November 8, 2018

GAS TURBINE ENGINE SECONDARY FLOW SYSTEMS

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Agenda

- What is Secondary Flow?
- Purpose for the Secondary Flow Systems
- Chargeable Vs Nonchargeable Flows
- Seals Selection and Leakage
- Effects of Geometry on Flow
- Modeling Secondary Flow Systems
- Best Practices and Lessons Learned

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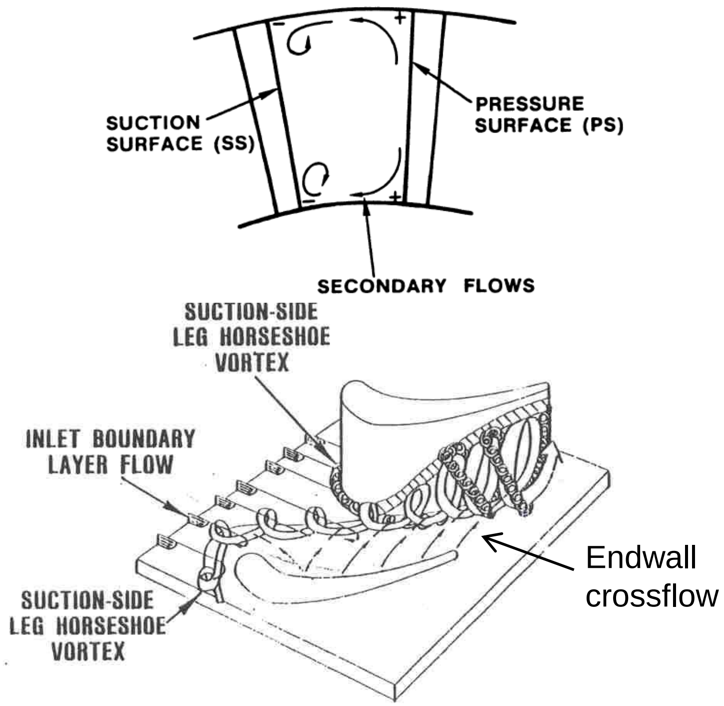
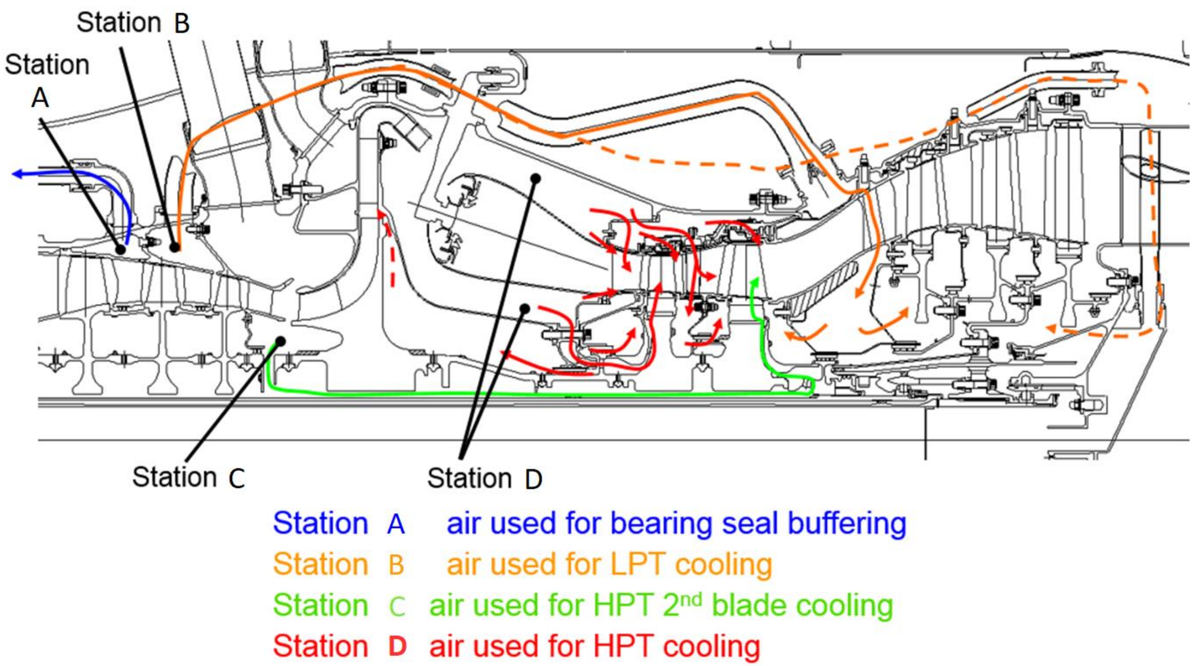
What is Secondary Flow?

- The secondary flow has at least two meanings in the Gas Turbine Industry



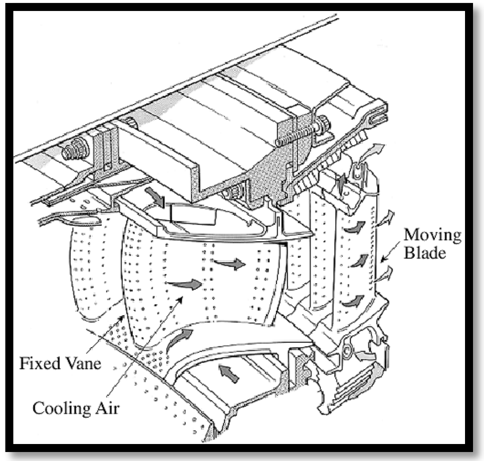


- To an aerodynamicist:
  - Flow within flowpath but not along streamlines.

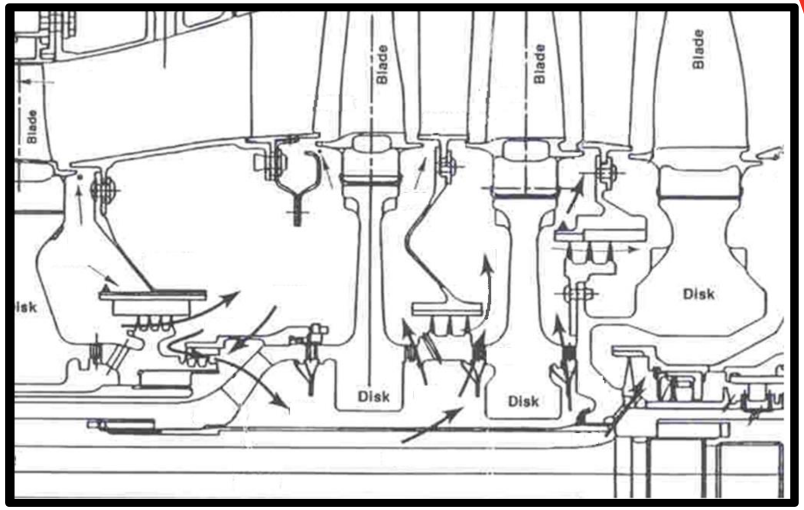
- To a Mechanical Designer
  - Flow outside the flowpath used to cool vanes, blades, shrouds and disk cavities. Provides seal buffering to oil sumps.

Non-Aerodynamic Secondary Flows Will Be Reviewed

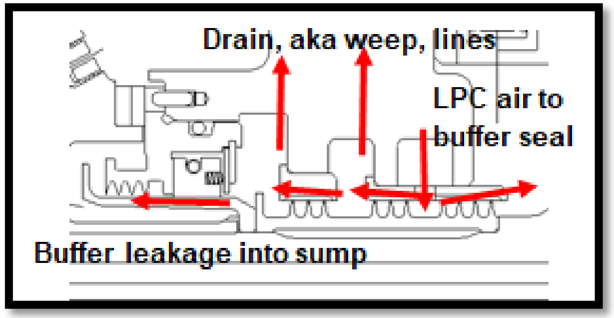
Purposes for the Secondary Flow System



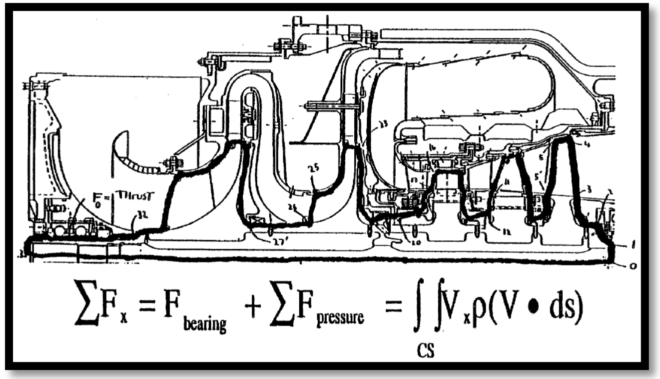
Deliver cooling air to vanes and blades



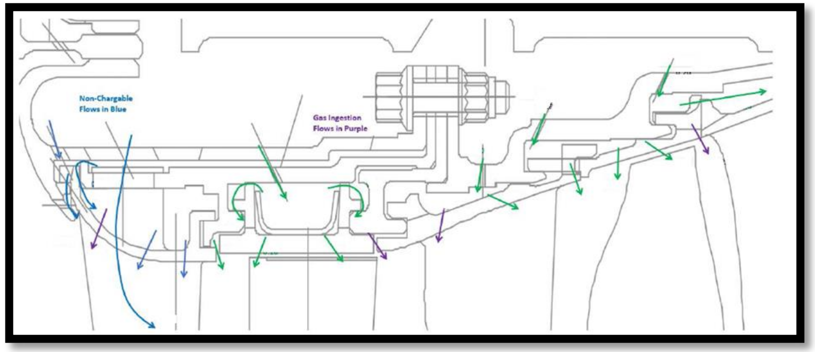
Disk cooling and cavity purging



Buffering to air/oil interfaces at the bearing cavities



Adequate spool thrust to support bearing life



Turbine Shroud cooling and purging

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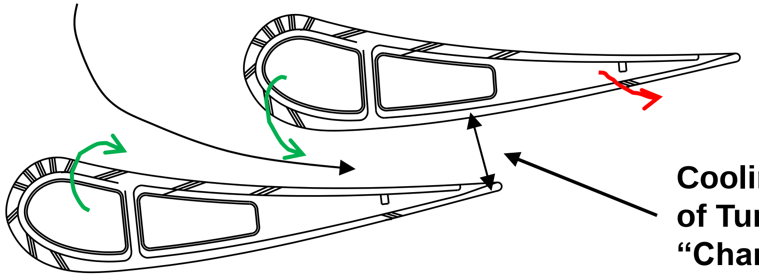
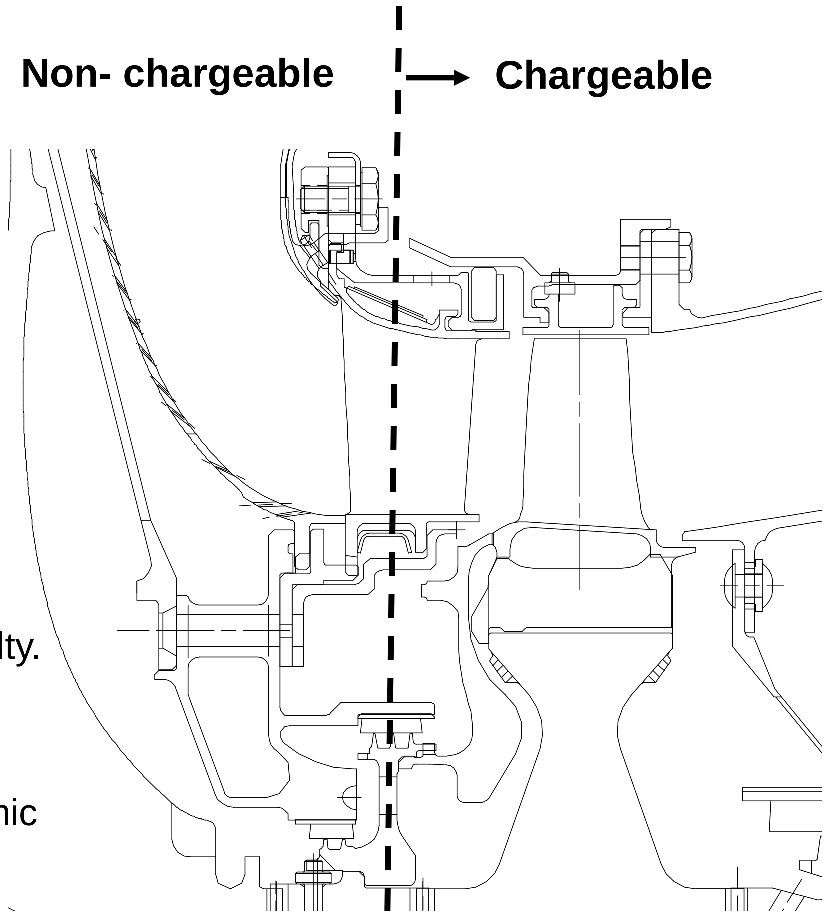
Chargeable Vs Nonchargeable Air



Cooling Air Entering Flowpath Downstream of Turbine 1st Stage Vane Throat is "Chargeable" to Cycle



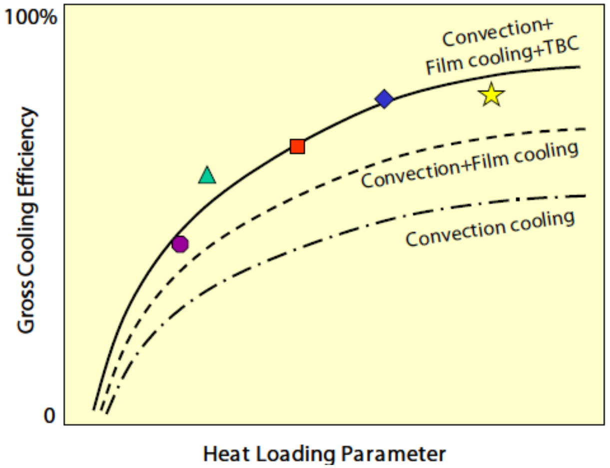
- **Total Air Used for Cooling** – approximately 20-30% of the total inlet core flow.
  - Efficiencies gained by higher turbine inlet temperature can be eliminated by increases in chargeable flows – be careful!
- **Chargeable Air** – when no work is extracted from the air by the downstream rotor.
  - The farther downstream the air is introduced back into the flowpath, the greater the penalty.
  - +1% air increases fuel consumption ~1% and Turbine inlet temperature by ~25 F to produce the same power.
  - The higher the source pressure of cooling air, the greater the penalty to the thermodynamic cycle.
- **Non-Chargeable Air** –
  - Reducing nonchargeable air ensures adequate air for combustion and reduces 1st stage turbine nozzle inlet gas temperature.

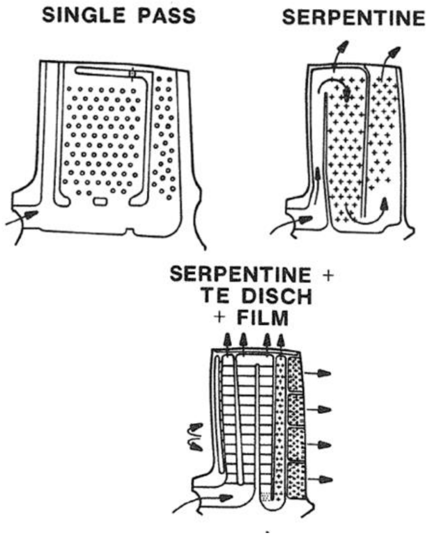
Minimizing Secondary Air Flow Use Is Important to Cycle Competitiveness

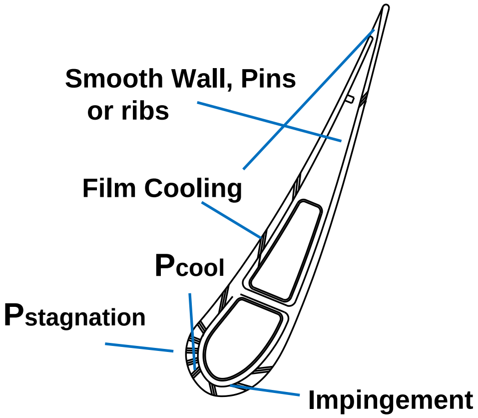
Basic Cooling Guidelines- Blades & Vanes Airfoils

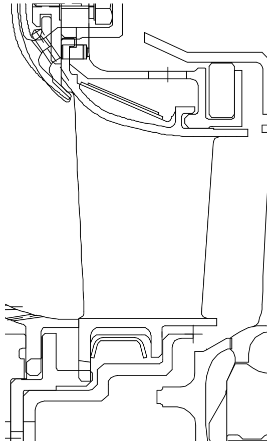
- Airfoils are basically complex heat exchangers.
- Goal:
  - Provide enough cooling air to achieve field durability.
- Common failure mechanisms:
  - Thermal Mechanical Fatigue (TMF)
  - Stress Rupture (Creep)
  - Environmental Attack (Oxidation/Corrosion)
- Solution:
  - Material Selection (i.e. single crystals)
  - Coating (i.e. MCrAlY, PtAl)
  - Thermal Barrier Coating (TBC)
  - Advanced cooling schemes (i.e. film cooling)

Cooled Blade







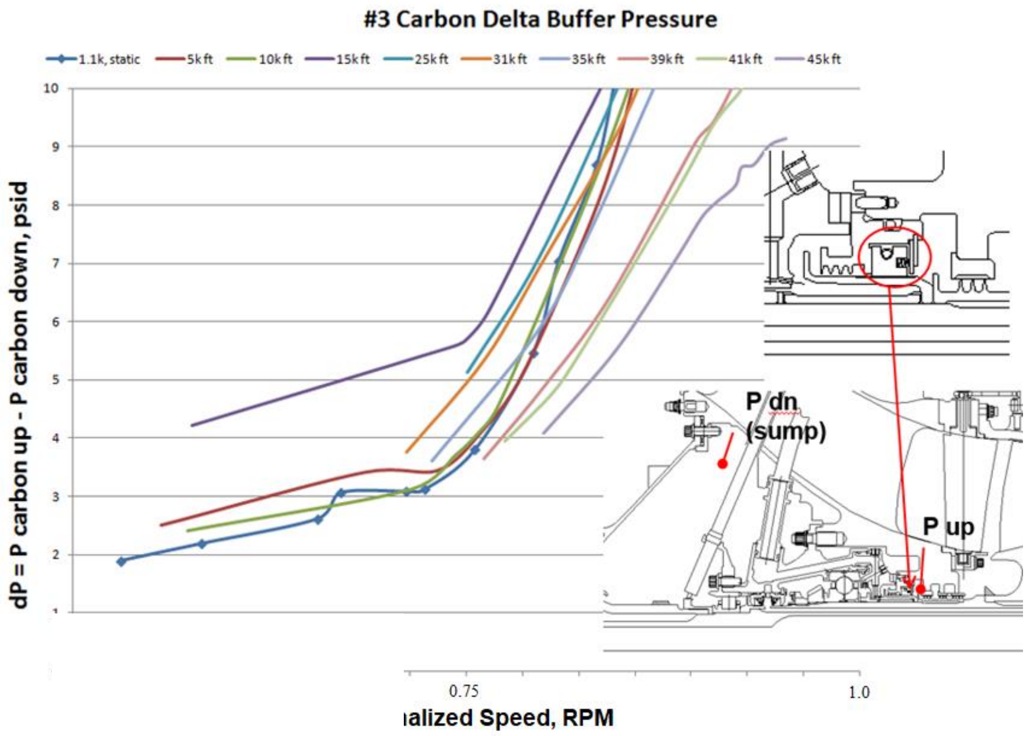


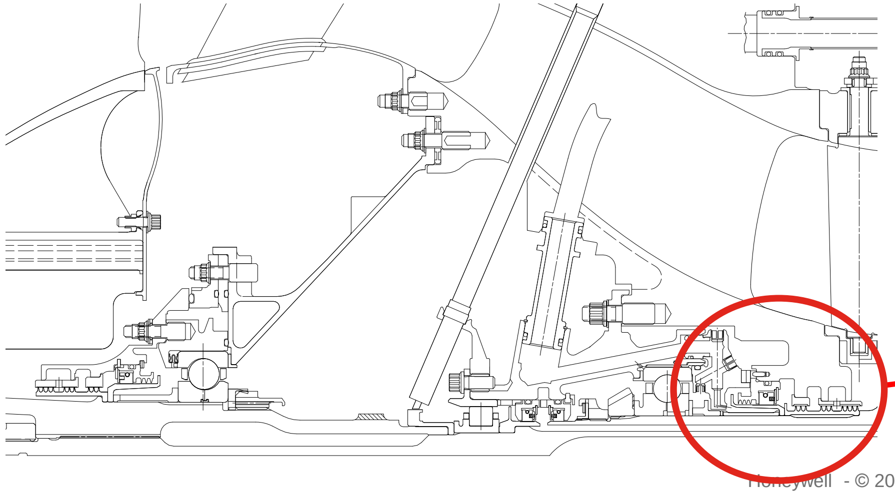
Cooled Nozzle

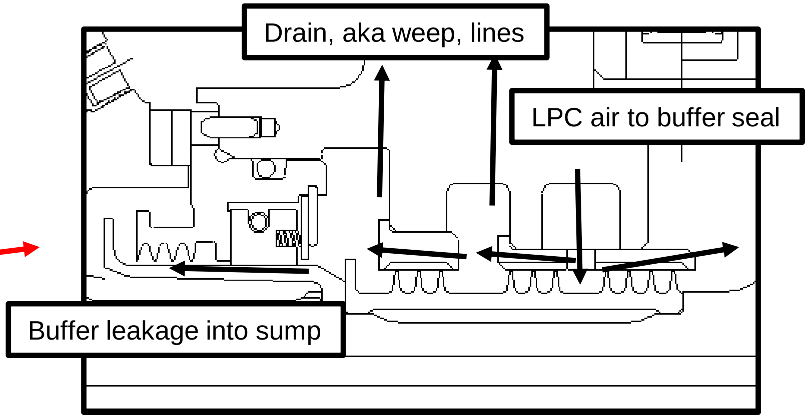
Advanced Cooling Schemes are Crucial to Reduce Secondary Flows

Air-Oil Seals Buffering

- Goal:
  - Low buffer air temperature to avoid coking and fire.
  - High enough pressure at low power and altitude to prevent oil leakage.
  - Low enough pressure load at high power to not damage seal.
- Common failure mechanisms:
  - Not positive buffering pressure at all operating conditions causing oil to leak out of the sump.
  - Carbon seal durability.







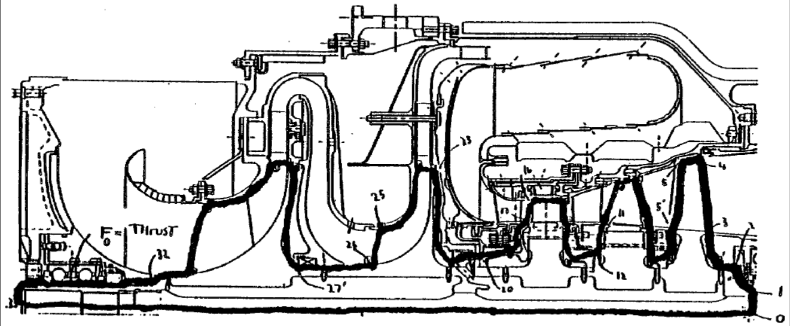
Buffering System Design is a Joint Secondary Flow-Lubrication Systems Team Effort

Bearing Axial Thrust Load

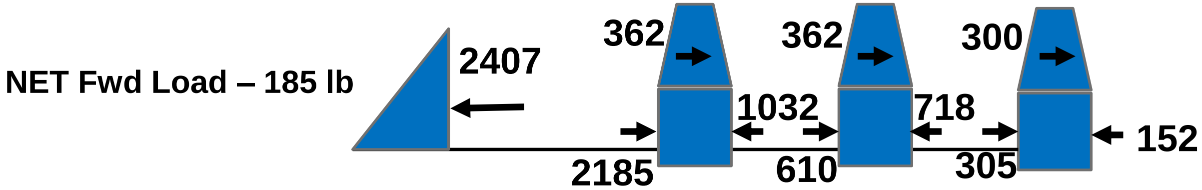
- Goal:
  - Predict engine thrust magnitude and direction at different operating conditions.
  - Results will be used to design thrust bearing.
- Potential Consequences:
  - Excessive axial motion causing potential rubs between static and rotating components.
  - Failure of thrust bearing due to skidding (sliding motion over the bearing track causing excessive pitting).

- Solution:
  - Control thrust direction and magnitude by changing impeller aft face flow, lab seal radii, airfoils reactions or/and adding “balance piston”.
  - Use duplex bearing

Analytical Calculation – Conservation of Momentum



$$\sum F_x = F_{bearing} + \sum F_{pressure} = \int_{CS}\int V_x \rho (V \bullet ds)$$

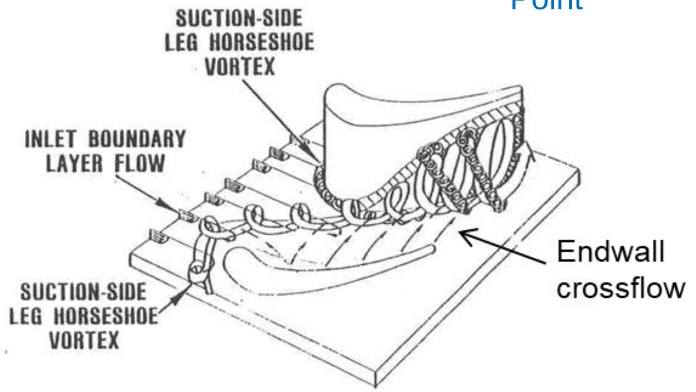


- Boundary Conditions:
  - Cavity pressures from secondary flow model.
  - Airfoil thrust from turbine and compressor aerodynamic models.

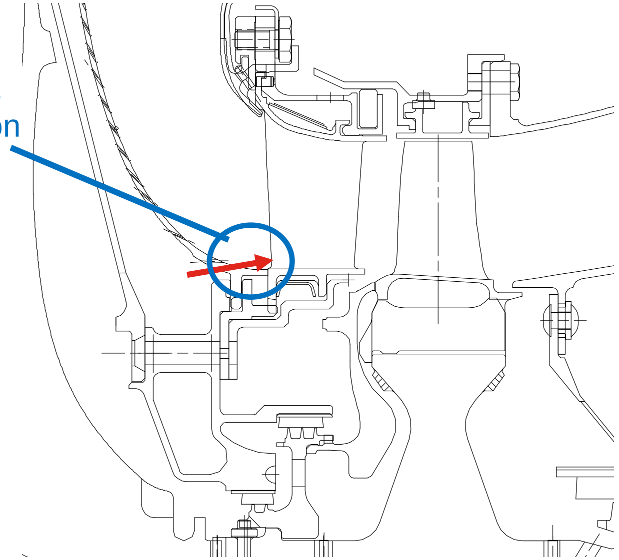
Thrust Prediction Accuracy Difficult Due to Being Differences Between Large Numbers

Basic Cooling Guidelines- Endwalls and Shrouds

- Endwall Cooling:
  - Goal:
    - Avoid/minimize disruption to nozzle exterior surface film cooling effectiveness.
  - Solution:
    - Use vane endwall vortex busters to dissipate the formation of horseshoe vortex that disperse film cooling.

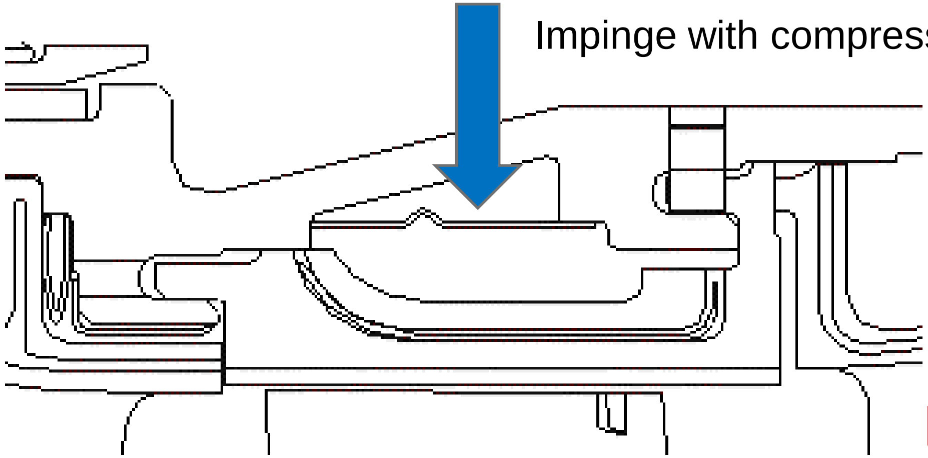


Vortex Buster
aka High Velocity Jet
Directed at Stagnation
Point



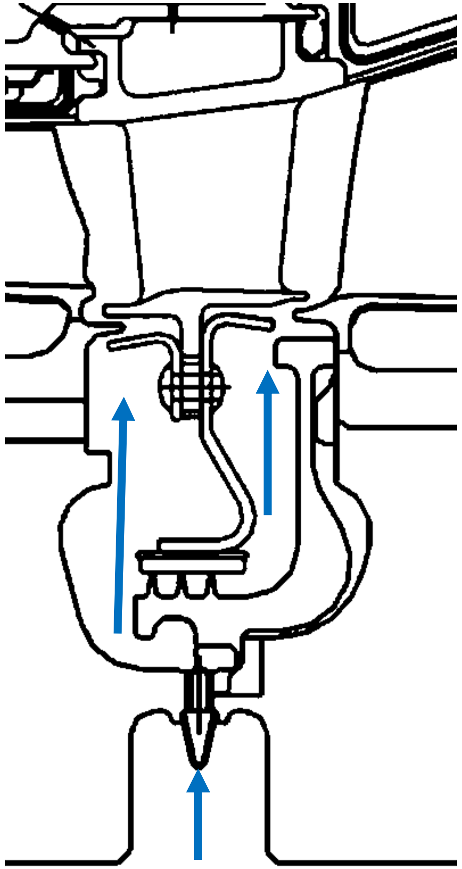
- Shroud Cooling:
  - Goal:
    - Avoid hot gas ingestion and keep metal temperature within design limits.
  - Solution:
    - Use seals (i.e. feather, etc.) to pressurize cool side to provide backflow margin against gaspath pressure variation.

Impinge with compressor discharge air



Basic Cooling Guidelines- Disks

- Goal:
  - Avoid hot gas ingestion into disk cavities caused by gaspath circumferential pressure gradient.
  - Keep cavity temperature within design limits.
- Potential Consequences:
  - Premature rotor failure that could results in disk separation (uncontained).
- Solution:
  - Use enough air to purge cavity. If cannot, use enough to dilute ingested air to meet Tcavity design
  - Use advanced flow discourager designs (i.e. fish mouth)



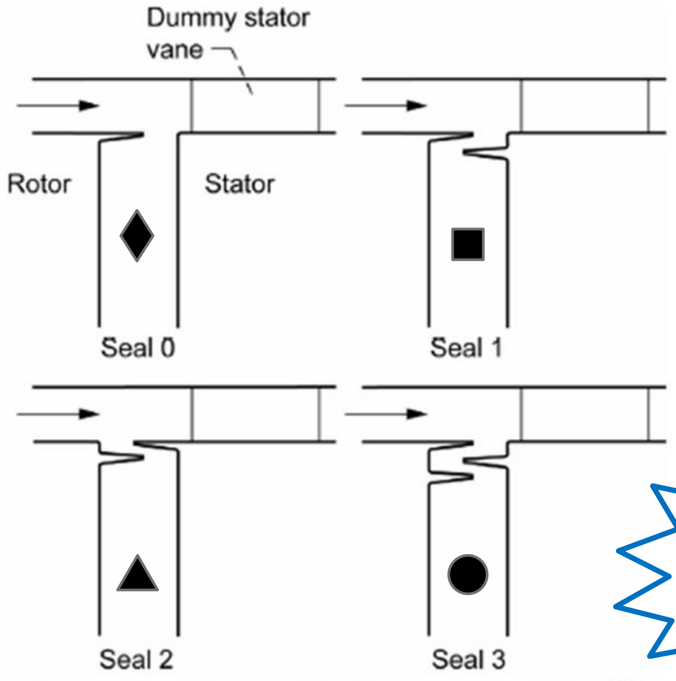
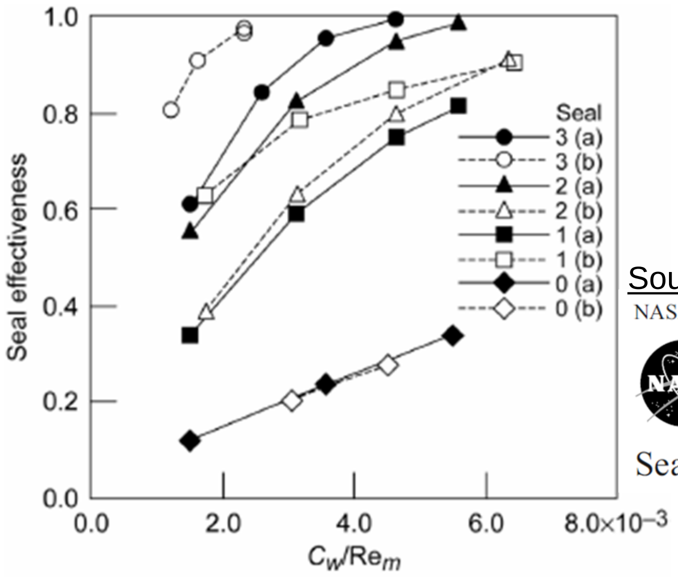


Figure A2.—Experimental rim seal configurations[175]

Best



Source:
NASA/TM—2006-214341

Sealing in Turbomachinery

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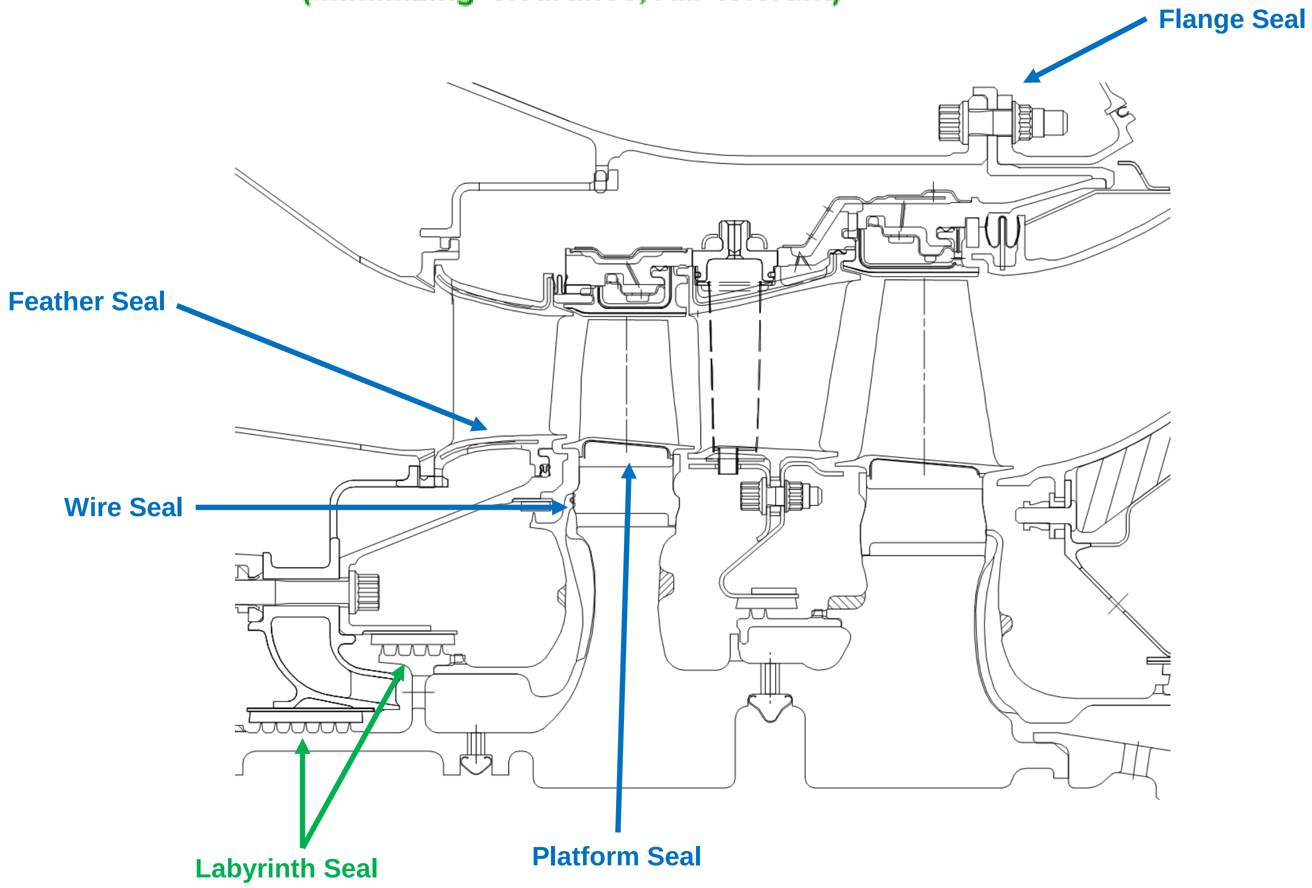
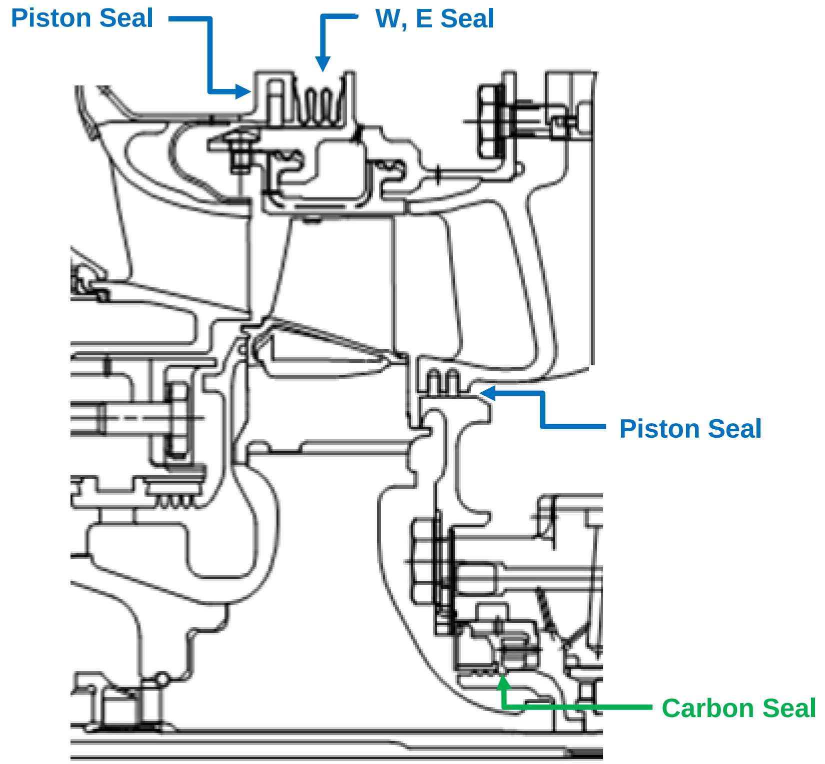
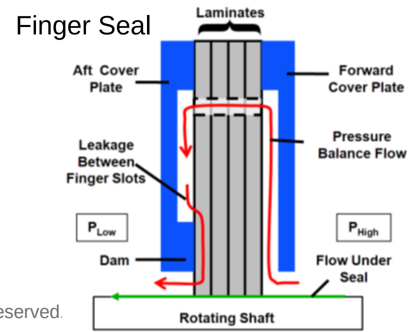
Commonly Used Seals in the Industry

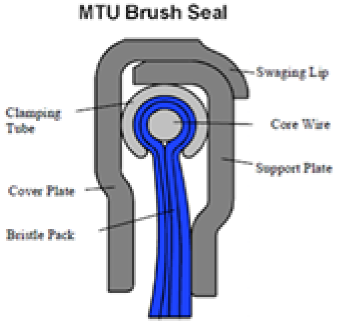
Rotating Part to Static Part Sealing
(minimizing clearance, rub tolerant)



Static to Static Part Sealing or Rotating to Rotating
(maintaining contact on sealing surfaces)



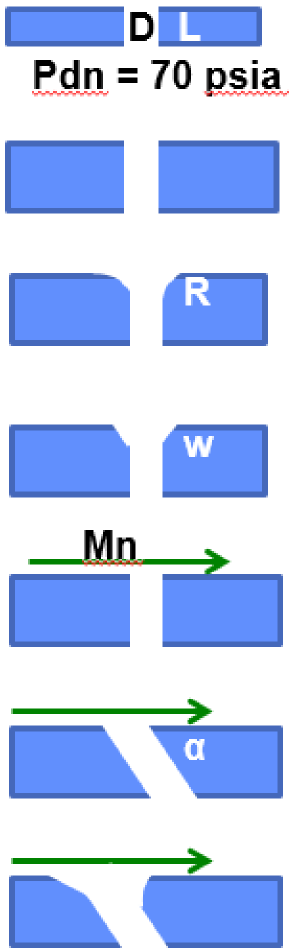




- Finger or brush seals provide better leakage control and durability than piston and Labyrinth seals.

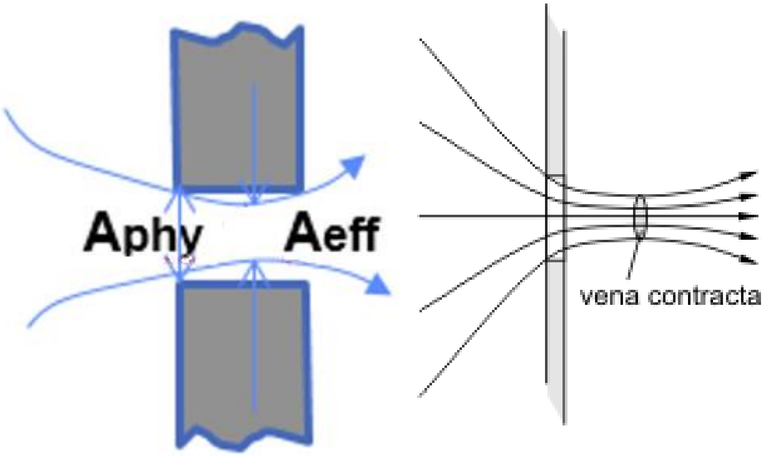
Effects of Geometry – Metering Hole

Pup=100 psia, Tup=800 F



Geometry	Parameter	Cf	Flow
Sharp Edge, Thin Wall	D=.03 in L=.015 in	Cf = .76	1X flow
Thick Wall	L=.045in	Cf = .79	1.04X
Rounded Inlet	R=.005	Cf = .94	1.24X
Chamfered Inlet	w=.005	Cf = .92	1.21X
Cross Flow, Sharp Edge	Mn= 0.6	Cf = .26	.34X
Inclined Sharp Edge	α=30	Cf = . 46	.61X
Rounded Inlet	R=.005	Cf = .52	.68X

$C_f = C_d$ = Effective Area/Physical Area



Correct Modeling of Geometry is Crucial for Accurate Prediction of Secondary Flows

Modeling of Secondary Flow Systems

- Modeling Secflo systems is commonly done solving one-dimensional compressible steady state flow problems (w/o shocks)
- Elements simulate the geometry in a typical gas turbine engine.
- Most common elements are depicted in Figure 1.
- More complex flow elements are described by flow tables (corrected flow versus pressure ratio) defined from actual flow testing of individual components or/and CFD analysis.

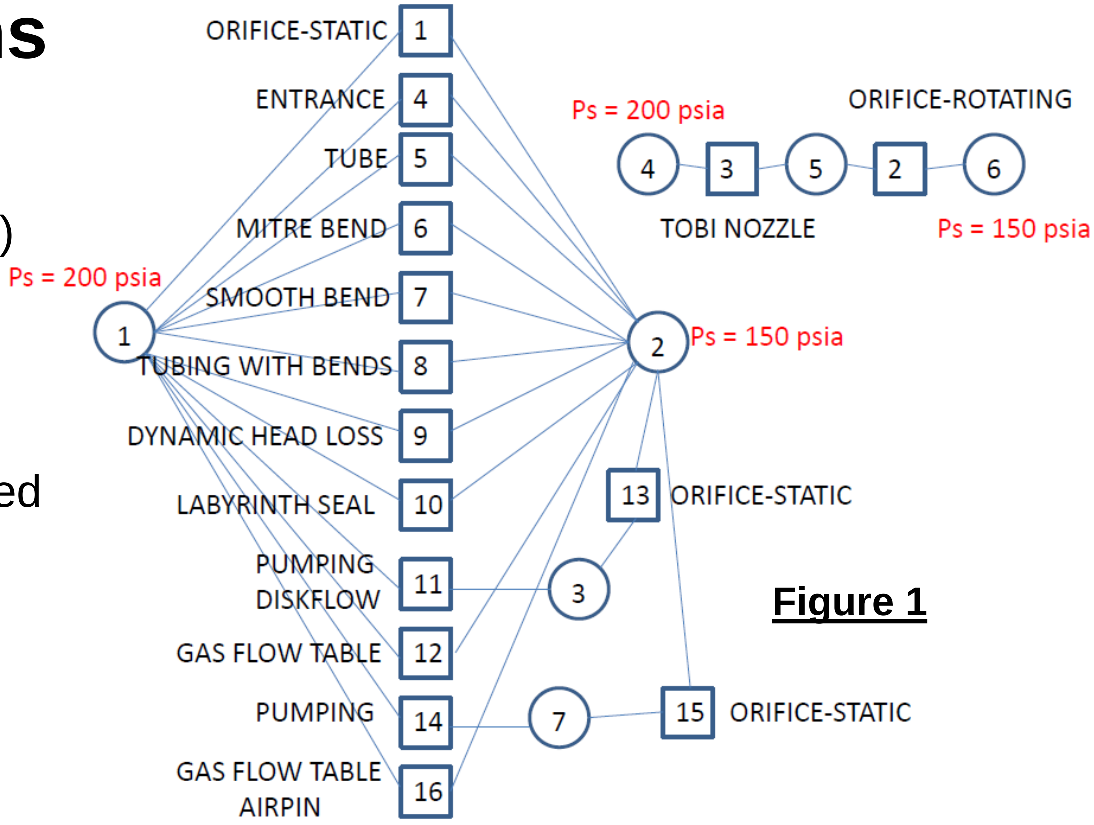


Figure 1

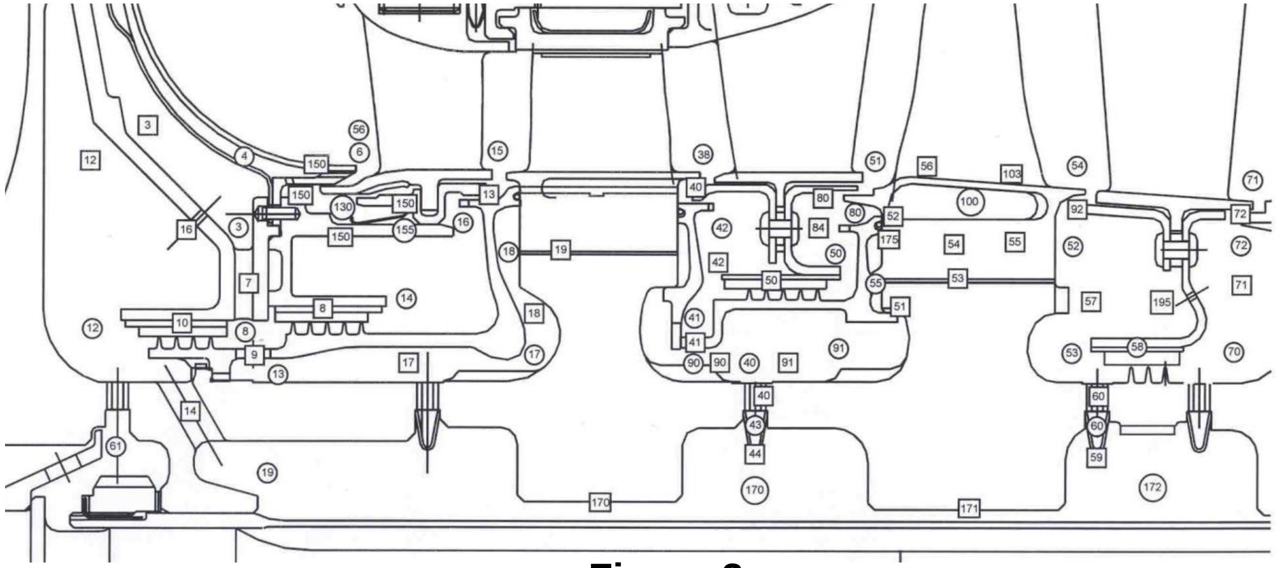


Figure 2

- Model Solution:
  - Model iterates to convergence based on conservation of mass and energy. It solves for mass flow, pressure and temperature.
  - Figure 2 shows a typical model.

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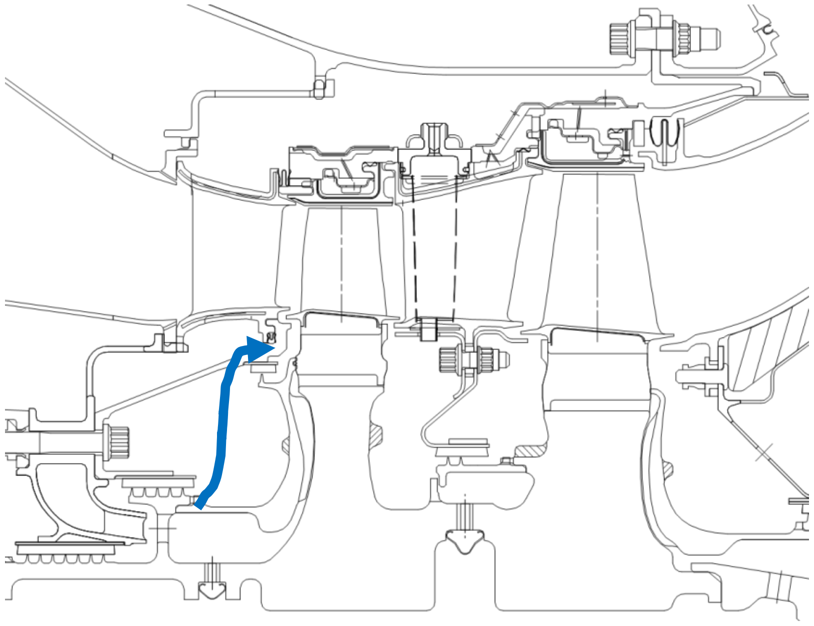
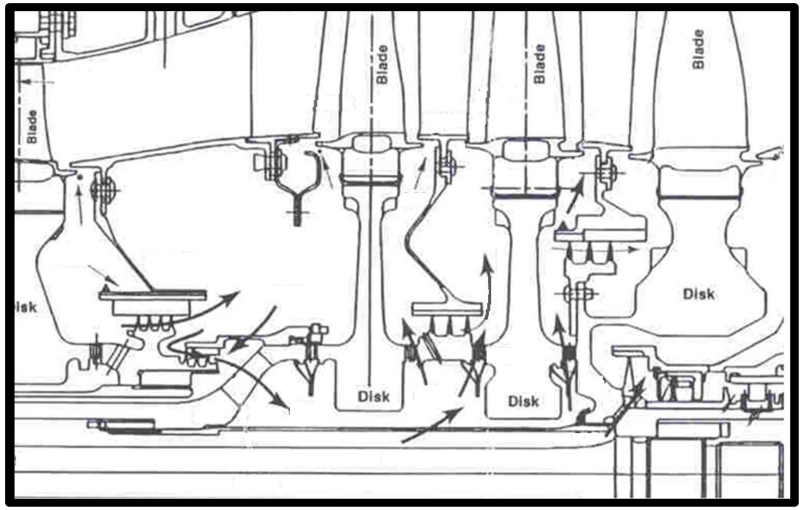
A Few Best Practices/Lessons Learned

1. Use lowest stage compressor for cooling that can deliver needed pressure; be sure to check throughout the operating envelope.
2. Double use cooling air whenever safely possible.
3. Use flow circuit metering locations to easily adjust air during development and for growth flow changes.
4. Look at flows throughout tolerance range, particularly for tight lab seals and for small hole diameters.
5. Lab seals clearances should be sized to show witness marks on land.
6. Performance models should include overboard and flange leakages.
7. Many (most) thermal problems in engines are not a result of heat transfer mistake, but rather of problem with cooling air delivery.
8. Run tests to validate secondary flow design.





Minimize the Use of Secondary Flows