Aerospace Propulsion

Lecture 16

Airbreathing Propulsion VI

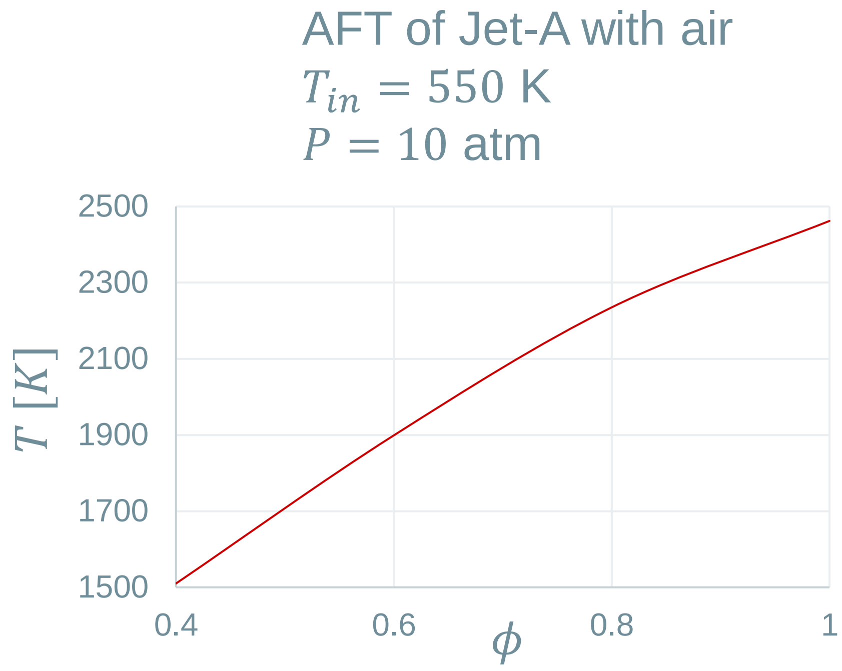
Airbreathing Propulsion: Part VI

- Cooling and Materials
- Combustor Cooling
- Turbine Cooling
- Nozzle Cooling

Cooling and Materials

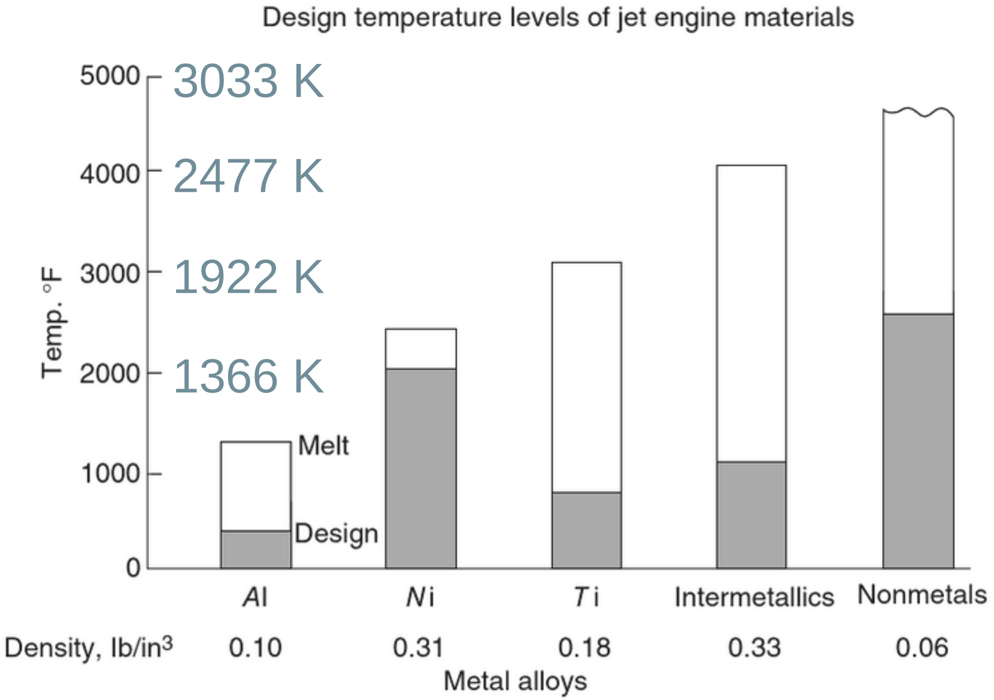
- Heat release from combustion is necessary and provides propulsion

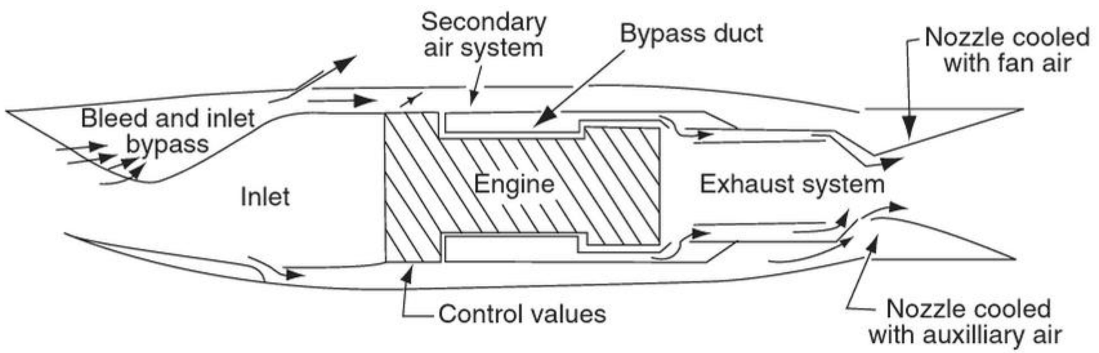
- Heat release from combustion leads to very high temperatures
  - Recall RQL-type combustors even briefly hit stoichiometric
  - Temperatures up to 2500 K possible



Cooling and Materials

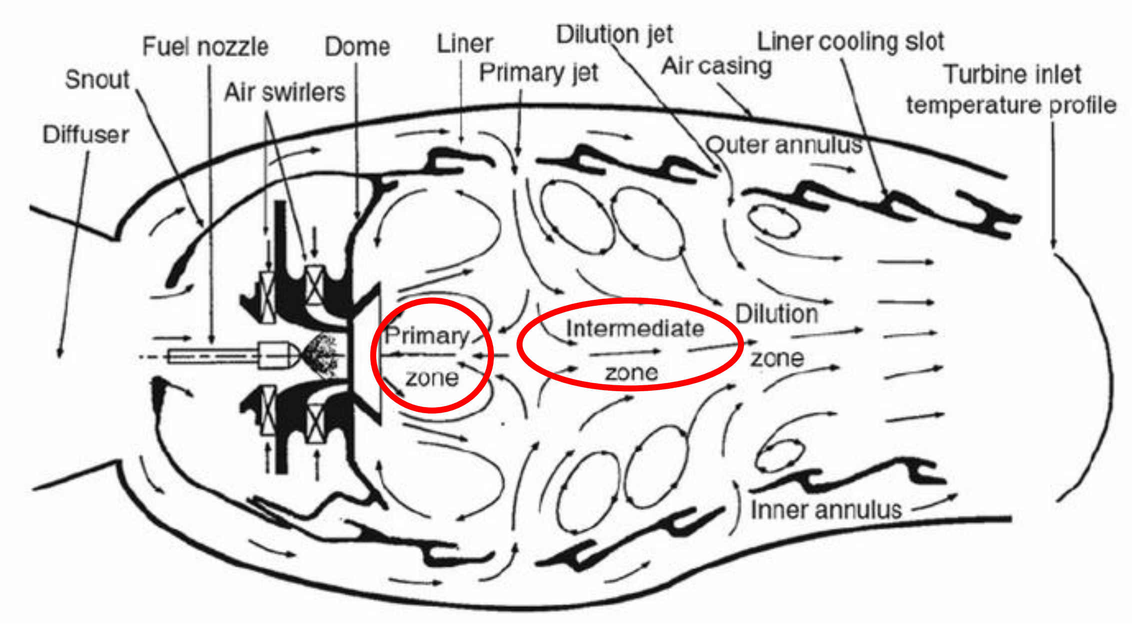
- Most modern jet engine materials cannot maintain steady state operation above ~1900 K
- Aircraft engine designs couple high-temperature materials with active cooling
  - Cold bypass air is used to cool walls
- Everything starting from combustor potentially needs cooling
  - Combustor -> Turbine -> Nozzle





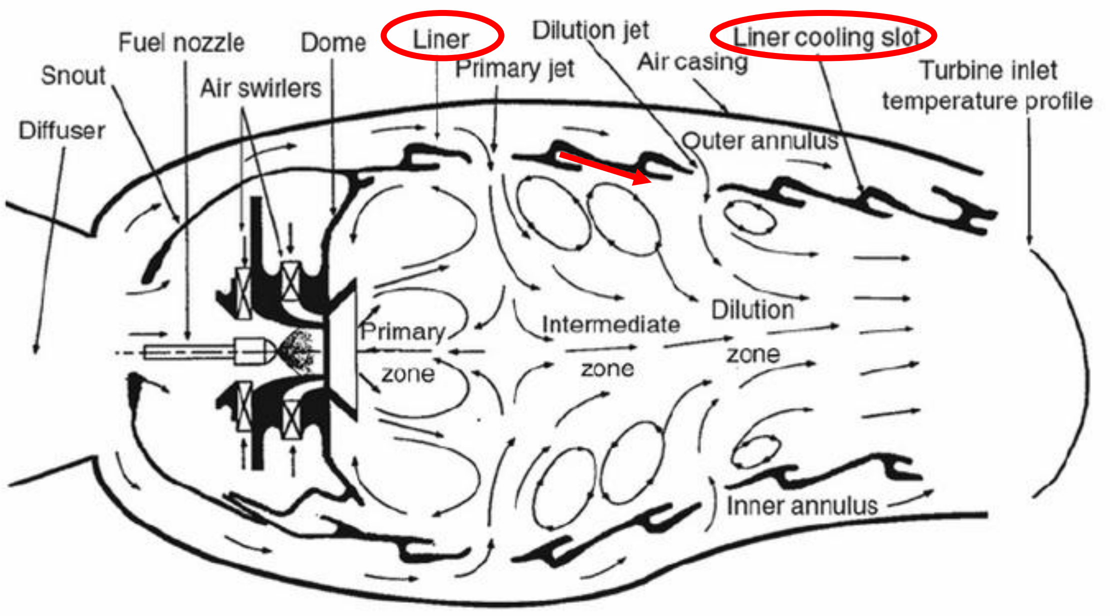
Combustor Cooling

- Primary zone
  - Main flame ignited and stabilized
  - High temperature combustion
    - Up to 2500 K
- Intermediate zone
  - Aids flame stabilization and complete combustion
  - Also high temperature combustion
- Flame <u>cannot</u> touch walls for extended periods without issue



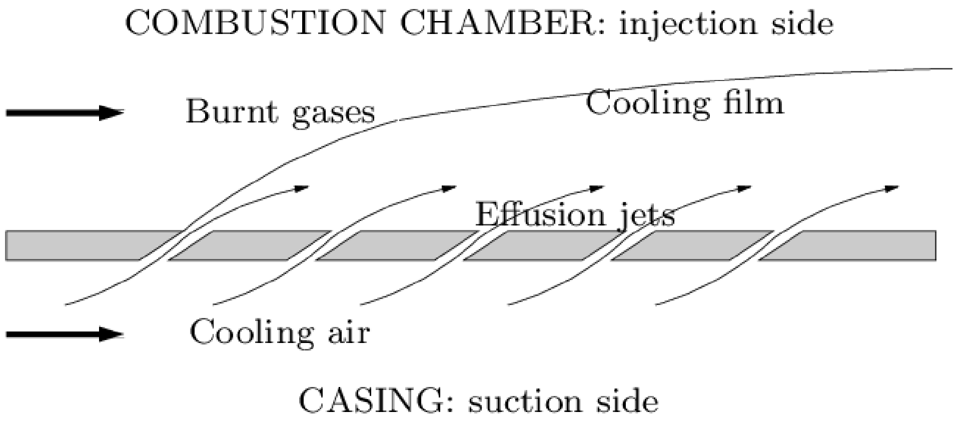
Combustor Cooling

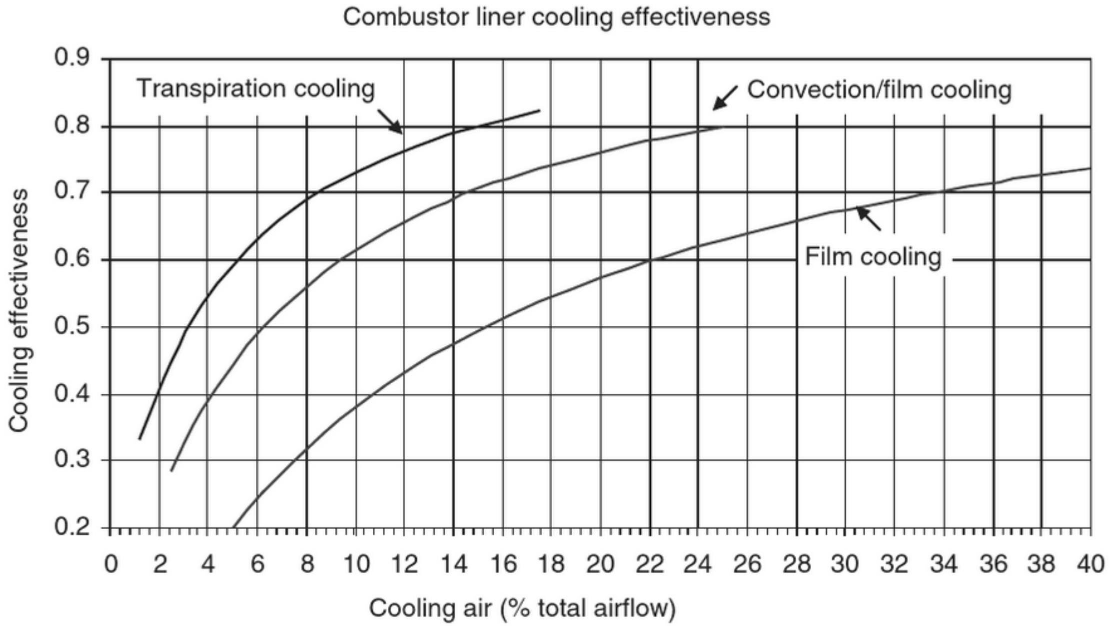
- A second "layer" of walls exist in the combustor called the liner
  - Combustion occurs inside liner
  - Cold bypass air flows around liner
- Liner generally needs to be kept below 1200 K
- Jets of cold air are blown nearly parallel to liner surface to separate liner from hot combustion gases
  - "Film Cooling"



Combustor Cooling

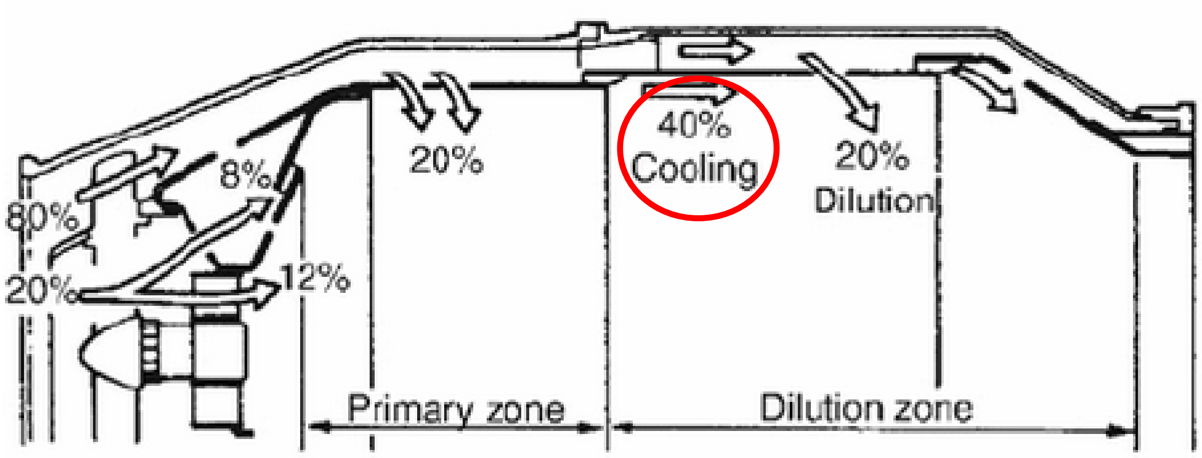
- Film Cooling
  - Produces a cold boundary layer separating liner from hot gases
  - Goal is to <u>minimize</u> heat transfer
- Transpiration Cooling
  - Cold air flows through a porous surface to separate liner from hot gas
  - "Limit" of film cooling with many holes
- Cooling effectiveness: $\epsilon = \frac{T_h - T_w}{T_h - T_c}$
  - T_h/T_c = Hot/cold gas temp
  - T_w = Wall temperature





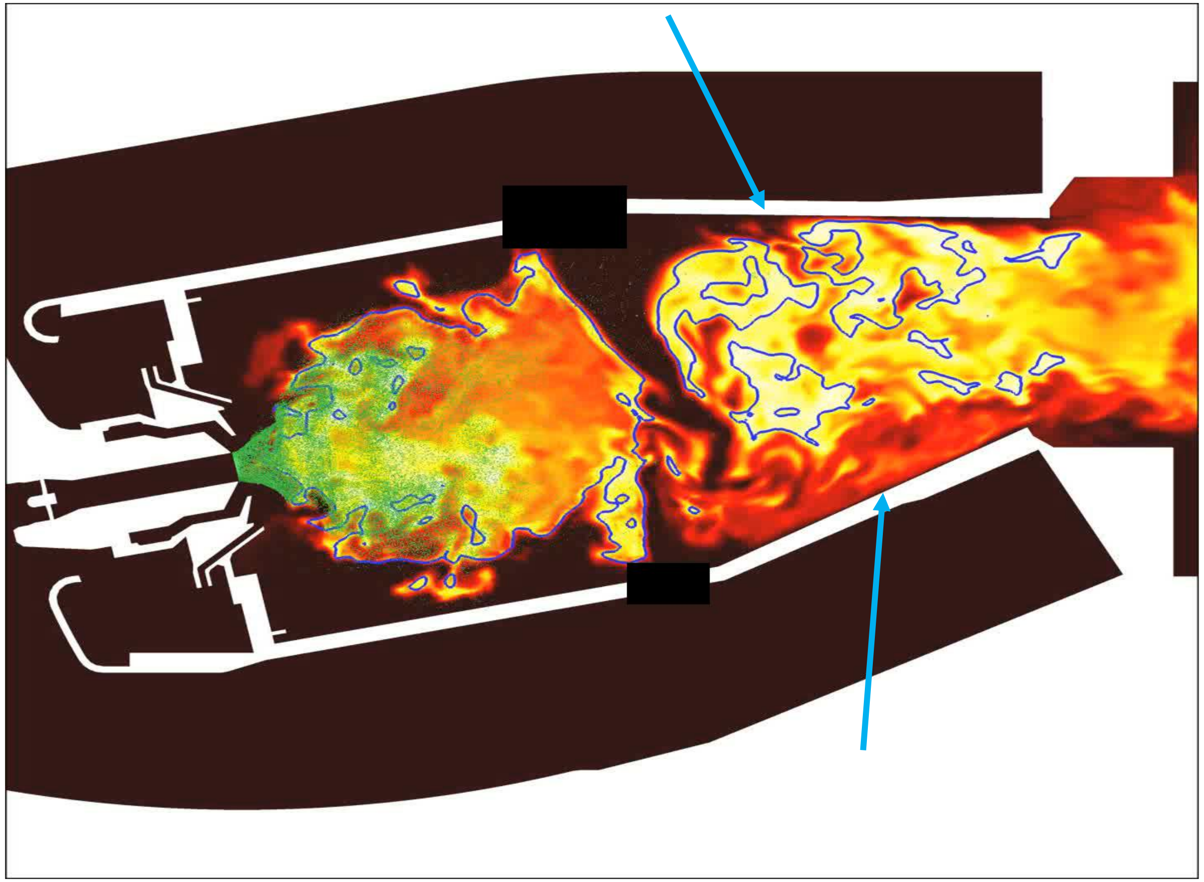
Combustor Cooling

- Up to 40% of air flowing into combustor is used for cooling
- 20% of air is used for primary combustion zone
- 20% of air is used for the intermediate zone
  - Complete combustion
  - Flame stabilization
- 20% of air is used for dilution
  - Cool gases before entering turbine



Combustor Cooling

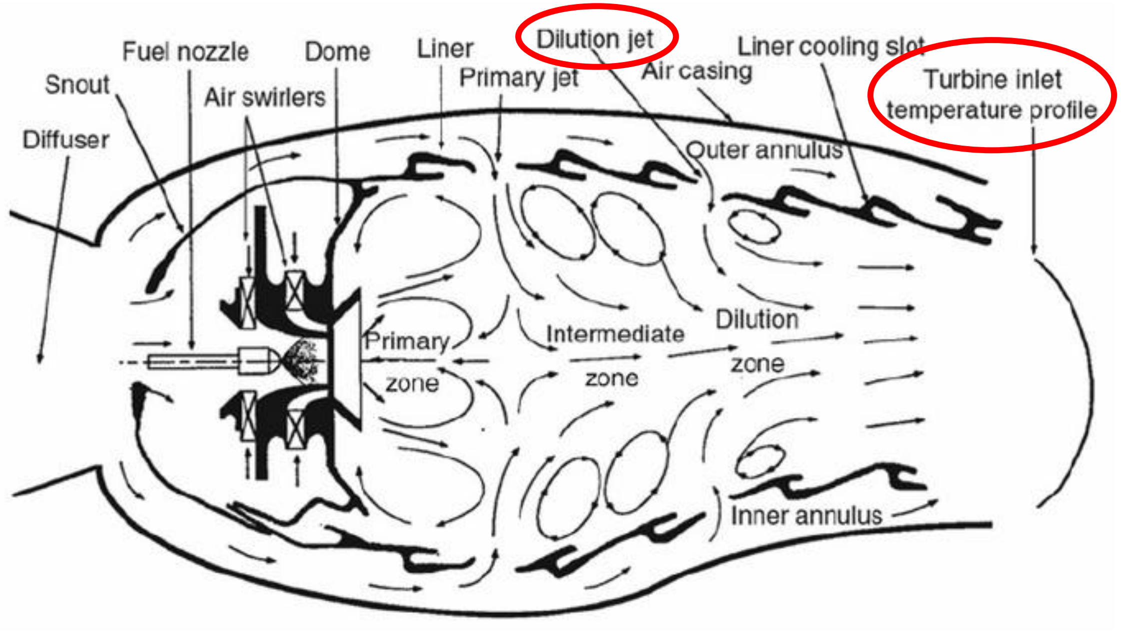
- Hot combustion products get "blown" away from walls
- At least a small region of cold air exists near walls



- Heat transfer from combustion gases to liner minimized
- Heat transfer from liner to cold bypass air (outside) maximized

Turbine Cooling

- As hot gases leave the combustor, they are hit with one last dilution air jet in preparation for the turbine
  - Doesn’t contribute much to combustion, mostly just cools
- Turbine still receives very hot gas
- Turbine inlet temperature profile is hot in the middle and cold near the liner (film cooling)
  - More discussion soon

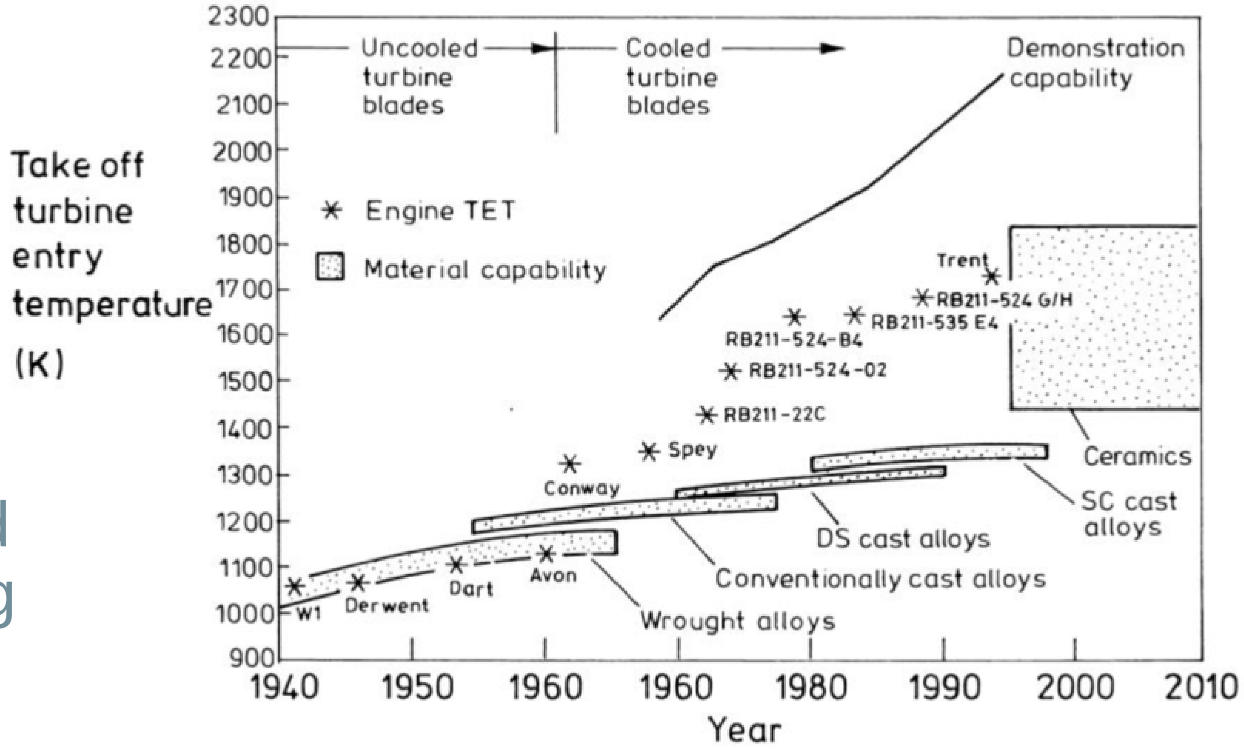


Turbine Cooling

- In theory, we want high turbine inlet temperatures
  - Ideal Brayton Cycle (with turbojet station numbering)
    - $\eta = 1 - r_p^{\frac{1-\gamma}{\gamma}}$ → Increasing pressure ratio increases efficiency
    - $\frac{T_{t3}}{T_{t2}} = r_p^{\frac{\gamma-1}{\gamma}}$ → Increasing pressure ratio increases combustor inlet temperature
    - Increases combustor inlet temperature increase turbine inlet temperature
    - Higher turbine inlet temperature gives higher efficiency
    - To increase pressure ratio (and efficiency) but limit turbine inlet temperature, must lower heat input in combustor, which reduces work input
    - Forced to choose: Power or Efficiency

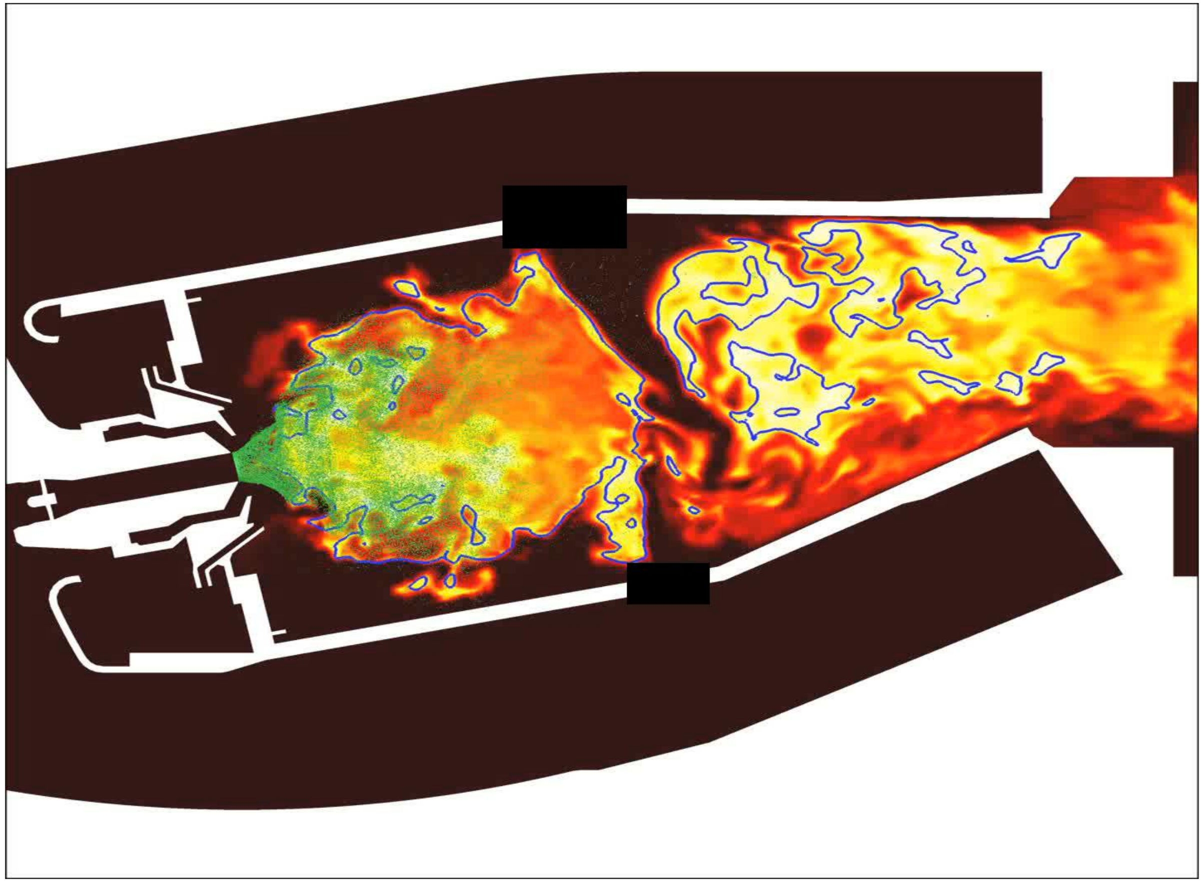
Turbine Cooling

- Turbine inlet temperature is capped by material and cooling
- Before 1960, cooling not used
  - Turbine inlet temperature directly limited by materials
- After 1960, cooling introduced
  - Turbine inlet temperatures limited by combined material and cooling
- Turbine temperatures continue to increase with new tech



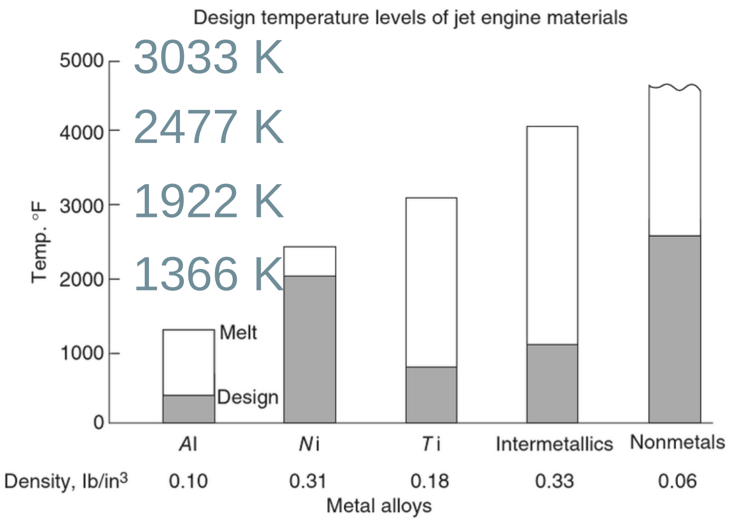
Turbine Cooling

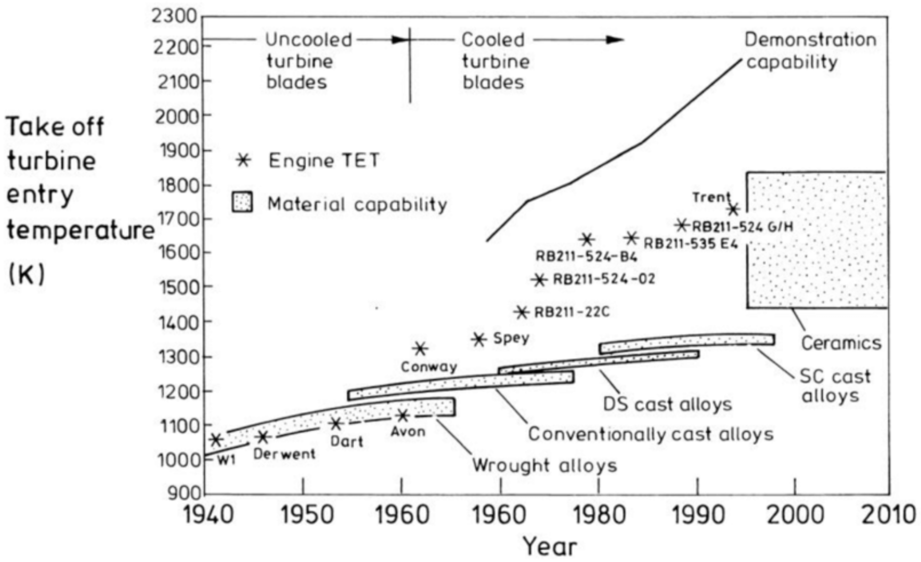
- What temperature profiles enter the turbine?
  - Pattern factor
    - $PF \equiv \frac{T_{t max} - T_{t4}}{T_{t4} - T_{t3}}$
    - Measure of magnitude of fluctuations at combustor exit
    - Maintained below 25%
  - Profile factor
    - $P_f \equiv \frac{T_{t max,avg} - T_{t3}}{T_{t4} - T_{t3}}$
    - Measure of uniformity of time-averaged temperature profile
    - Maintained below 1.1



Turbine Cooling

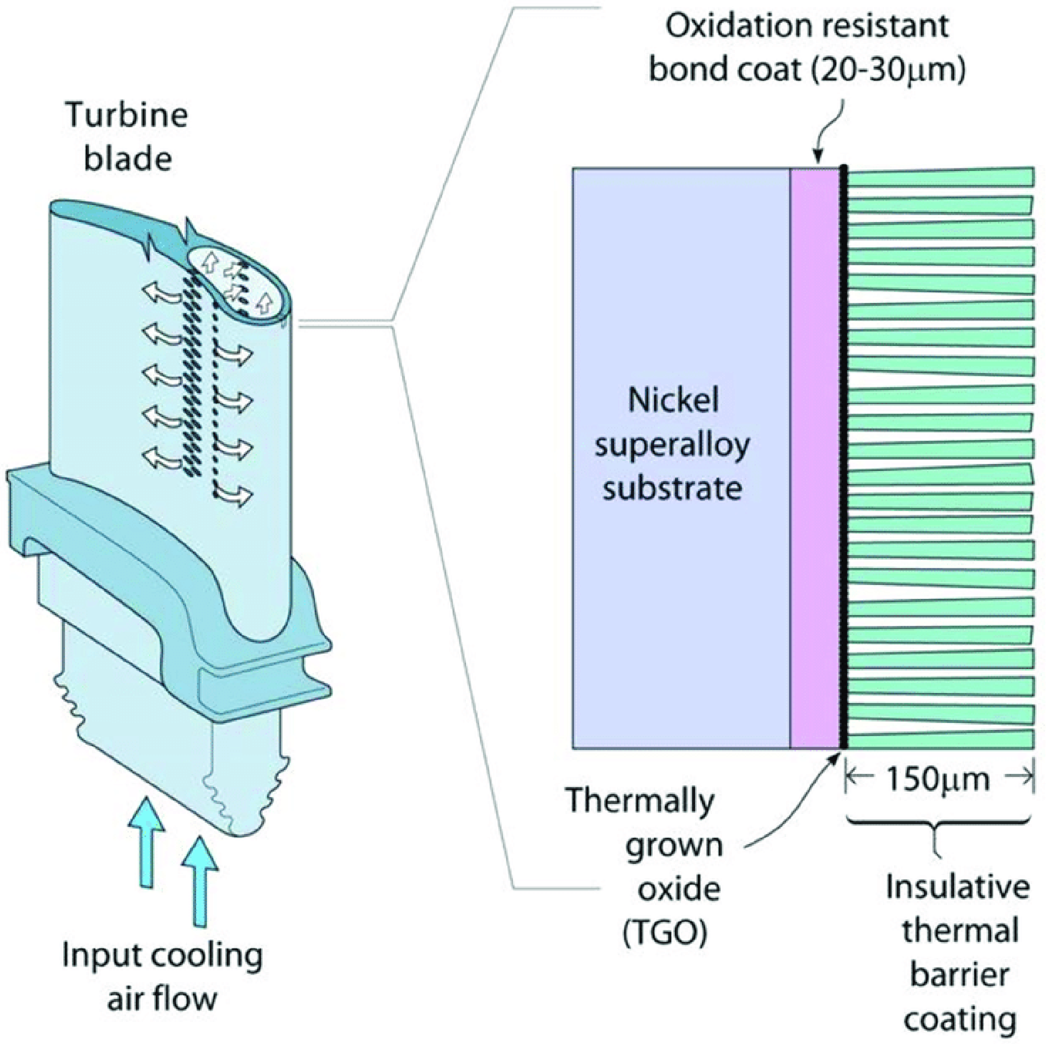
- Materials
  - Even high-performance superalloys do not provide sufficient temperature resistance
  - Most superalloys used in turbines are nickel-based
    - Highest design temperature of all metals
  - Improvements in strength and temperature resistance come through material structure
    - Directional solidification (DS)
    - Single crystal (SC) alloys
  - Ceramics are (currently) too brittle to be manufactured into turbine blades





Turbine Cooling

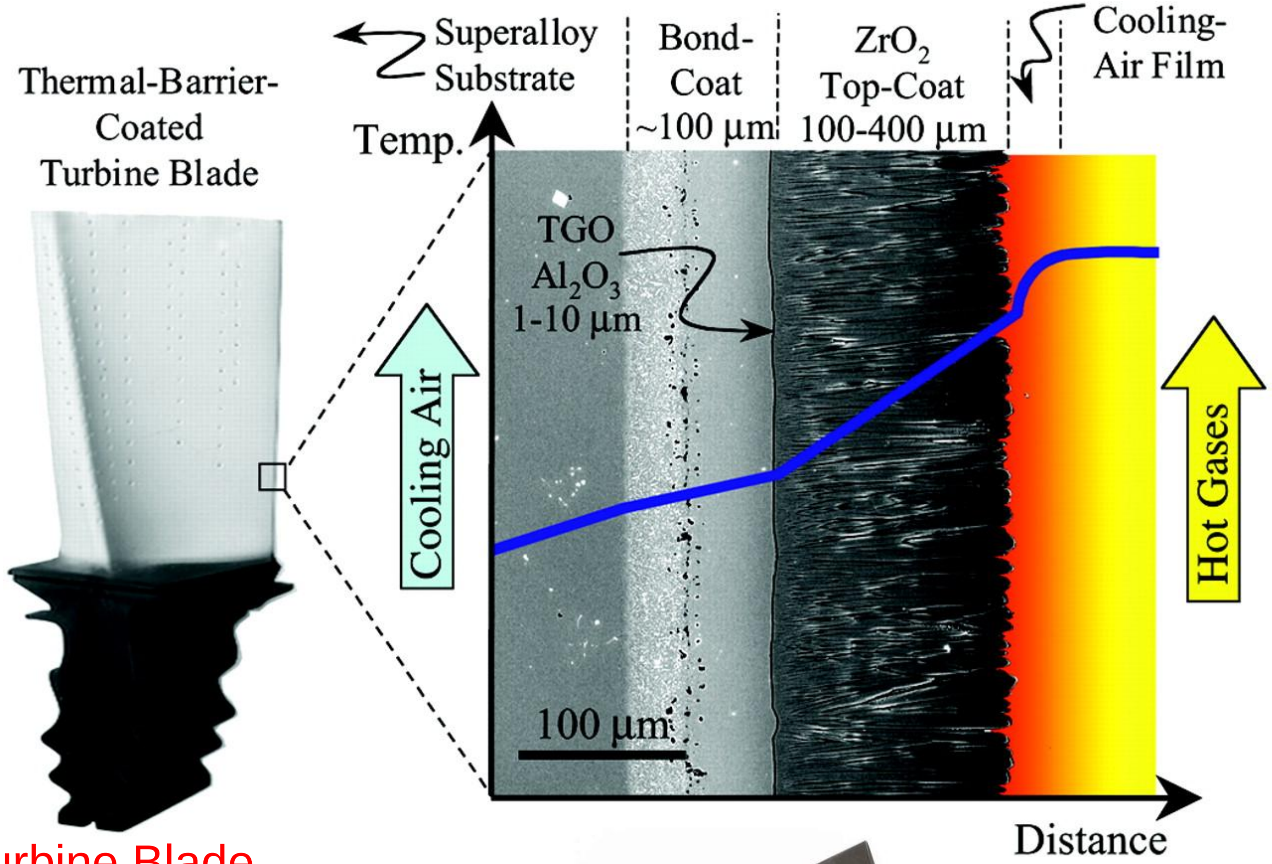
- Thermal barrier coatings
  - Introduced in the 1970's
  - Bond a low-conductivity ceramic to a superalloy to reduce heat transfer to metal
  - Up to 100 K increase in turbine inlet temperature



Turbine Cooling

- Film cooling
  - Similar to cooling in combustor
  - Introduce holes with cold bypass air jets to “protect” surface
  - Typically used in conjunction with ceramic coating

- Note that compressor blades look different from turbine blades because cooling is not required (no holes)

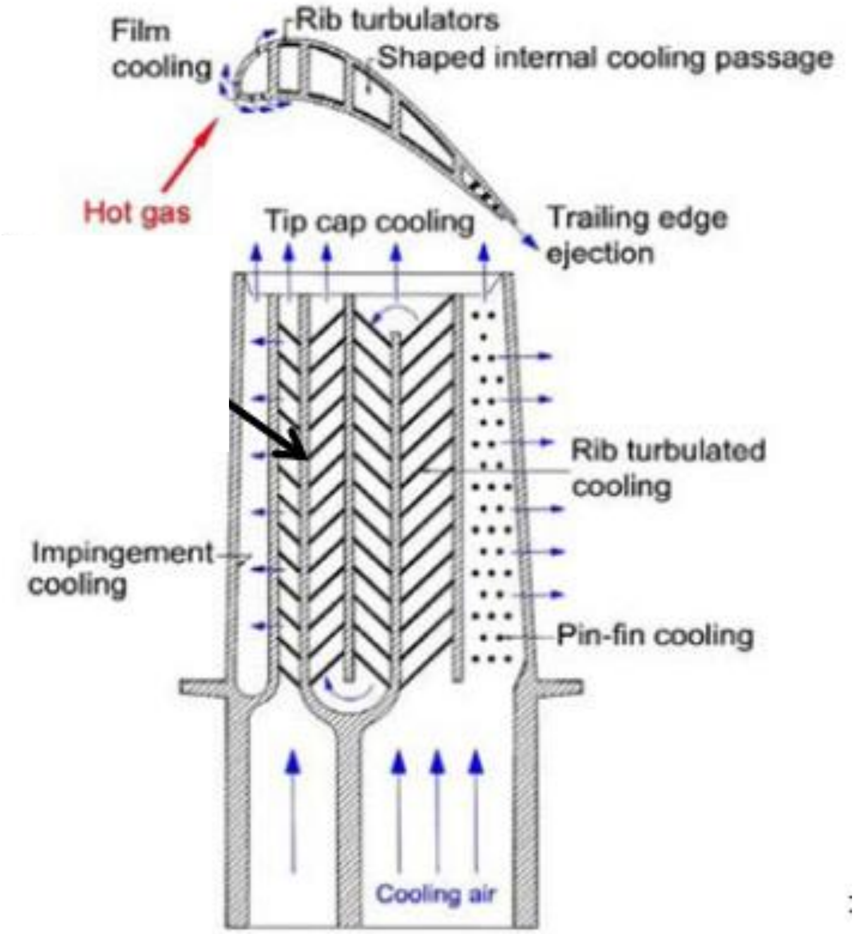


Turbine Blade

Compressor Blade

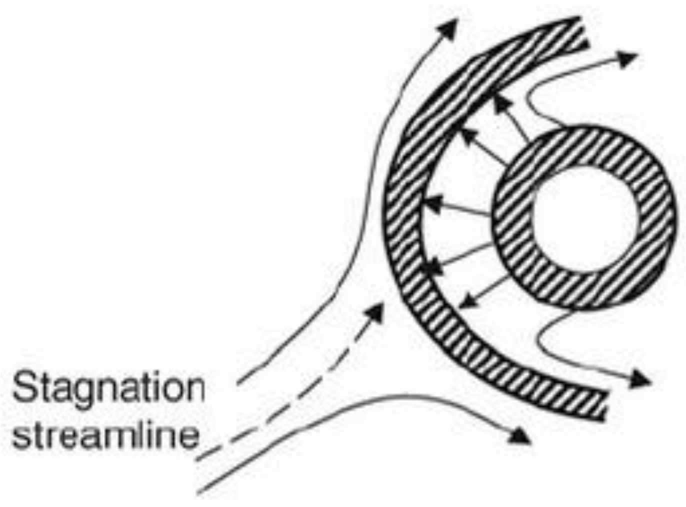
Turbine Cooling

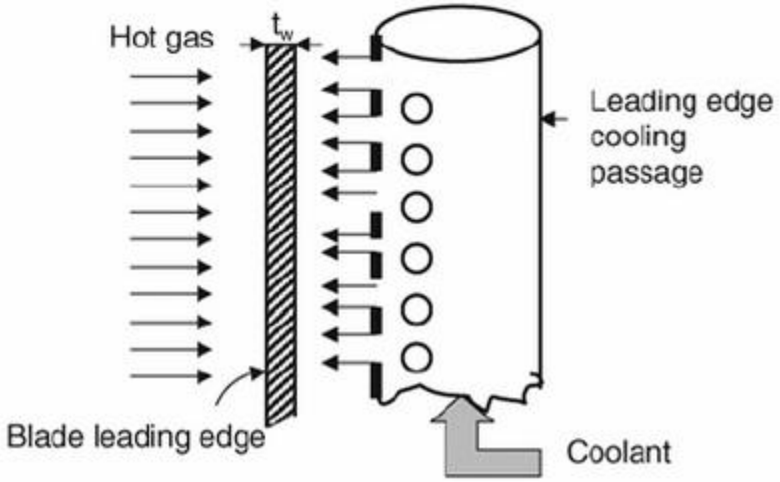
- Film cooling
  - Film cooling occurs through internal passageways in blade
- Convective cooling
  - Internal flow that does not exit the blade for film cooling follows a serpentine pathway through the blade to remove heat from blade
  - Increase mixing intensity to <u>maximize</u> convective heat transfer



Turbine Cooling

- Impingement Cooling
  - Front of blade experience largest heat input
  - Internal flow is routed to impinge against the (internal) surface, increasing heat transfer
  - Sometimes, holes may also be present at leading edge to allow impinging flow to also provide film cooling



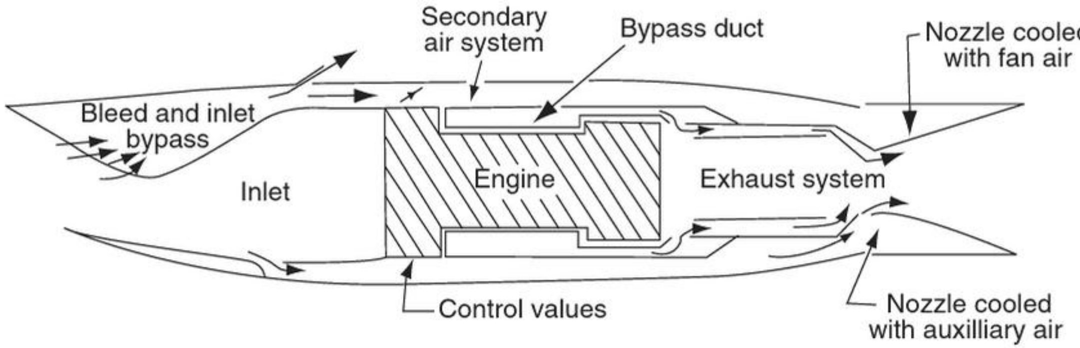


Turbine Cooling

- Remember that this cooling air comes from somewhere
  - Generally, bled from the high-pressure compressor
- Overall efficiency decreased because:
  - Coolant mass flow rate not participate in turbine power production
    - 1% cooling air fraction gives ~1% loss in power
  - Mixing and drag losses when injected from turbine blades
  - Total pressure drop from flow pattern inside turbine blades
  - Heat transfer between hot gas and coolant leads to entropy rise
- Losses due to these inefficiencies estimated at ~3%
- These are more than offset by increase efficiency from higher temperatures in turbine inlet

Nozzle Cooling

- Why would we ever need to cool the nozzle?



- Nothing particularly new here
  - Liner is used to control combustion location
  - Cold bypass air for film cooling
    - Air can come from compressor or fan
  - High-temperature resistant materials

Summary

- How do we deal with high temperatures in gas turbines?
  - Advanced Materials
  - Active Cooling
- High turbine inlet temperatures lead to high efficiencies
- Materials
  - Turbine blades typically made from nickel alloys with ceramic coatings
- Cooling
  - Cold air bled from compressor or fan
  - Film – “Blanket” the material in a cold flow; minimize heat transfer
  - Convective – Carry heat away from hot surfaces; maximize heat transfer