Aerospace Propulsion

Lecture 13

Airbreathing Propulsion III

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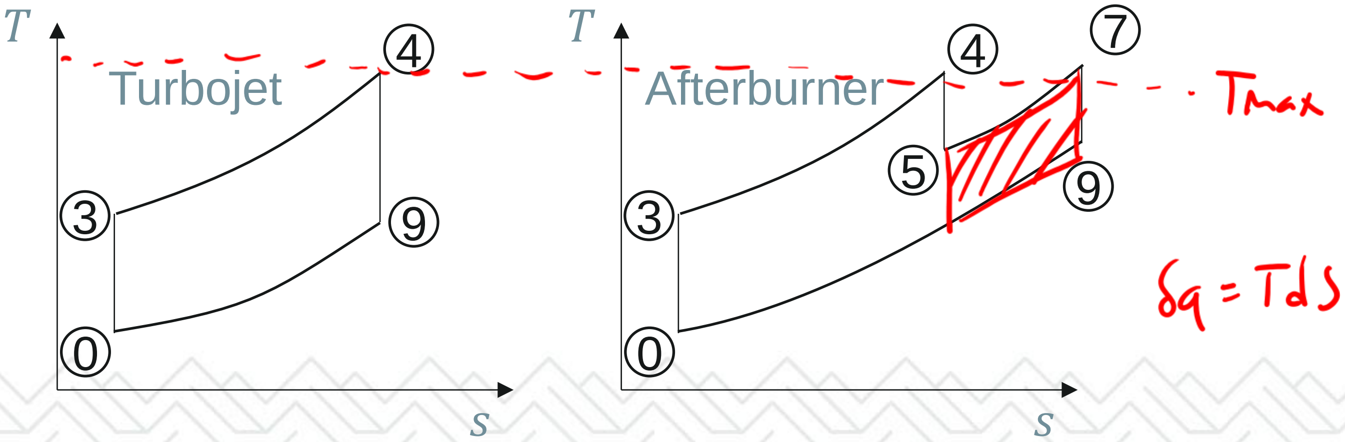
Airbreathing Propulsion: Part III

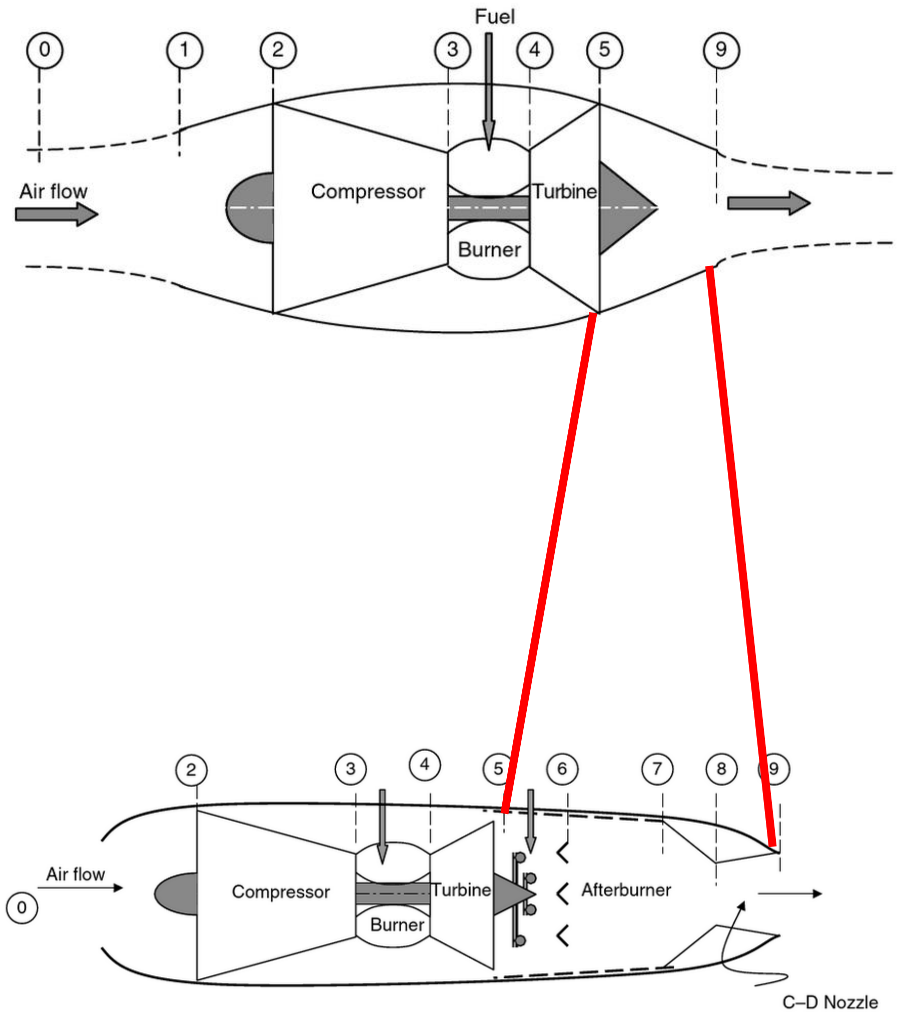
- Afterburners
- Turbofans
- Mixed Exhaust
- Turboprops

Afterburners

- Afterburner is used to further <u>increase the thrust</u> of a jet engine but is <u>very inefficient</u>
- Burn more fuel after turbine
  - Extra fuel can't be added in combustor due to maximum temperature limitations
- Up to approximately 2x thrust for 4x fuel

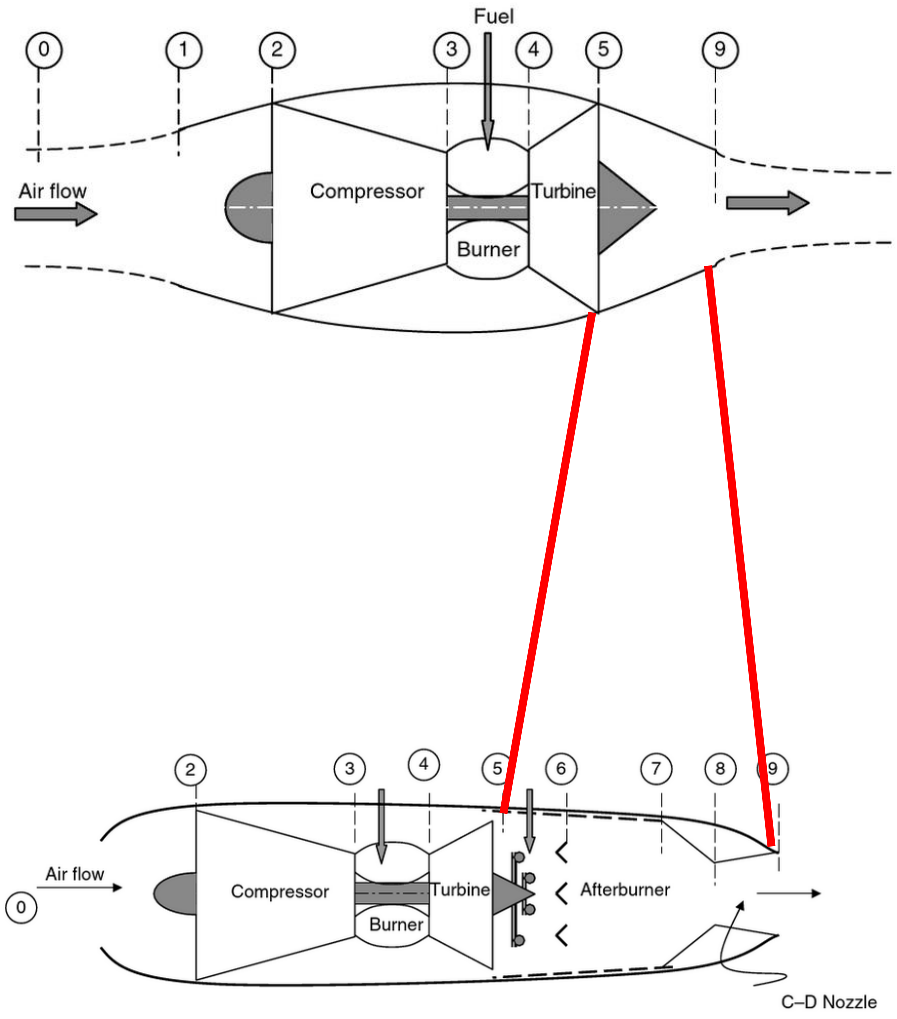


$\delta q = T ds$

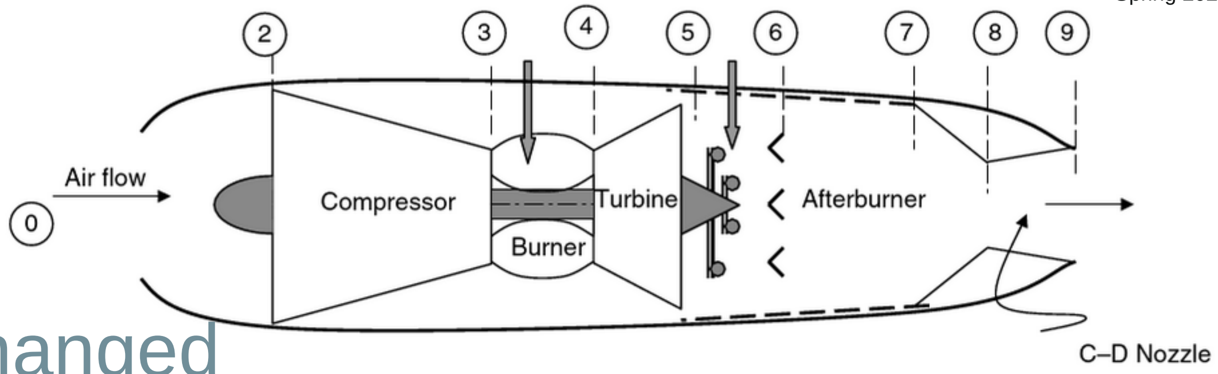


Afterburners

- Emissions are generally ignored
    - Mainly used in short bursts
- Generally, only installed in military aircraft
    - Standard on fighter aircraft
- Regular turbo-jet exit Mach number is already nearly sonic
    - Requires a converging-diverging nozzle
- Can be used with either turbojet/turbofan

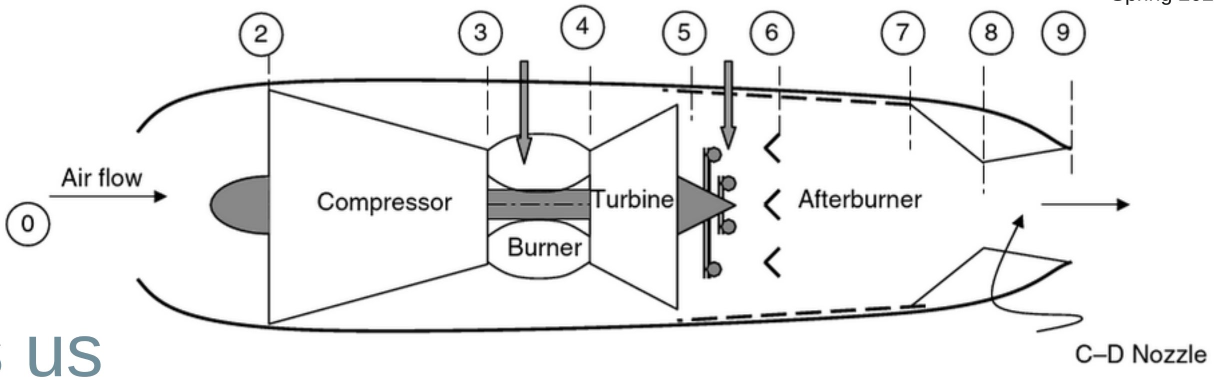


Afterburners



- Analysis before afterburner unchanged
  - Same equations as turbojet for 1-5
- Afterburner (5-6)
  - Same assumptions as in combustor
    - No work, heat input only from combustion
    - Constant stagnation pressure $p_{t5} = p_{t6}$
  - Second fuel addition (i.e., different mass flow rate, equivalence ratio, etc. from combustor)
  - $T_{t6} = T_{t5} + \frac{\phi\left(\frac{F}{A}\right)_{st} LHV}{c_p} = T_{t5} + \frac{\left(\frac{F}{A}\right) LHV}{c_p}$

Afterburners

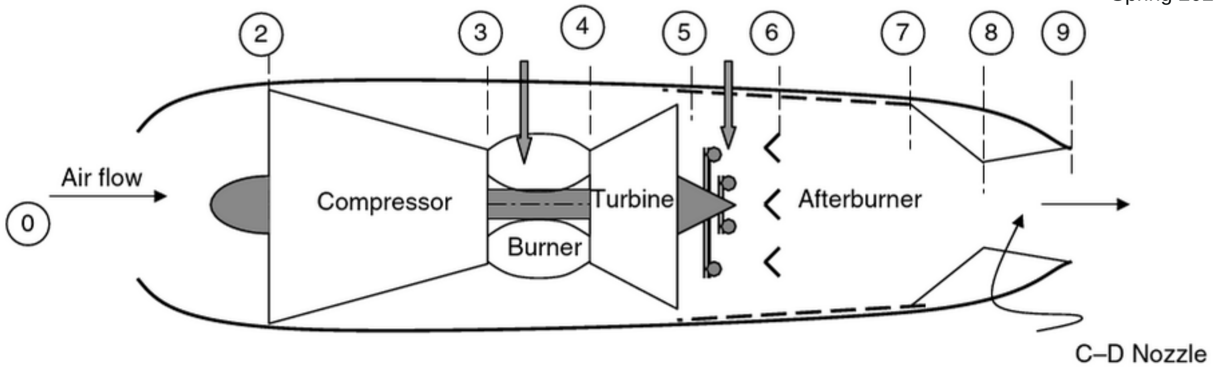


- Recall that thermodynamics tells us heat addition at high pressures is generally more efficient

- Brayton cycle thermal efficiency
  - $\eta = 1 - r_p^{\frac{1-\gamma}{\gamma}}$

- Afterburner heat addition occurs at <u>lower pressure</u> (i.e., post turbine) and is therefore inefficient

Afterburners



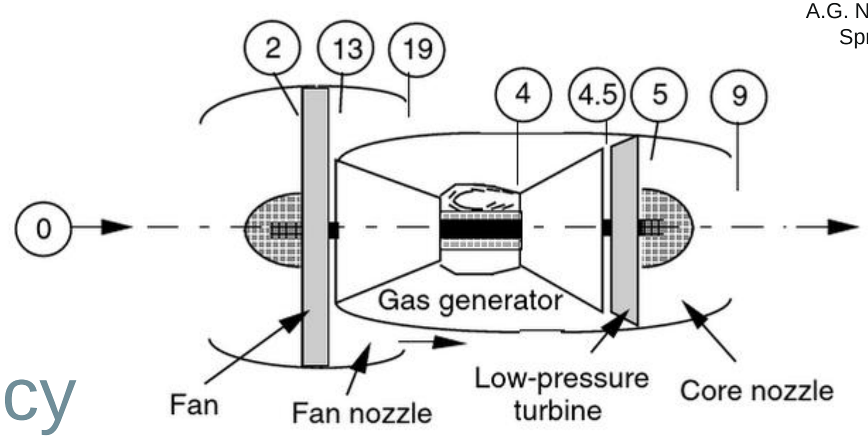
- Afterburner exhaust nozzle (6-9)
  - Can analyze converging-diverging nozzle as we did in earlier lectures about compressible flows
  - In our analysis, assume we're operating the nozzle without any shocks at maximum M_e
  - Exhaust velocity
    - No afterburner (dry): $V_{e,d} = \sqrt{2\frac{\gamma}{\gamma-1}\eta_n R \boldsymbol{T_{t5}}\left[1-\left(\frac{p_a}{p_{t5}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$
    - Afterburner (wet): $V_{e,w} = \sqrt{2\frac{\gamma}{\gamma-1}\eta_n R \boldsymbol{T_{t6}}\left[1-\left(\frac{p_a}{p_{t5}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$

Exhaust velocity (gross thrust) increased by $\sqrt{T_{t6}/T_{t5}}$

Afterburners

Afterburners

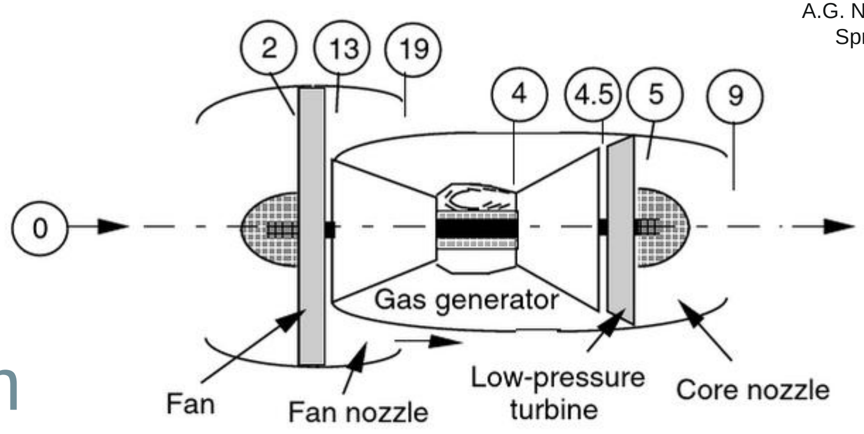
Turbofans



- Recall we showed the propulsive efficiency was maximized when $V_e = V$
  - $\eta_p = \frac{2V}{V_e + V}$
  - However, this case leads to zero thrust

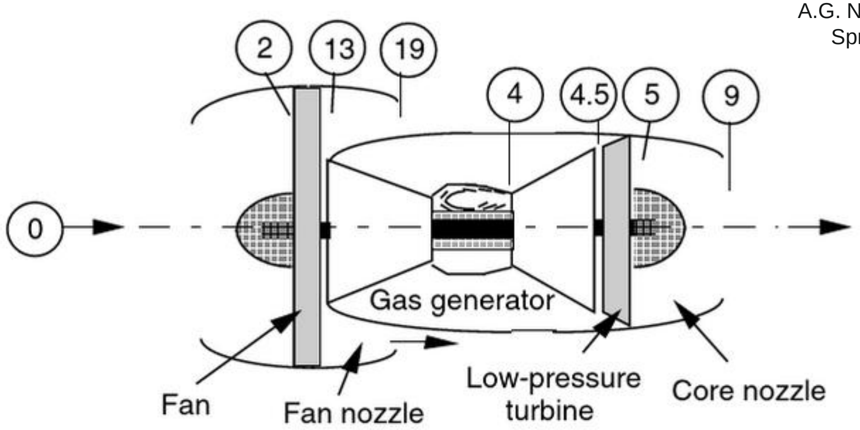
- Accelerating a lot of fluid a small amount is more efficient than accelerating a bit of fluid a large amount
- Turbofans distribute energy from gas turbine across a lot of air for efficiency

Turbofans

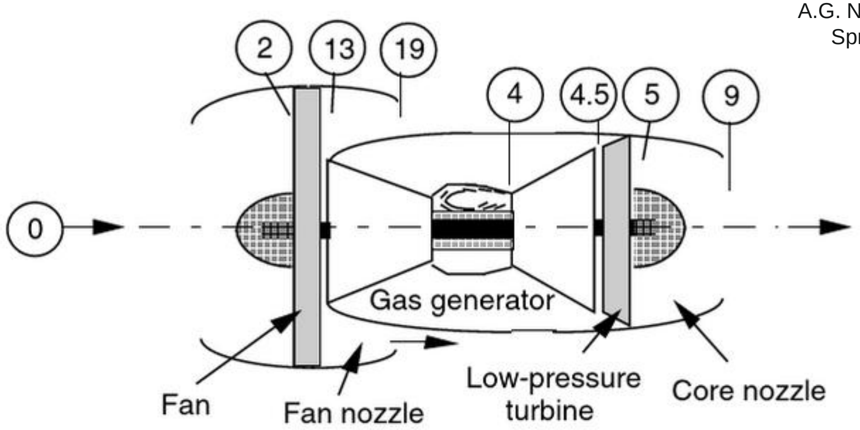


- Turbofans introduce a large fan upstream to slightly accelerate a lot of flow
- $\dot{m}_{core}$ to central core
  - Essentially same analysis as turbojet
- $\dot{m}_{bp}$ outside central core
  - Accelerated by fan
- Bypass ratio: $BPR = \dfrac{\dot{m}_{bp}}{\dot{m}_{core}}$
- Generally, two turbine stages
  - High-pressure turbine powers compressor
  - Low-pressure turbine powers fan

Turbofans



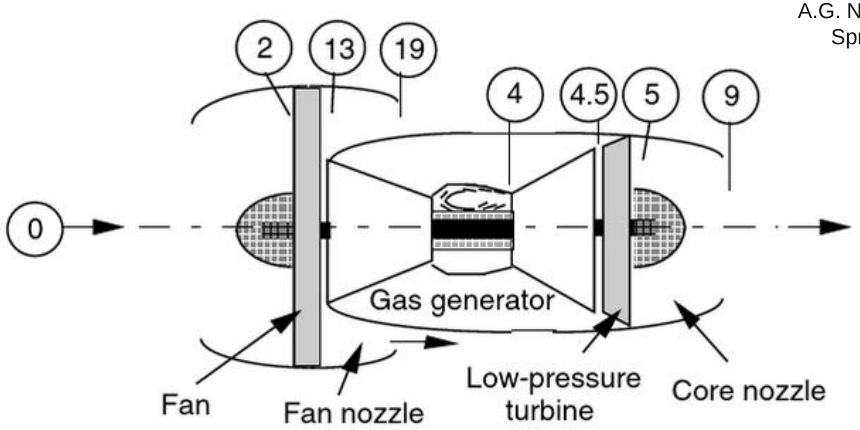
- Fan (2-13)
  - The fan acts approximately as a compressor
  - Fan compression ratio $r_f = \frac{p_{t13}}{p_{t2}}$
  - Same analysis as turbojet compressor
    - $\eta_f = \frac{h_{t13s} - h_{t2}}{h_{t13} - h_{t2}} = \frac{T_{t13s} - T_{t2}}{T_{t13} - T_{t2}}$
    - $\frac{T_{t13}}{T_{t2}} = 1 + \frac{1}{\eta_f}\left(r_f^{\frac{\gamma-1}{\gamma}} - 1\right)$
    - $\dot{W}_{in,f} = \dot{m}_c c_p (1 + BPR)\frac{T_{t2}}{\eta_f}\left(r_f^{\frac{\gamma-1}{\gamma}} - 1\right)$



Turbofans

- Compressor (13-3)
  - Same analysis as before, but only needs power from the high-pressure turbine
    - $r_p = \frac{p_{t3}}{p_{t13}}$
    - $\eta_c = \frac{h_{t3s} - h_{t13}}{h_{t3} - h_{t13}} = \frac{T_{t3s} - T_{t13}}{T_{t3} - T_{t13}}$
    - $\frac{T_{t3}}{T_{t13}} = 1 + \frac{1}{\eta_c}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)$
    - $\dot{W}_{in,f} = \dot{m}_c c_p \frac{T_{t13}}{\eta_c}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)$

Turbofans

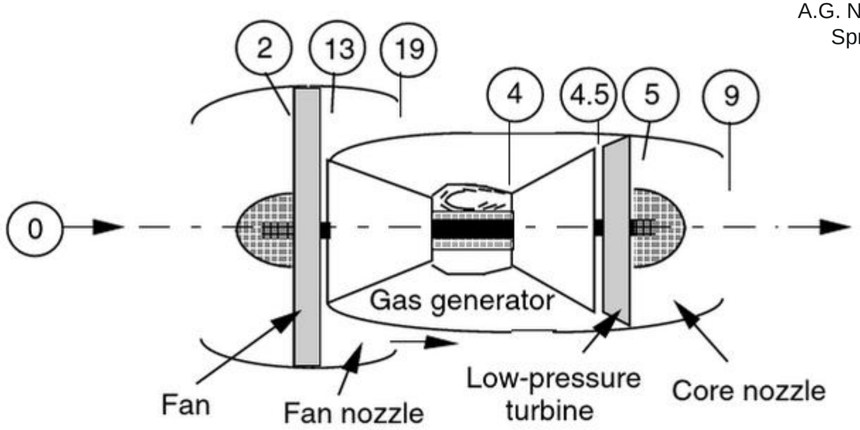


- Burner (3-4)
  - No work input/output
  - Heat input from combustion
  - Analysis is unchanged

  - $p_{t4} \approx p_{t3}$

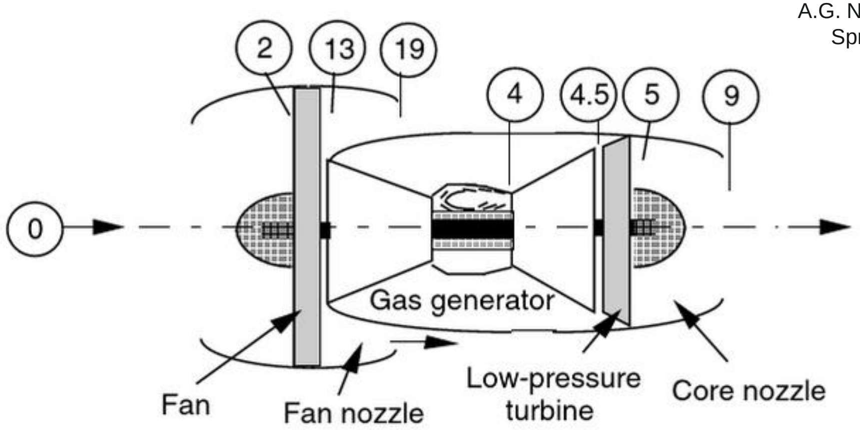
  - $T_{t4} = T_{t3} + \dfrac{\phi\left(\frac{F}{A}\right)_{st} LHV}{c_p} = T_{t3} + \dfrac{\left(\frac{F}{A}\right) LHV}{c_p}$

Turbofans



- High-pressure turbine (4-4.5)
  - Drives compressor
  - Same analysis as turbojet
  - $\eta_{HPT} = \frac{h_{t4} - h_{t4.5}}{h_{t4} - h_{t4.5s}} = \frac{T_{t4} - T_{t4.5}}{T_{t4} - T_{t4.5s}}$
  - $T_{t4.5} = T_{t4} - \frac{T_{t13}}{\eta_c}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)$
  - $p_{t4.5} = p_{t4}\left[1 - \frac{1}{\eta_c \eta_{HPT}} \frac{T_{t13}}{T_{t4}}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right)\right]^{\frac{\gamma}{\gamma-1}}$

Turbofans



- Low-pressure turbine (4.5-5)
  - Drives fan
  - $\eta_{LPT} = \frac{h_{t4.5}-h_{t5}}{h_{t4.5}-h_{t5s}} = \frac{T_{t4.5}-T_{t5}}{T_{t4.5}-T_{t5s}}$
  - $T_{t5} = T_{t4.5} - (1+BPR)\frac{T_{t2}}{\eta_f}\left(r_f^{\frac{\gamma-1}{\gamma}} - 1\right)$
  - $p_{t5} = p_{t4.5}\left[1 - \frac{1+BPR}{\eta_f \eta_{LPT}}\frac{T_{t2}}{T_{t4.5}}\left(r_f^{\frac{\gamma-1}{\gamma}} - 1\right)\right]^{\frac{\gamma}{\gamma-1}}$

(power balance) 1 $\dot{W}_{out,LPT} = \dot{W}_{in,F}$

(1st law) 2 $\dot{W}_{out,LPT} = \dot{m} c_p (T_{t4.5} - T_{t5})$

3 $\dot{W}_{out,LPT} = \eta_{LPT}\, \dot{m}_c\, c_p T_{t4.5}\left[1 - \left(\frac{p_{t5}}{p_{t4.5}}\right)^{\frac{\gamma-1}{\gamma}}\right]$

4 $\dot{W}_{in,F} = \dot{m} c_p (1+BPR)\frac{T_{t2}}{\eta_F}\left(r_f^{\frac{\gamma-1}{\gamma}} - 1\right)$

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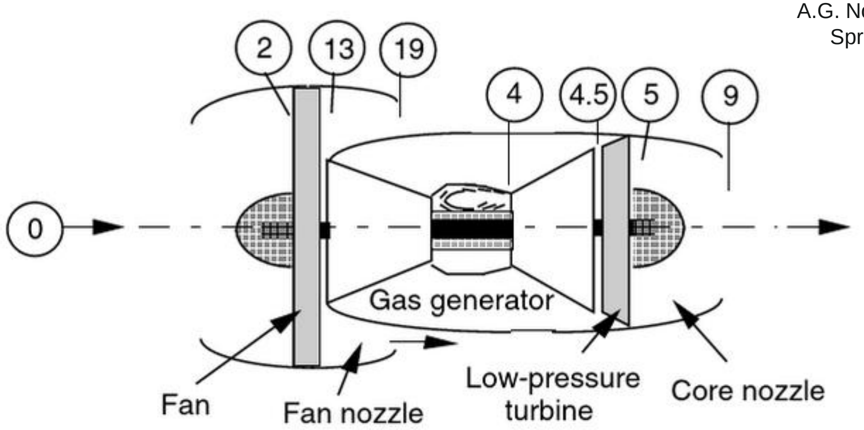
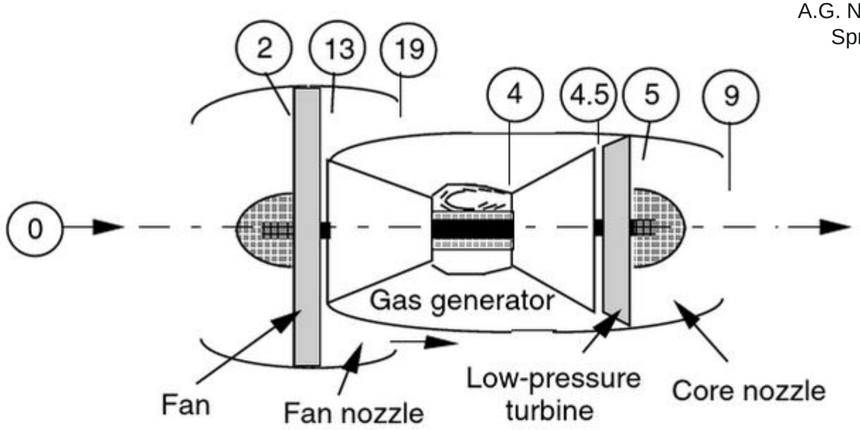
Turbofans



- Exhaust nozzle (13-19 and 5-9)
  - Two separate exhaust nozzles for core and fan
  - Same analysis as turbojet
  - $V_{e,c} = \sqrt{2\frac{\gamma}{\gamma-1}\eta_{n,c}RT_{t5}\left[1-\left(\frac{p_a}{p_{t5}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$
  - $V_{e,bp} = \sqrt{2\frac{\gamma}{\gamma-1}\eta_{n,bp}RT_{t13}\left[1-\left(\frac{p_a}{p_{t13}}\right)^{\frac{\gamma-1}{\gamma}}\right]}$

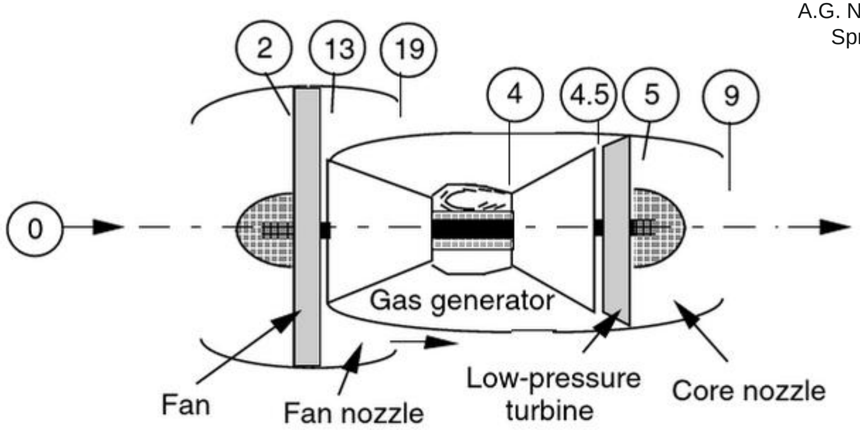
Turbofans



- Thrust
  - $T = T_c + T_{bp} = \dot{m}_{bp}\left(V_{e,bp} - V\right) + \dot{m}_c\left(V_{e,c} - V\right)$

- Propulsive Efficiency
  - $\eta_p = \dfrac{TV}{\dot{m}_{bp}\left[\frac{V_{e,bp}^2}{2} - \frac{V^2}{2}\right] + \dot{m}_c\left[\frac{V_{e,c}^2}{2} - \frac{V^2}{2}\right]}$

Turbofans

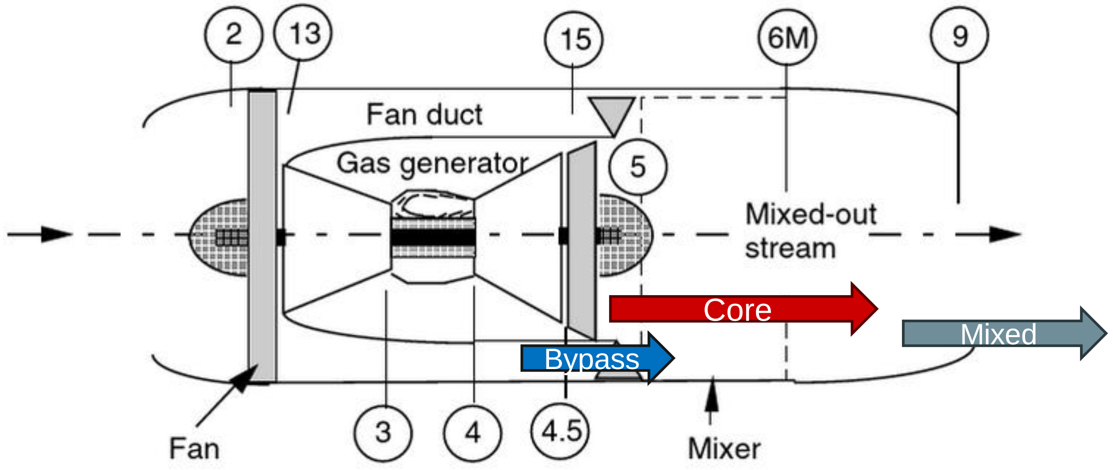


- Pros
  - High propulsive efficiency due to fan
  - Can lead to smaller core gas turbine
- Cons
  - Big fans approach sonic tip speed
  - Lose efficiency in energy conversion for shaft
- Modern engines have $BPR \approx 6 - 8$
- Ultra-High Bypass technology has $BPR > 12$
  - ~15% fuel savings

Topics we won't discuss in depth

- Mixed exhaust turbofan
  - Fan outlet mixes with core outlet
  - Reduces noise/thermal signature
  - Farokhi 4.4
- Turboprop engine
  - Gas turbine primarily to spin propeller
  - Only relevant at low speeds
  - Farokhi 4.5
- Non-gas turbine-based engines
  - Reciprocating engines (Gasoline/Diesel)
  - Only relevant at **very** low speeds
  - Farokhi 5

Mixed exhaust turbofans

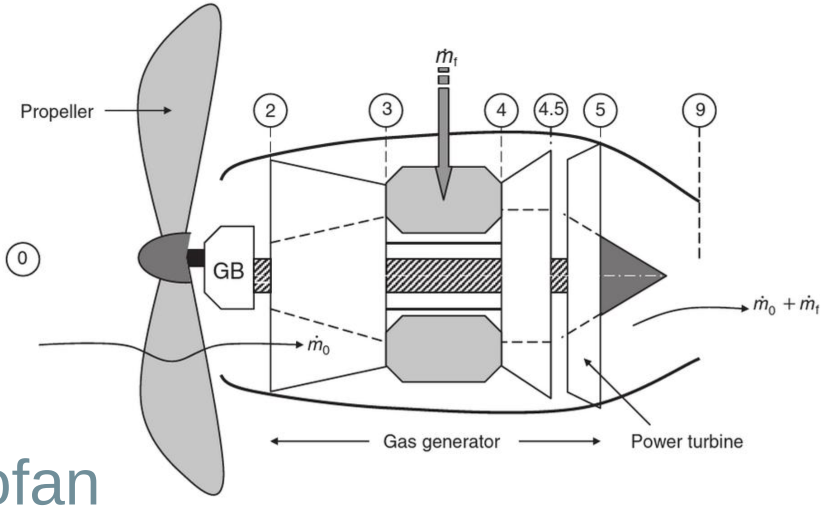


- Core flow is fast and hot
  - For military aircraft:
    - Thermal signature easy to track
    - Noise easy to track
      - Noise scales with outlet velocity
- Bypass flow is slow and cold
- Mix the two flows internally to reduce maximum temperature and velocity making aircraft harder to track

Mixed exhaust turbofans

- High exit velocity leads to
  - High thrust
  - Low propulsive efficiency
- By mixing the velocities, reduce maximum velocity
  - Potential to increase efficiency
  - Also potential to lose thrust, need to balance carefully

Turboprop engine



- Gas turbine primarily spins propeller
  - From 2-9, analysis similar to core of turbofan
  - Must include additional analysis of how fan generates thrust
    - Unlike a fan, inaccurate to "assume" a pressure ratio
    - Propeller theory (e.g., momentum theory or blade element theory)
  - At low speeds:
    - Aim to pull maximum power from exhaust
    - Propeller is most efficient form of thrust
      - Propeller power comes from second turbine (4.5 – 5)
  - At higher speeds:
    - Becomes more efficient to leave some power in exhaust
    - Propeller still dominant