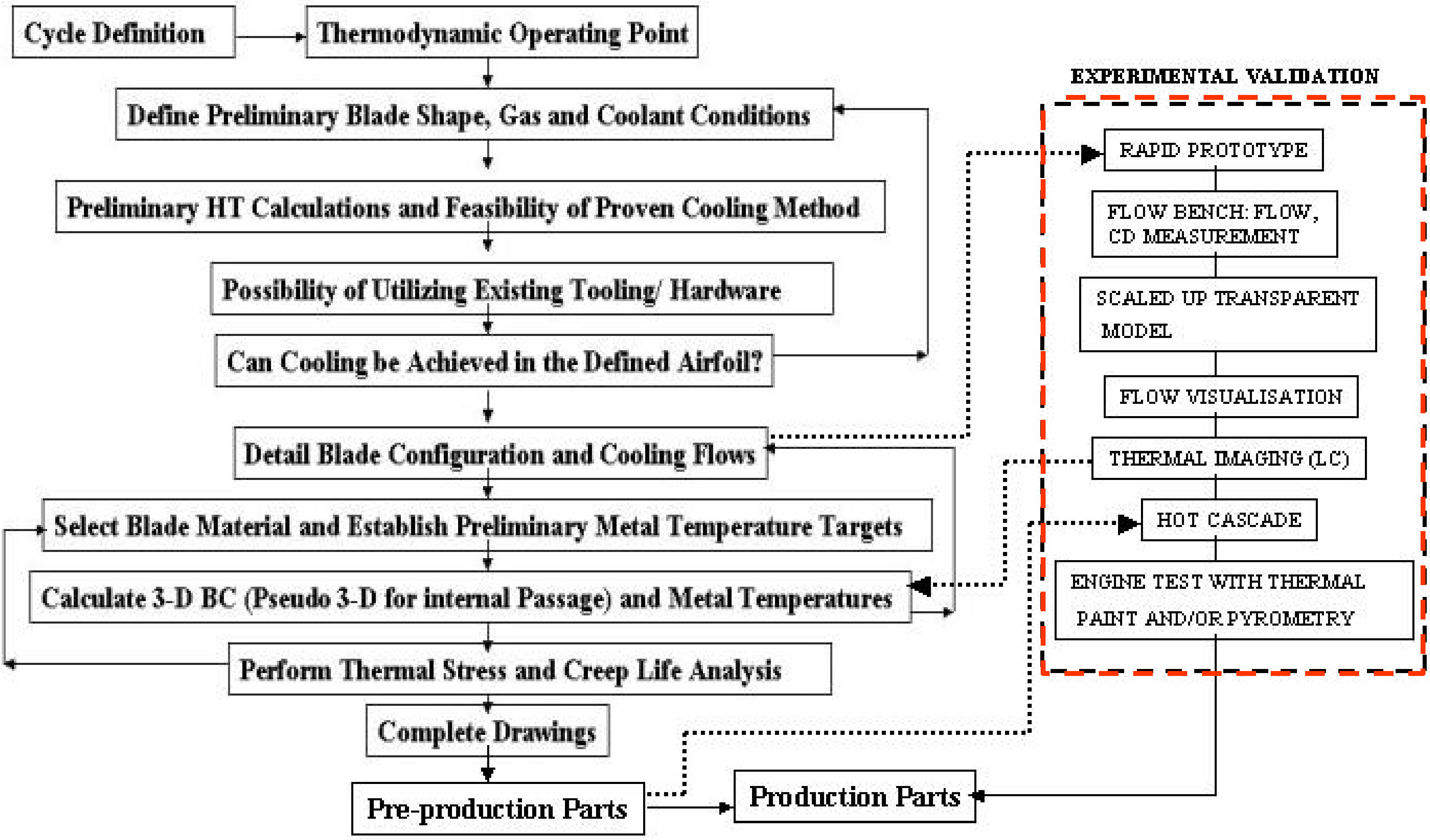


Combined Heating/Cooling for Semi-active Transient TC Control (US patent5779436, 1998)



Turbine Discs Thermal Growth Control (Proven Concept)

3. UNCERTAINTY OF ANALYTICAL PREDICTIONS AND EXPERIMENTAL VALIDATION PRACTICES



Development Process for Cooled Turbine Airfoil

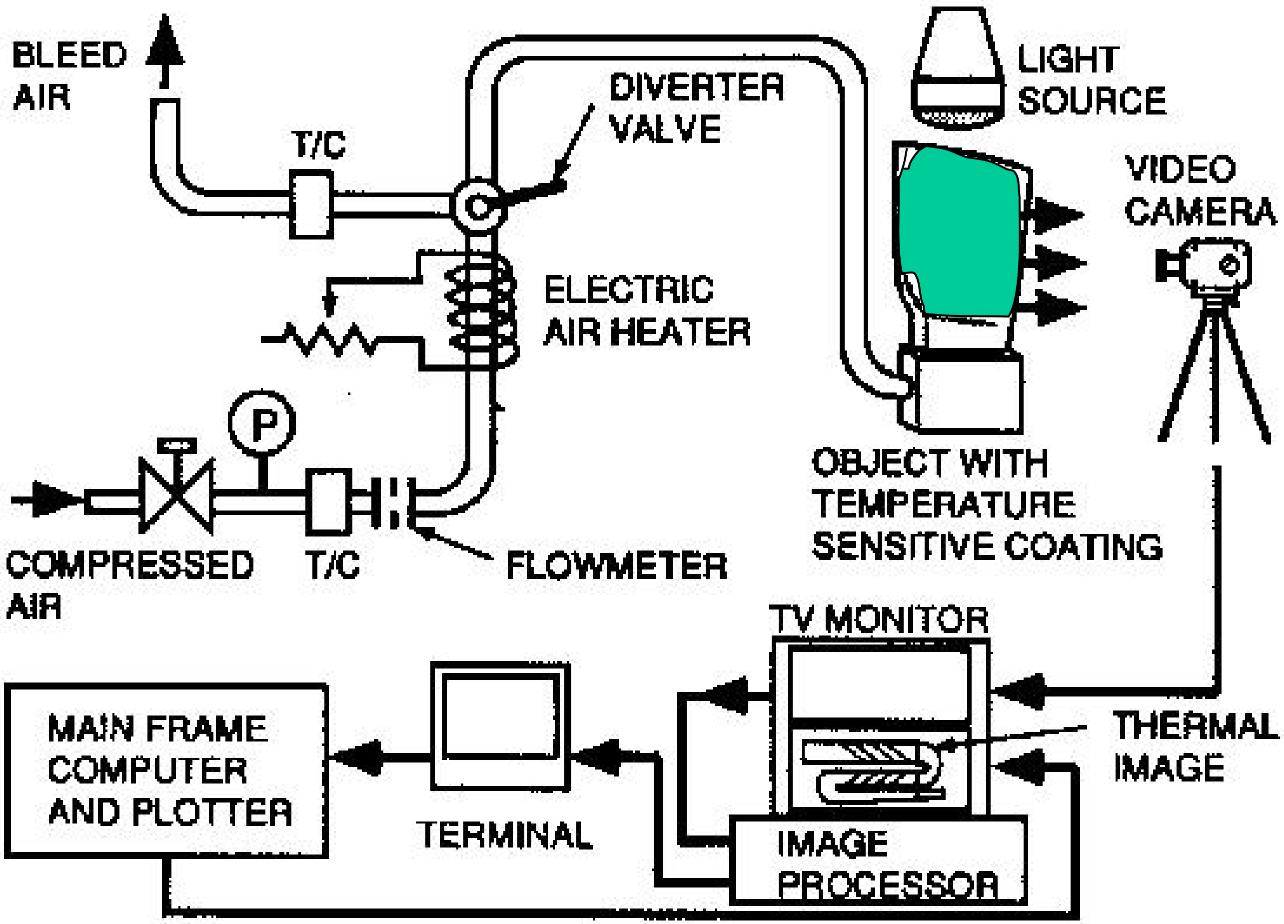
Experimental calibration and validation of analysis continue to play a major role in engine development

- Variation in properties of materials
- Inaccuracy of available correlations
- Manufacturing and assembly tolerances
- Uncertainty of instrumentation measurements
- Varying effects of operation in the field (surface roughness, type and quality of fuel, deposits)
- Inconsistent combustor temperature pattern factor
- Tolerance in expected radial temperature profile of the mainstream flow is applied as input for the turbine blade analysis

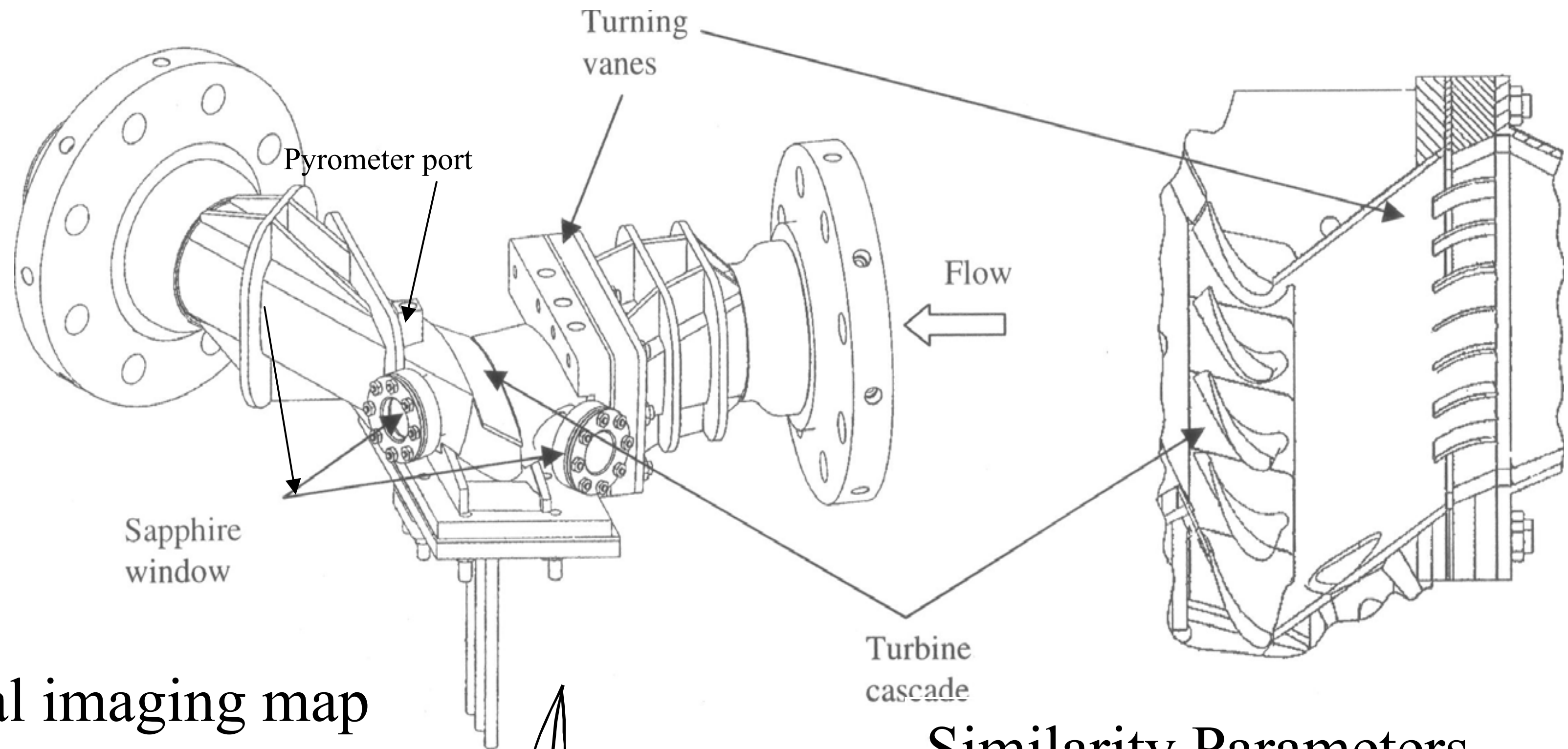
Sources of Uncertainty In Life Prediction

- **Airfoil internal flow study- flow vis in up-scaled models**
- **Liquid crystal technique –internal HT**
- **Up-scaled film cooling rig -PSP application**
- **Airfoil hot cascade – validation of conjugate HT predictions**
- **Disc/rim seal/preswirler flow and HT rig**
- **Rotating rig – effects of buoyancy/ Coriolis forces on blade internal flow and heat transfer**
- **Other supporting rigs: flow benches, calibrating devices**

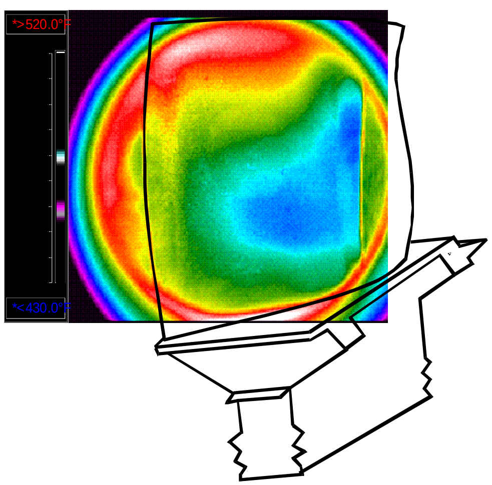
Recommended Experimental HT Facility

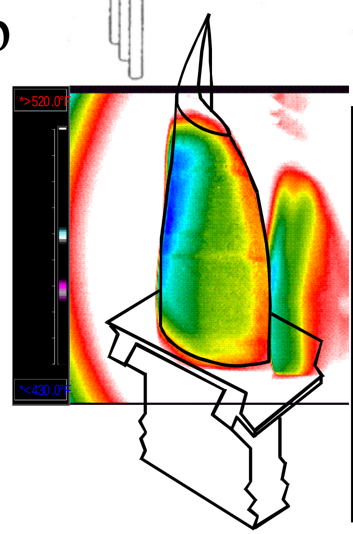


Internal blade HT studies with LC technique



Thermal imaging map

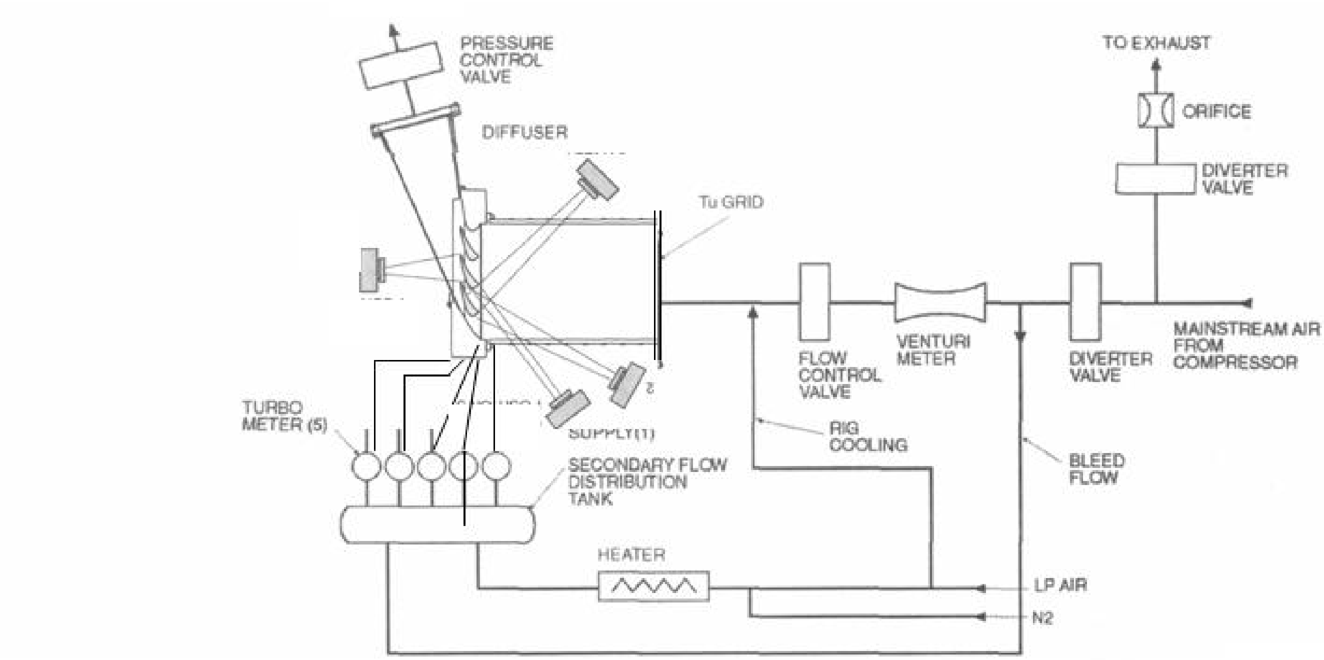


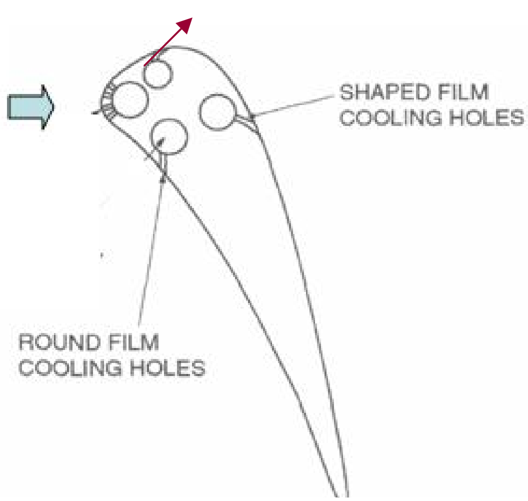


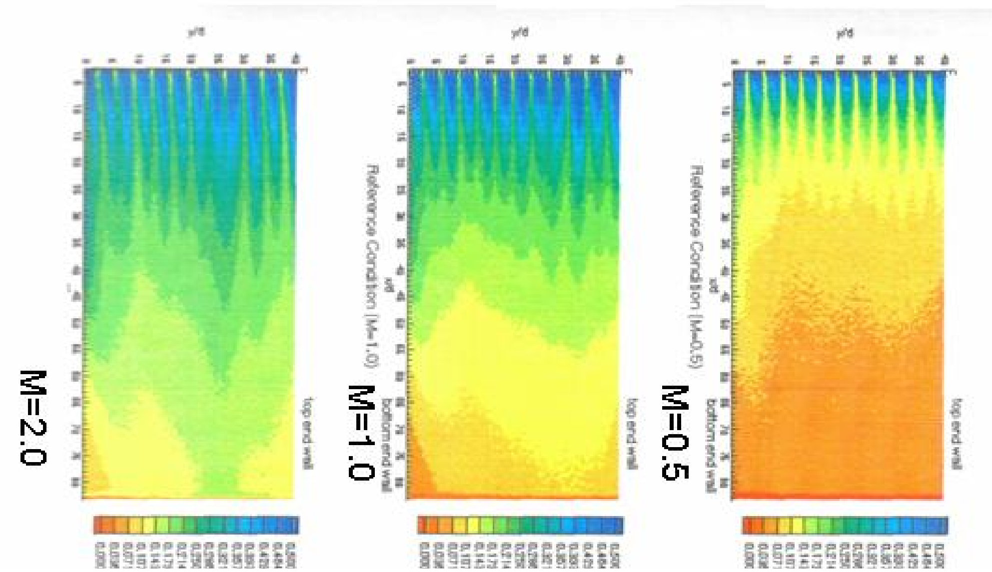
Similarity Parameters

- **The solutions of the Navier-Stokes and energy equations for compressible flow depend on a number of dimensionless groups including Re, Pr, Ma, Tw/Tg and Cp/Cv**
- **Turbulence intensity (from past experience) emulation is required**
- **Full geometric similarity including internal features are required**
- **Pr, Tw/Tg and Cp/Cv can be matched exactly**
- **Airfoil Re inlet and Ma exit matching are satisfactory**

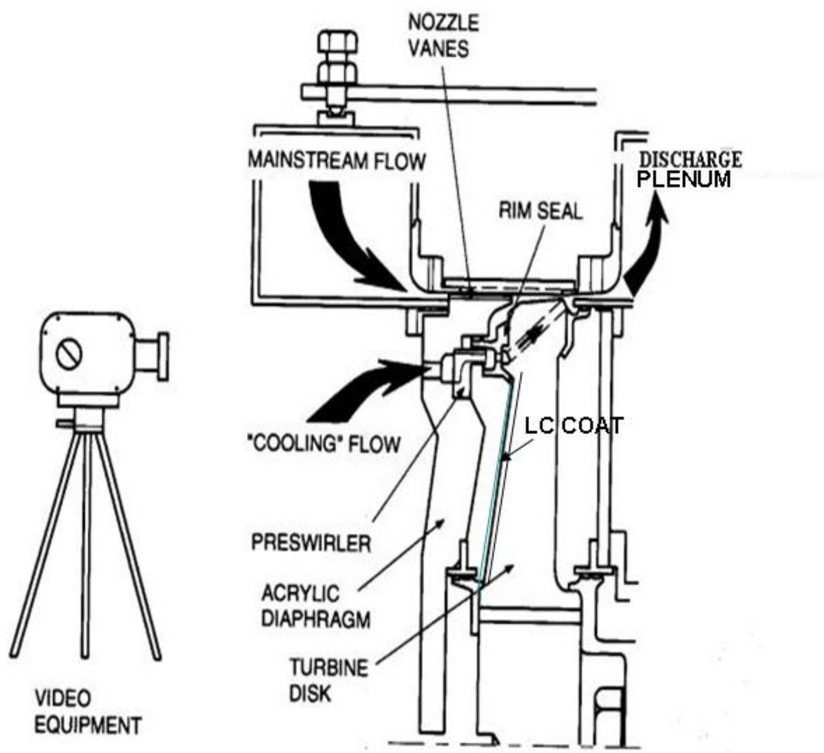
Hot Cascade Test Section

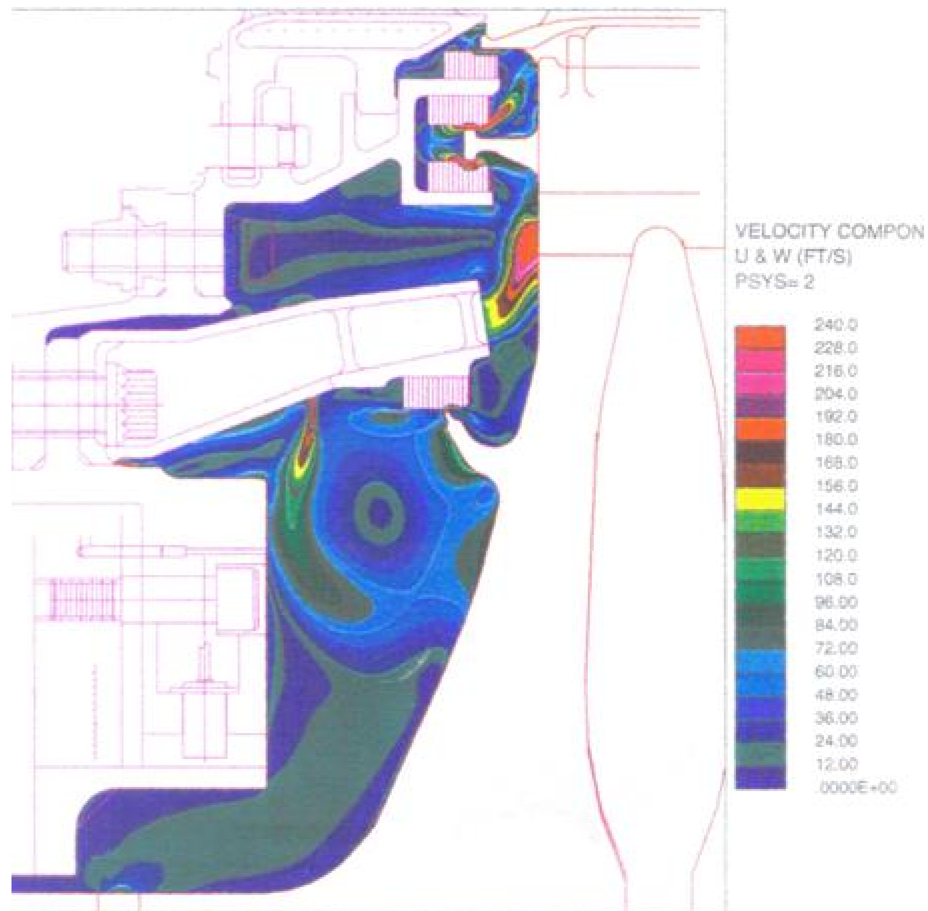




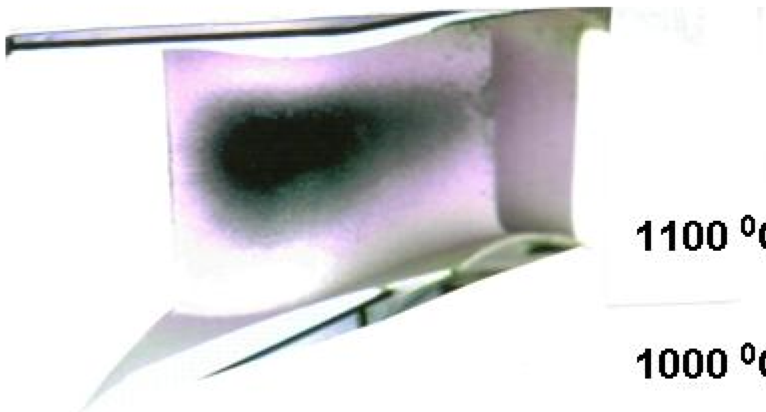


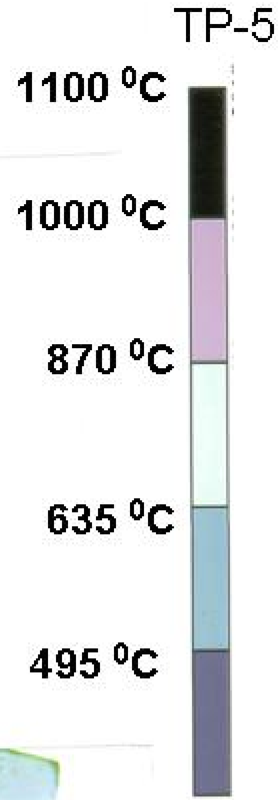
Pressure Sensitive Paint Application for Film Studies

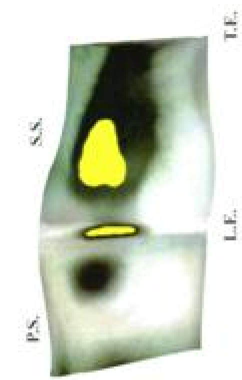


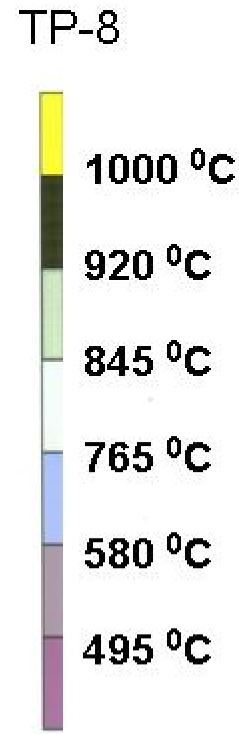


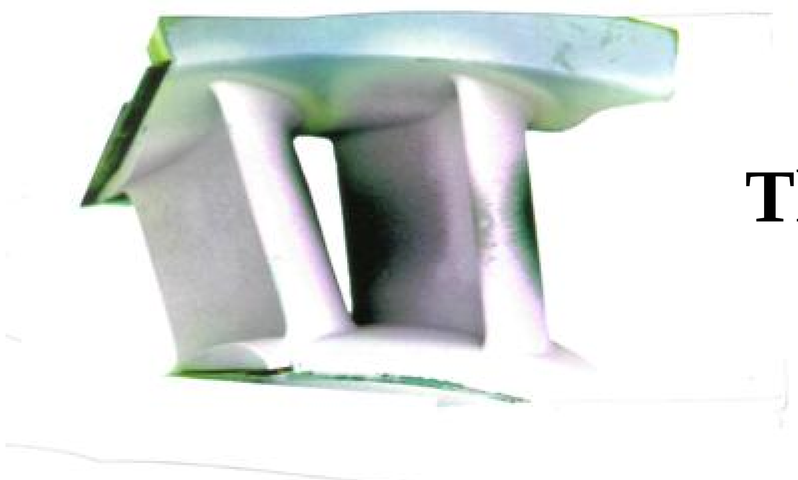
Rig Schematics and Analysis of Rim-Sealed Disc Cavity





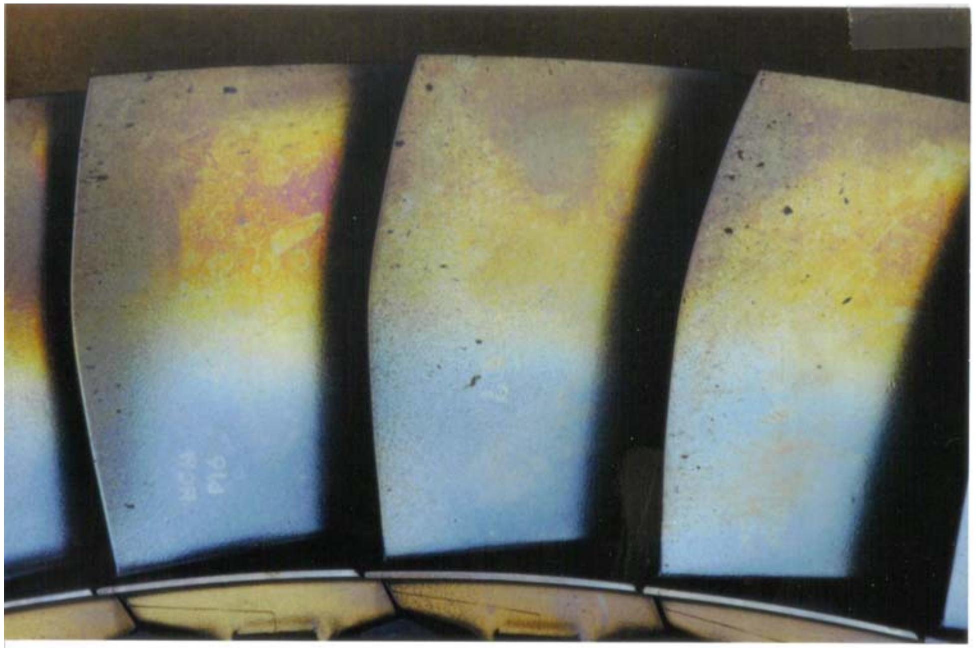


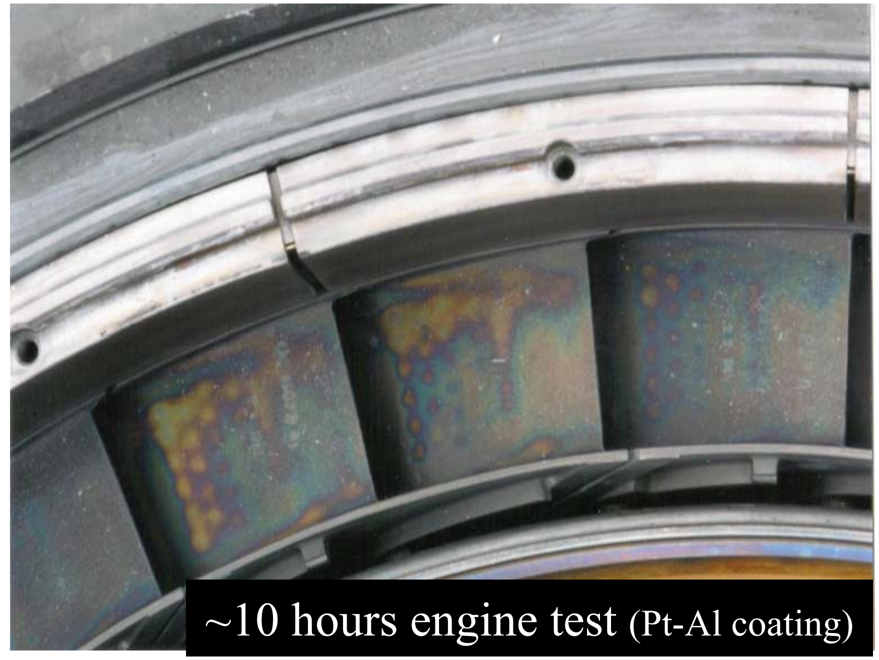


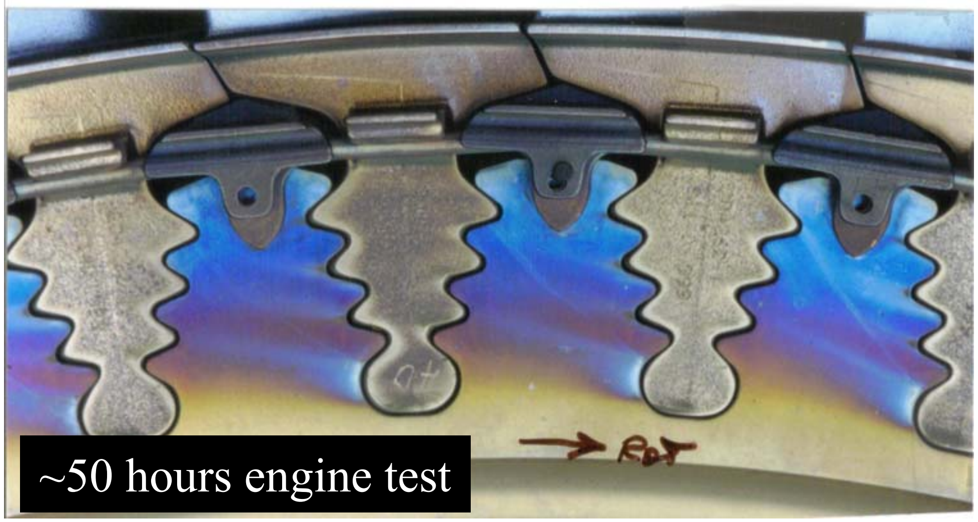


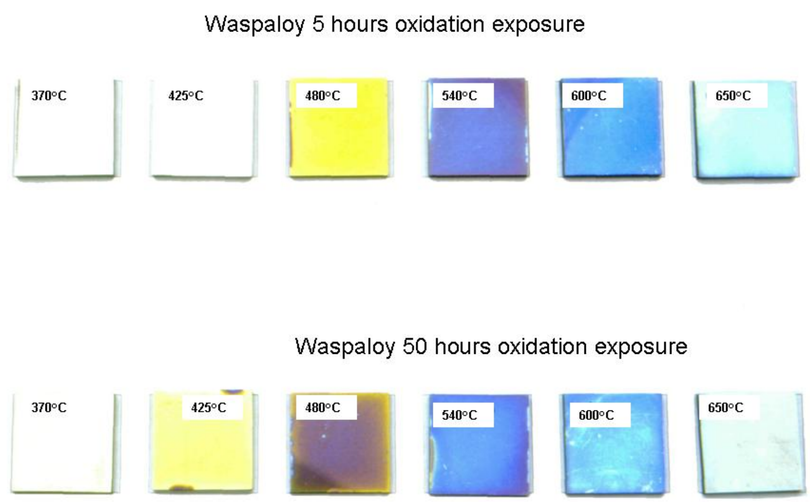
Thermal Paints Application

(Auto color recognition US patent









Natural Oxidation In Turbine Components

Concluding Remarks

- OPTIMIZED DESIGN FOR HOT SECTION GAS TURBINE COMPONENTS REQUIRES CONSTANT COMPROMISE BETWEEN LAWS OF PHYSICS, ECONOMICS AND HUMAN PSYCHOLOGY

- SKILFUL INTERDISCIPLINARY INPUT IS A KEY FOR SUCCESSFUL DESIGN

- USUALLY THERE ARE MORE THAN ONE POSSIBLE SOLUTIONS TO A PROBLEM ENCOURAGING NEW IDEAS AT EARLY DESIGN STAGE

- A PRINCIPAL OF A "LOW HANGING FRUIT" AT LESSER RISK AND IMPLEMENTATION COST IS USUALLY PREFERRED

- THE BEST NUMERICAL PREDICTIONS HAVE TO BE VALIDATED EXPERIMENTALLY

- CREATIVITY WITH "OUT OF THE BOX" IDEAS IS A NECESSARY ELEMENT OF ADVANCED DEVELOPMENT, EVEN IF IT PRODUCES A SOLUTION THAT MIGHT APPEAR INITIALLY RISKY