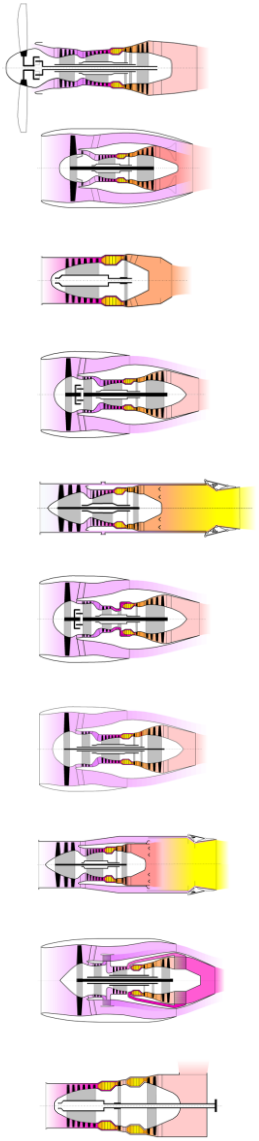

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# The Basics of Gas Turbine Off-Design Performance

A tutorial presented at the Turbo Expo 2025 in Memphis, TN, USA

Joachim Kurzke

joachim@kurzke-consulting.de

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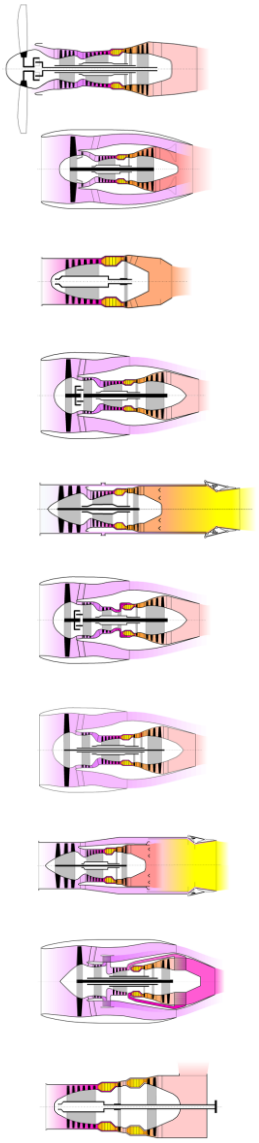
# Let's clarify what we're discussing here…



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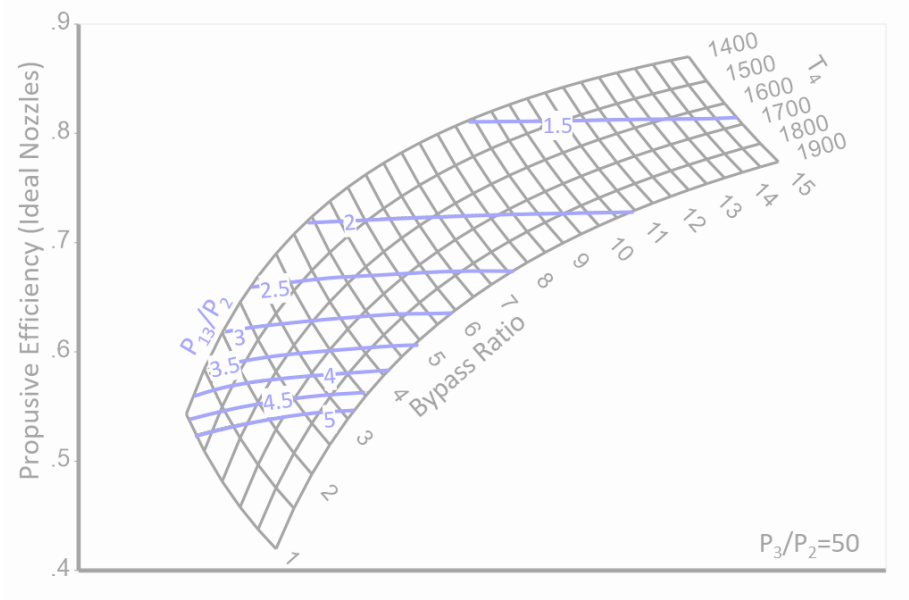
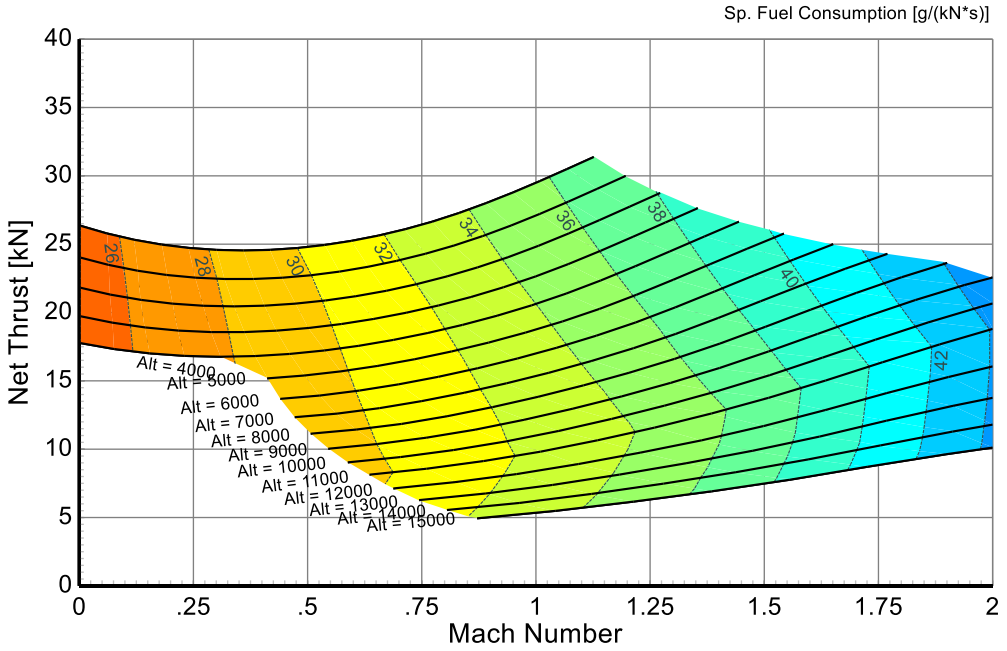
## Design

Defining the geometry of an engine




## Off-Design

The performance for a given geometry



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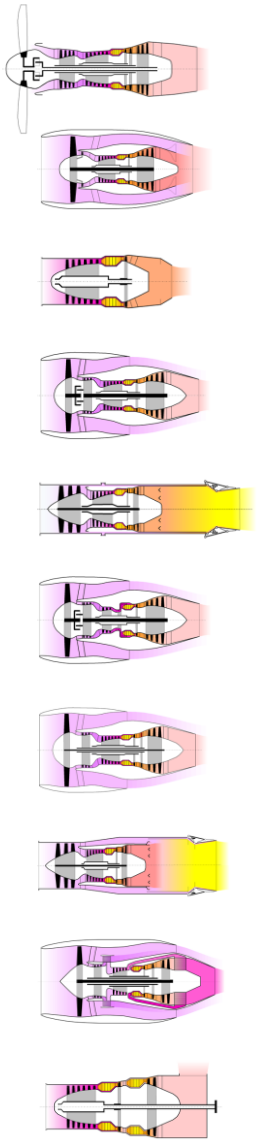

# Why is off-design performance important?

- Performance under environmental conditions that are different from those of the design point
- Operability
  - Compressor surge margin
- Safety
  - Overspeed, overtemperature, engine life
- Optimize fuel consumption
  - How can we use the available engine control variables best?

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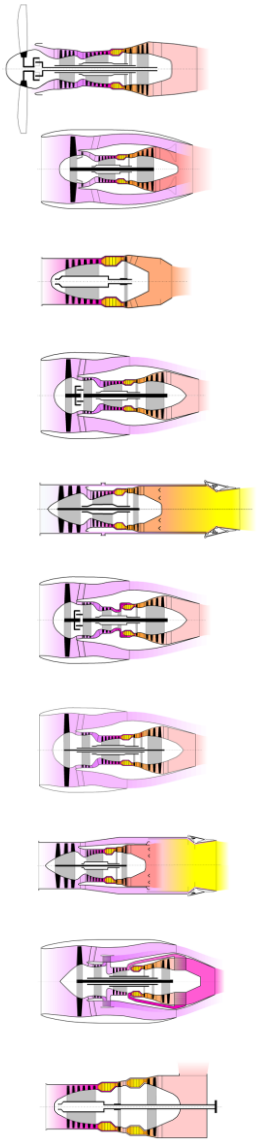

# Outline

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components

Cooperation of the Components

Gas Generator +

Variable Geometry

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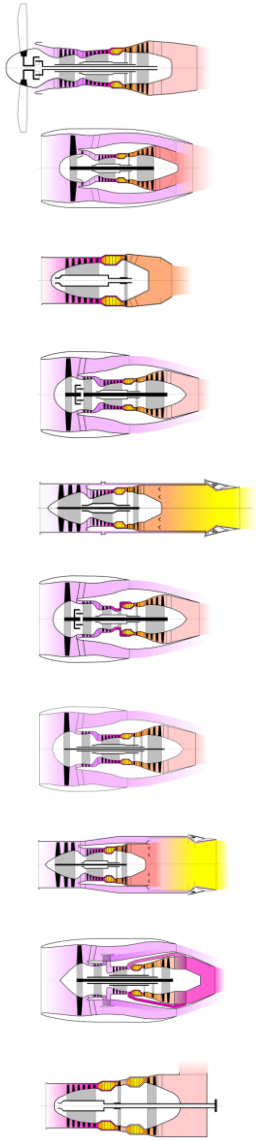
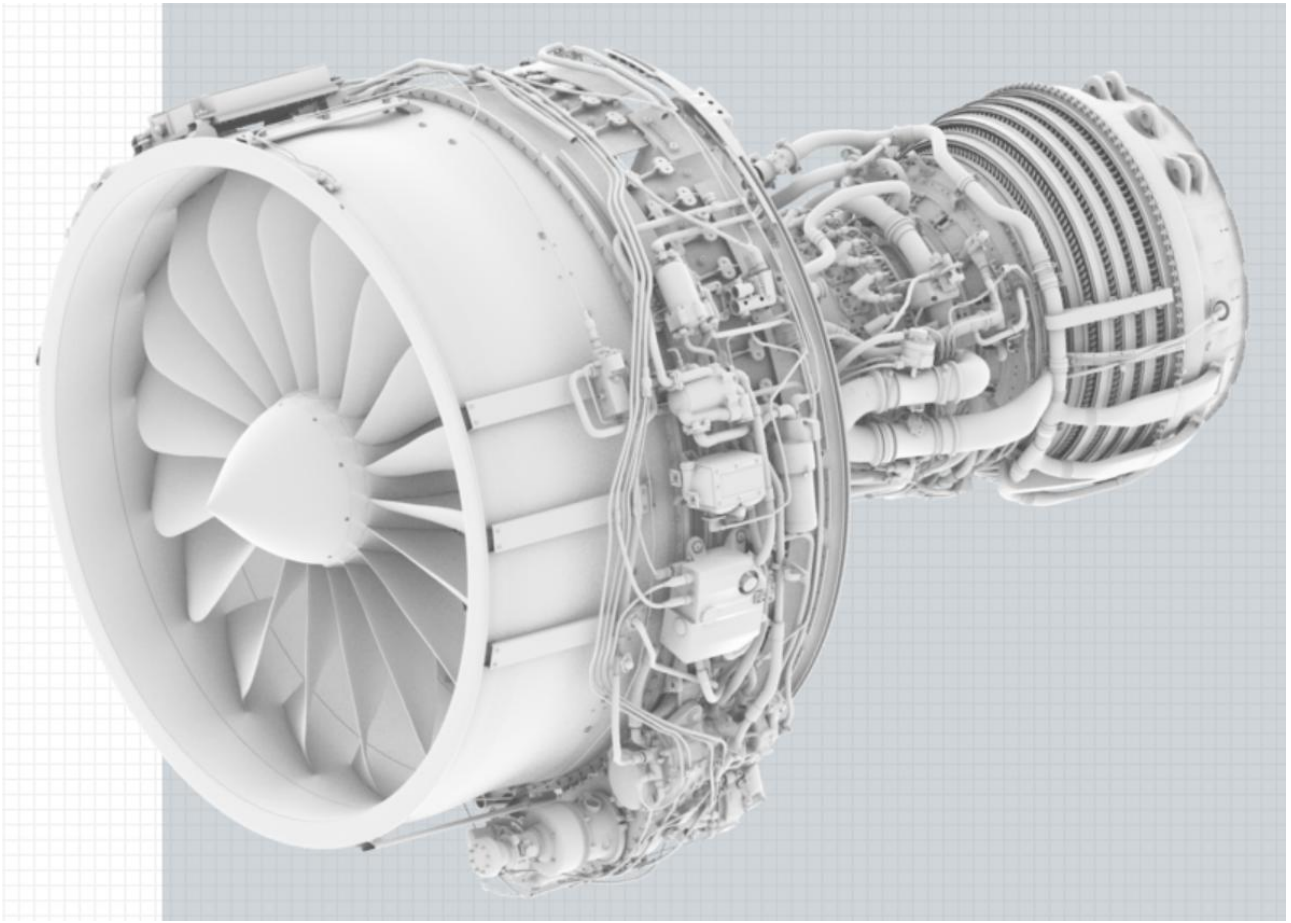
# CFM 56-3
## The Engine of the Boeing 737-400





ISA SLS Cycle Data

Ref. Propulsion and Power

| | |
|---|---|
| Thrust | 99.4 kN |
| Mass Flow 314 kg/s | |
| Bypass Ratio | 4.94 |
| $P_3/P_2$ | 24.2 |
| $T_{41}$ | 1523 K |

https://www.cfmaeroengines.com/documentary/?l=en

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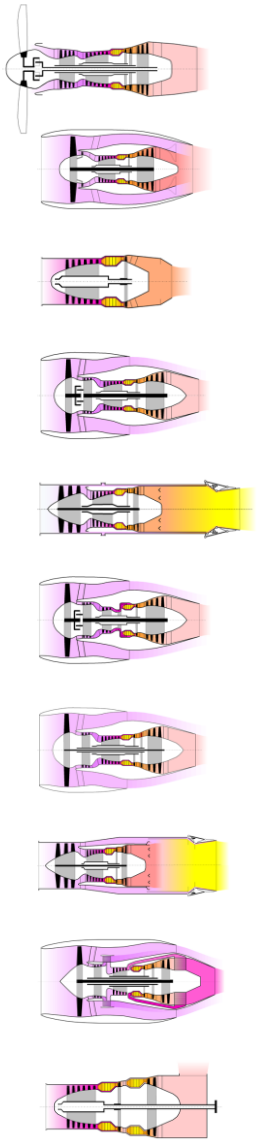
# CFM56-3 Reference Cycle

## ISA SLS



| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 2 | 313.700 | 288.15 | 101.325 | 313.700 |
| 13 | 260.853 | 338.16 | 167.693 | 170.745 |
| 21 | 52.847 | 327.40 | 151.988 | 37.554 |
| 22 | 52.847 | 327.40 | 151.988 | 37.554 |
| 24 | 52.847 | 369.90 | 221.130 | 27.436 |
| 25 | 52.847 | 369.90 | 221.130 | 27.436 |
| 3 | 52.847 | 770.80 | 2447.817 | 3.578 |
| 31 | 45.396 | 770.80 | 2447.817 | |
| 4 | 46.491 | 1577.54 | 2325.426 | 4.740 |
| 41 | 50.190 | 1522.89 | 2325.426 | 5.028 |
| 43 | 50.190 | 1162.73 | 541.392 | |
| 44 | 53.361 | 1140.91 | 541.392 | |
| 45 | 53.361 | 1140.91 | 541.392 | 19.872 |
| 49 | 53.361 | 862.60 | 148.137 | |
| 5 | 53.361 | 862.60 | 148.137 | 63.149 |
| 8 | 53.942 | 861.65 | 146.656 | 64.447 |
| 18 | 260.853 | 338.16 | 164.117 | 174.465 |
| Bleed | 0.000 | 770.80 | 2447.817 | |

| Efficiency | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Outer LPC | 0.8900 | 0.8975 | 1.000 | 1.655 |
| Inner LPC | 0.9000 | 0.9055 | 1.000 | 1.500 |
| IP Compressor | 0.8679 | 0.8747 | 1.289 | 1.455 |
| HP Compressor | 0.8677 | 0.9025 | 1.621 | 11.070 |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | 0.8250 | 0.7985 | 3.281 | 4.295 |
| LP Turbine | 0.8999 | 0.8842 | 1.064 | 3.655 |

HP Spl mech Eff 0.9900 Nom Spd 14324 rpm
LP Spl mech Eff 1.0000 Nom Spd 4835 rpm
P22/P21=1.0000 P25/P24=1.0000 P45/P44=1.0000

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | | |
|---|---|---|---|
| | | | Cycle Design Point |
| FN | = | 99.41 kN | Net Thrust |
| TSFC | = | 11.0161 g/(kN*s) | Thrust Specific Fuel Consumption |
| WF | = | 1.09510 kg/s | Fuel Flow |
| FN/W2 | = | 316.9 m/s | Specific Thrust |
| Core Eff | = | 0.4132 | Core Efficiency |
| Prop Eff | = | 0.0000 | Propulsion Efficiency |
| BPR | = | 4.9360 | Bypass Ratio |
| P2/P1 | = | 1.0000 | Inlet Pressure Ratio |
| P3/P2 | = | 24.16 | Overall Pressure Ratio |
| P5/P2 | = | 1.4620 | Engine Pressure Ratio |
| P16/P13 | = | 0.9787 | Bypass Duct Pressure Ratio |
| P16/P6 | = | 1.11907 | Bypass Exit Pressure/Core Exit Pressure |
| P16/P2 | = | 1.61971 | Bypass Exit Pressure/Engine Inlet Pressure |
| P6/P5 | = | 0.99000 | Turbine Exit Duct Pressure Ratio |
| A8 | = | 0.29325 m² | Geometric Nozzle Throat Area |
| A18 | = | 0.74236 m² | Geometric Bypass Nozzle Throat Area |
| XM8 | = | 0.75983 | Nozzle Throat Mach No. |
| XM18 | = | 0.85955 | Bypass Nozzle Throat Mach No. |
| WBLD/W25 | = | 0.00000 | Bleed Air Flow/Mass Flow W25 |
| CD8 | = | 0.97884 | Nozzle Discharge Coefficient |
| CD18 | = | 0.99183 | Bypass Nozzle Discharge Coefficient |
| V18/V8,id= | | 0.70788 | Ideal Jet Velocity Ratio |
| Wreci/W25= | | 0.00000 | Recirculating Air/Air Mass Flow W25 |
| WBLD/W22 = | | 0.00000 | Bleed Air Flow/Mass Flow W22 |
| WlkLP/W25= | | 0.01100 | HP Leakage to LPT Exit/Mass Flow W25 |
| Loading | = | 100.00 % | Burner Loading in % of the Cycle Design Point Value |
| WCHN/W25 | = | 0.07000 | HPT Nozzle Guide Vane Cooling Air / W25 |
| WCHR/W25 | = | 0.06000 | HPT Rotor Cooling Air / W25 |
| WCLN/W25 | = | 0.00000 | LPT Nozzle Guide Vane Cooling Air / W25 |
| WCLR/W25 | = | 0.00000 | LPT Rotor Cooling Air / W25 |

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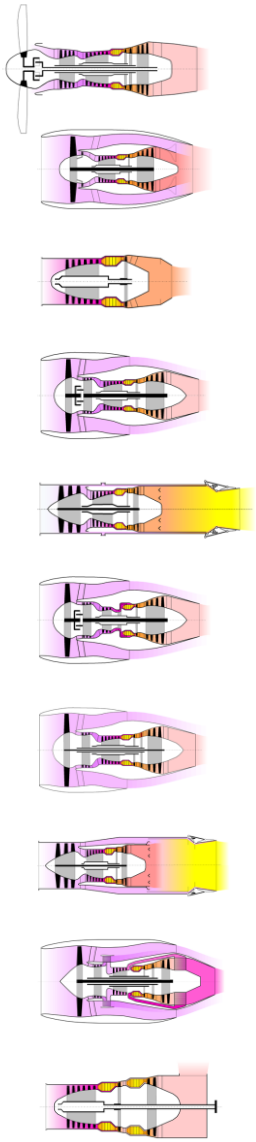
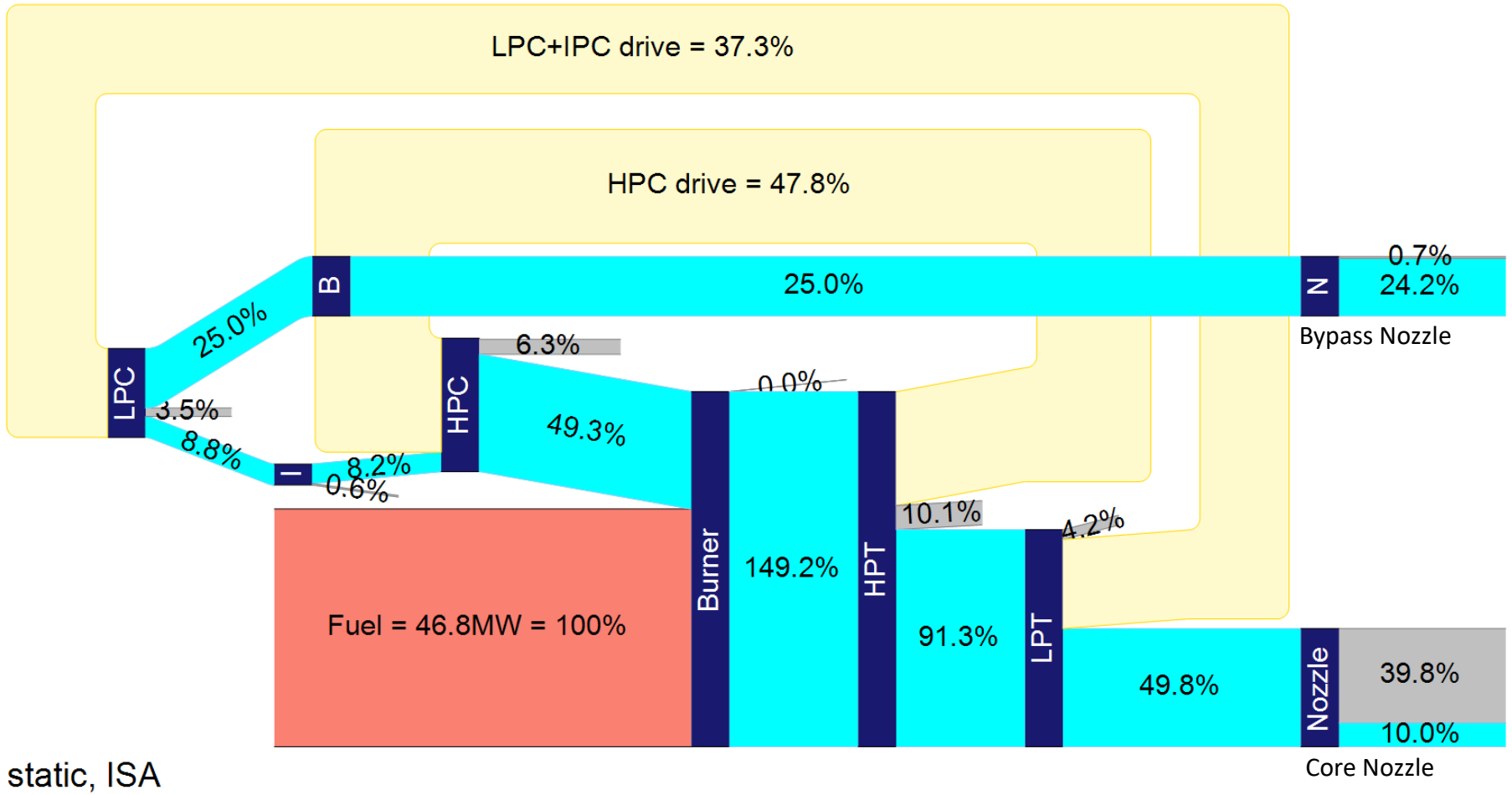
# Sankey Diagram
## Shows Energy Streams






SL static, ISA

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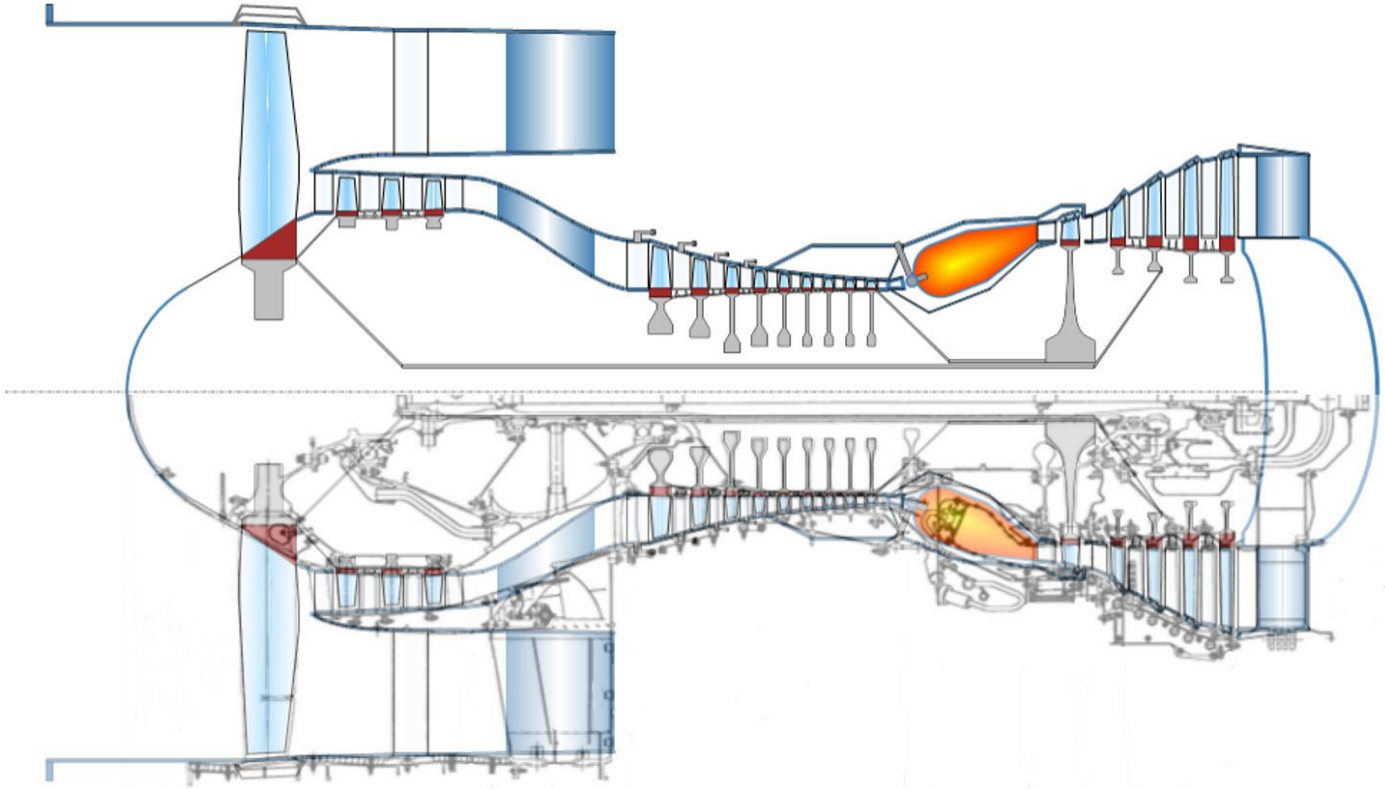
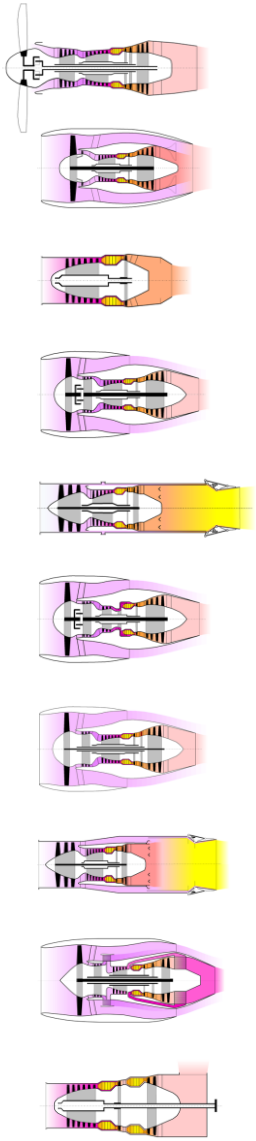
# A Geometry Model of The CFM56-3





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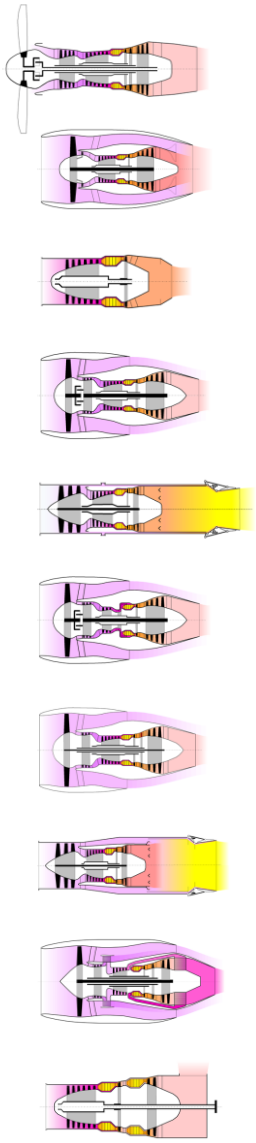
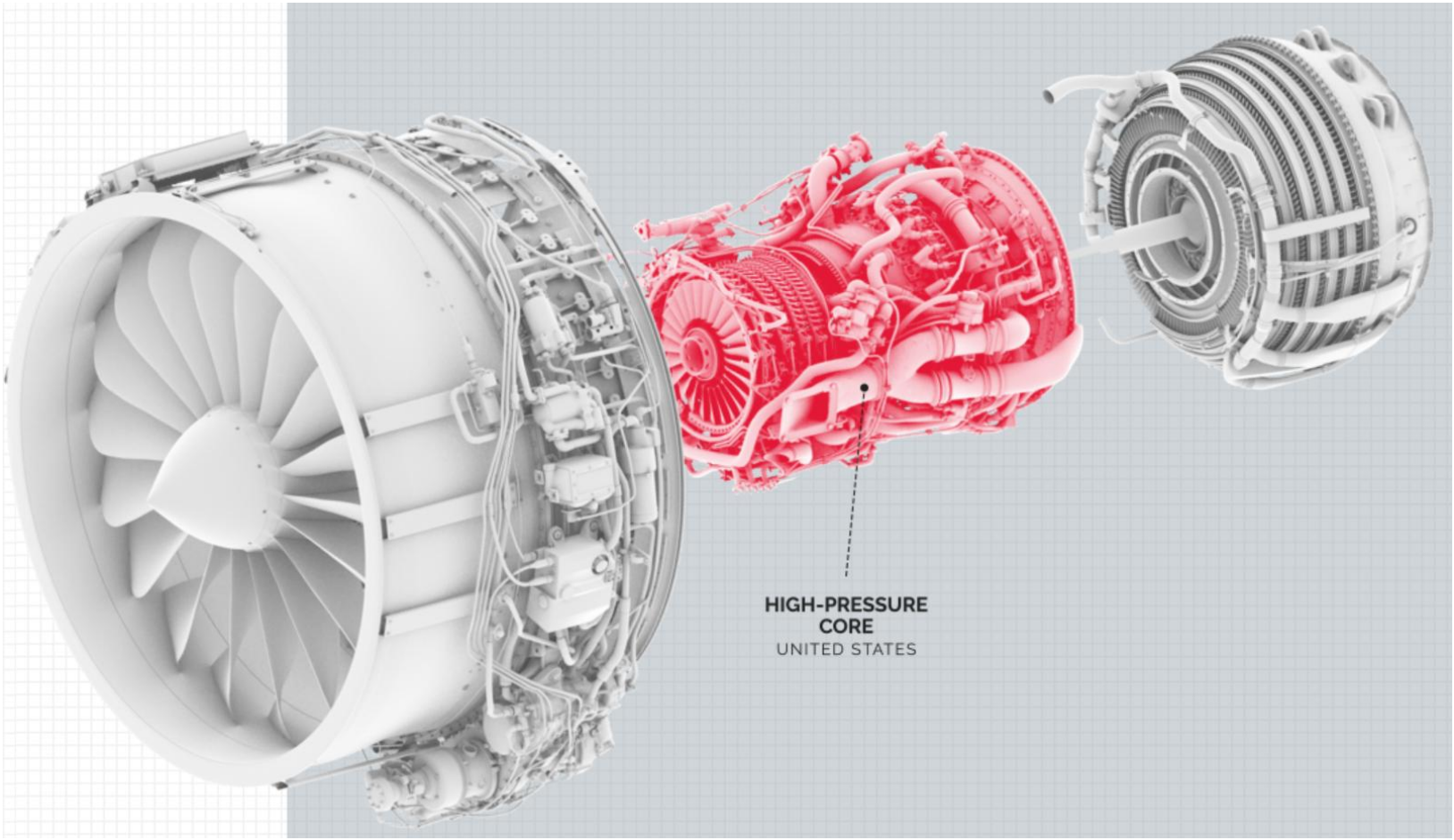
# CFM56-3 Modular Design



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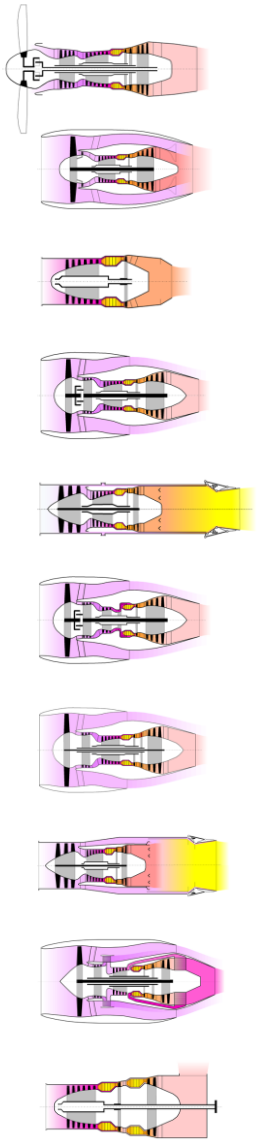
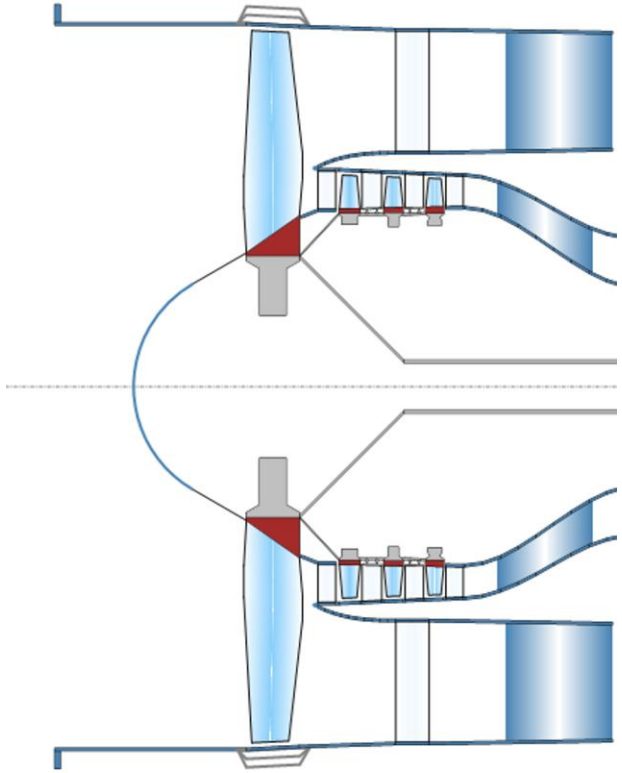
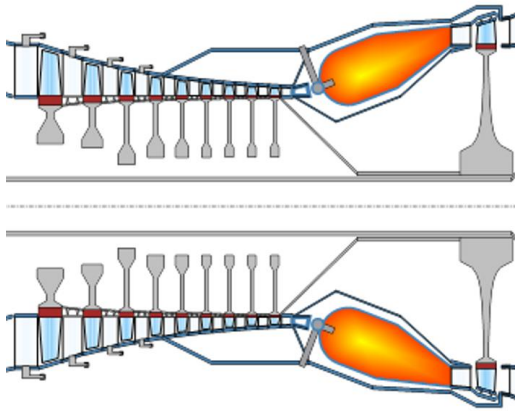
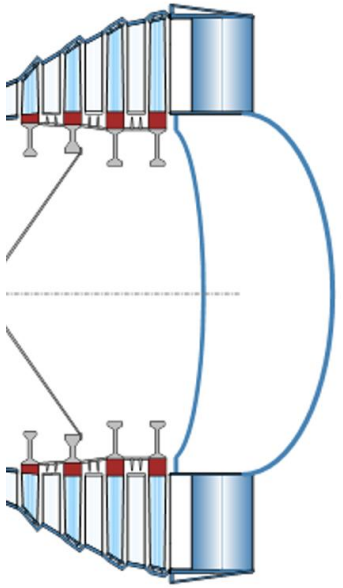
# The Engine Modules





## Gas Generator





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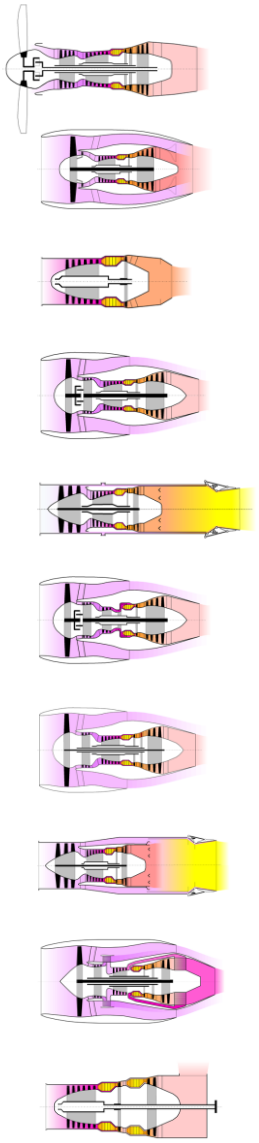
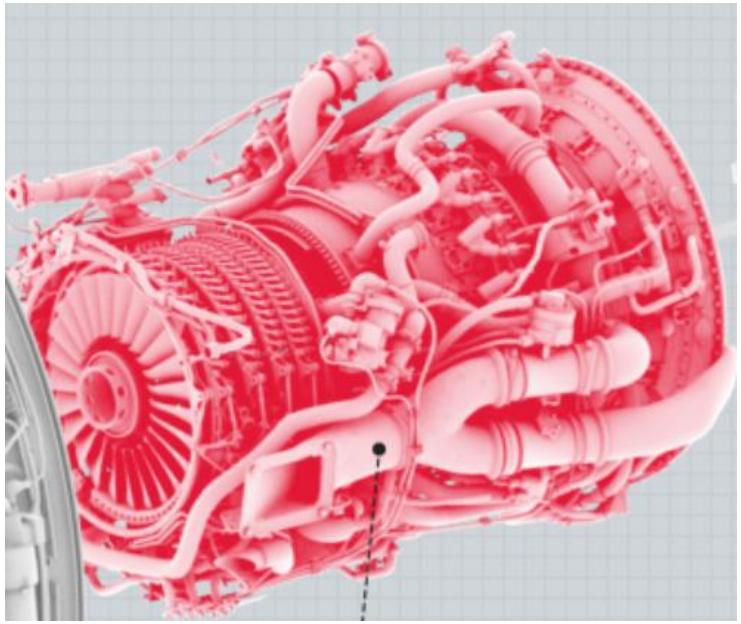
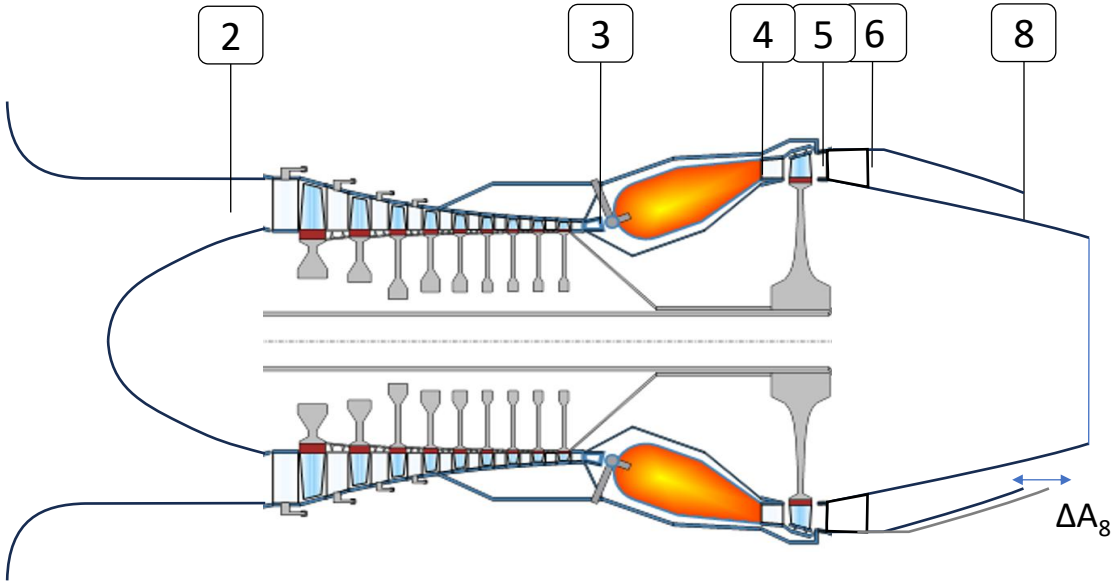
# The Gas Generator
## (Core Engine)







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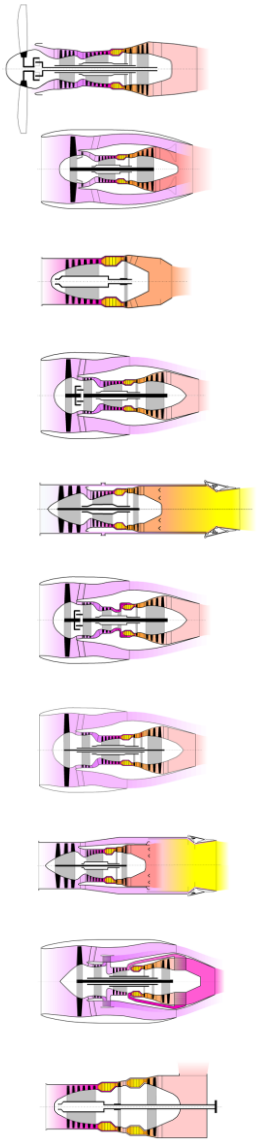

# CFM56-3 Reference Cycle

## ISA SLS

| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 2 | 313.700 | 288.15 | 101.325 | 313.700 |
| 13 | 260.853 | 338.16 | 167.693 | 170.745 |
| 21 | 52.847 | 327.40 | 151.988 | 37.554 |
| 22 | 52.847 | 327.40 | 151.988 | 37.554 |
| 24 | 52.847 | 369.90 | 221.130 | 27.436 |
| 25 | 52.847 | 369.90 | 221.130 | 27.436 |
| 3 | 52.847 | 770.80 | 2447.817 | 3.578 |
| 31 | 45.396 | 770.80 | 2447.817 | |
| 4 | 46.491 | 1577.54 | 2325.426 | 4.740 |
| 41 | 50.190 | 1522.89 | 2325.426 | 5.028 |
| 43 | 50.190 | 1162.73 | 541.392 | |
| 44 | 53.361 | 1140.91 | 541.392 | |
| 45 | 53.361 | 1140.91 | 541.392 | 19.872 |
| 49 | 53.361 | 862.60 | 148.137 | |
| 5 | 53.361 | 862.60 | 148.137 | 63.149 |
| 8 | 53.942 | 861.65 | 146.656 | 64.447 |
| 18 | 260.853 | 338.16 | 164.117 | 174.465 |
| Bleed | 0.000 | 770.80 | 2447.817 | |

| Efficiency | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Outer LPC | 0.8900 | 0.8975 | 1.000 | 1.655 |
| Inner LPC | 0.9000 | 0.9055 | 1.000 | 1.500 |
| IP Compressor | 0.8679 | 0.8747 | 1.289 | 1.455 |
| HP Compressor | 0.8677 | 0.9025 | 1.621 | 11.070 |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | 0.8250 | 0.7985 | 3.281 | 4.295 |
| LP Turbine | 0.8999 | 0.8842 | 1.064 | 3.655 |

HP Spl mech Eff 0.9900 Nom Spd 14324 rpm
LP Spl mech Eff 1.0000 Nom Spd 4835 rpm
P22/P21=1.0000 P25/P24=1.0000 P45/P44=1.0000

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | |
|---|---|---|
| FN | = | 99.41 kN |
| TSFC | = | 11.0161 g/(kN*s) |
| WF | = | 1.09510 kg/s |
| FN/W2 | = | 316.9 m/s |
| Core Eff | = | 0.4132 |
| Prop Eff | = | 0.0000 |
| BPR | = | 4.9360 |
| P2/P1 | = | 1.0000 |
| P3/P2 | = | 24.16 |
| P5/P2 | = | 1.4620 |
| P16/P13 | = | 0.9787 |
| P16/P6 | = | 1.11907 |
| P16/P2 | = | 1.61971 |
| P6/P5 | = | 0.99000 |
| A8 | = | 0.29325 m² |
| A18 | = | 0.74236 m² |
| XM8 | = | 0.75983 |
| XM18 | = | 0.85955 |
| WBLD/W25 | = | 0.00000 |
| CD8 | = | 0.97884 |
| CD18 | = | 0.99183 |
| V18/V8,id | = | 0.70788 |
| Wreci/W25 | = | 0.00000 |
| WBLD/W22 | = | 0.00000 |
| WlkLP/W25 | = | 0.01100 |
| Loading | = | 100.00 % |
| WCHN/W25 | = | 0.07000 |
| WCHR/W25 | = | 0.06000 |
| WCLN/W25 | = | 0.00000 |
| WCLR/W25 | = | 0.00000 |

# Gas Generator Reference Cycle

## ISA SLS

| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 1 | 27.436 | 288.15 | 101.325 | |
| 2 | 27.436 | 288.15 | 101.325 | 27.436 |
| 3 | 27.436 | 609.27 | 1121.668 | 3.604 |
| 31 | 23.568 | 609.27 | 1121.668 | |
| 4 | 23.989 | 1250.00 | 1065.584 | 4.751 |
| 41 | 25.910 | 1206.10 | 1065.584 | 5.040 |
| 49 | 25.910 | 908.46 | 247.090 | |
| 5 | 27.556 | 891.50 | 247.090 | 19.876 |
| 6 | 27.556 | 891.50 | 247.090 | |
| 8 | 27.556 | 891.50 | 247.090 | 19.876 |
| Bleed | 0.302 | 609.27 | 1121.668 | |

P2/P1 = 1.0000 P4/P3 = 0.9500 P6/P5 1.0000

| Efficiencies: | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Compressor | 0.8677 | 0.9033 | 1.000 | 11.070 |
| Burner | 0.9995 | | | 0.950 |
| Turbine | 0.8250 | 0.7969 | 1.964 | 4.313 |

Spool mech Eff 0.9900 Nom Spd 13498 rpm

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | |
|---|---|---|
| FN | = | 17.57 kN |
| TSFC | = | 23.9840 g/(kN*s) |
| FN/W2 | = | 640.52 m/s |
| Prop Eff | = | 0.0000 |
| eta core | = | 0.3120 |
| WF | = | 0.42148 kg/s |
| s NOx | = | 0.24987 |
| XM8 | = | 1.0000 |
| A8 | = | 0.0836 m² |
| P8/Pamb | = | 2.4386 |
| WBld/W2 | = | 0.01100 |
| Ang8 | = | 0 deg |
| CD8 | = | 1.0000 |
| WClN/W2 | = | 0.07000 |
| WClR/W2 | = | 0.06000 |
| Loading | = | 100.00 % |
| e45 th | = | 0.80024 |
| far8 | = | 0.01553 |
| PWX | = | 0.00 kW |

Secondary air system: LPT cooling air appears as 1.1% overboard bleed

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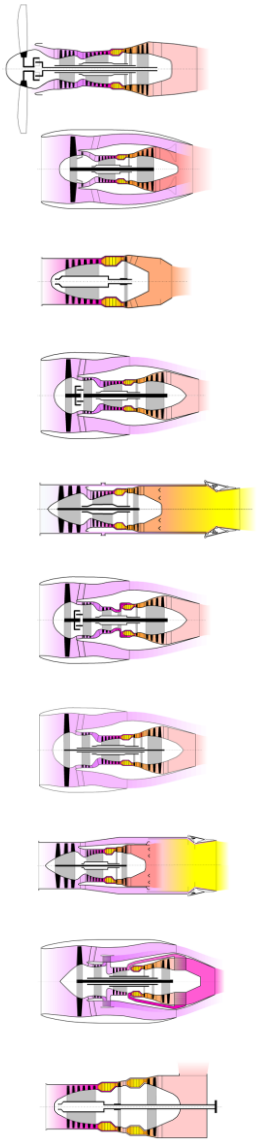
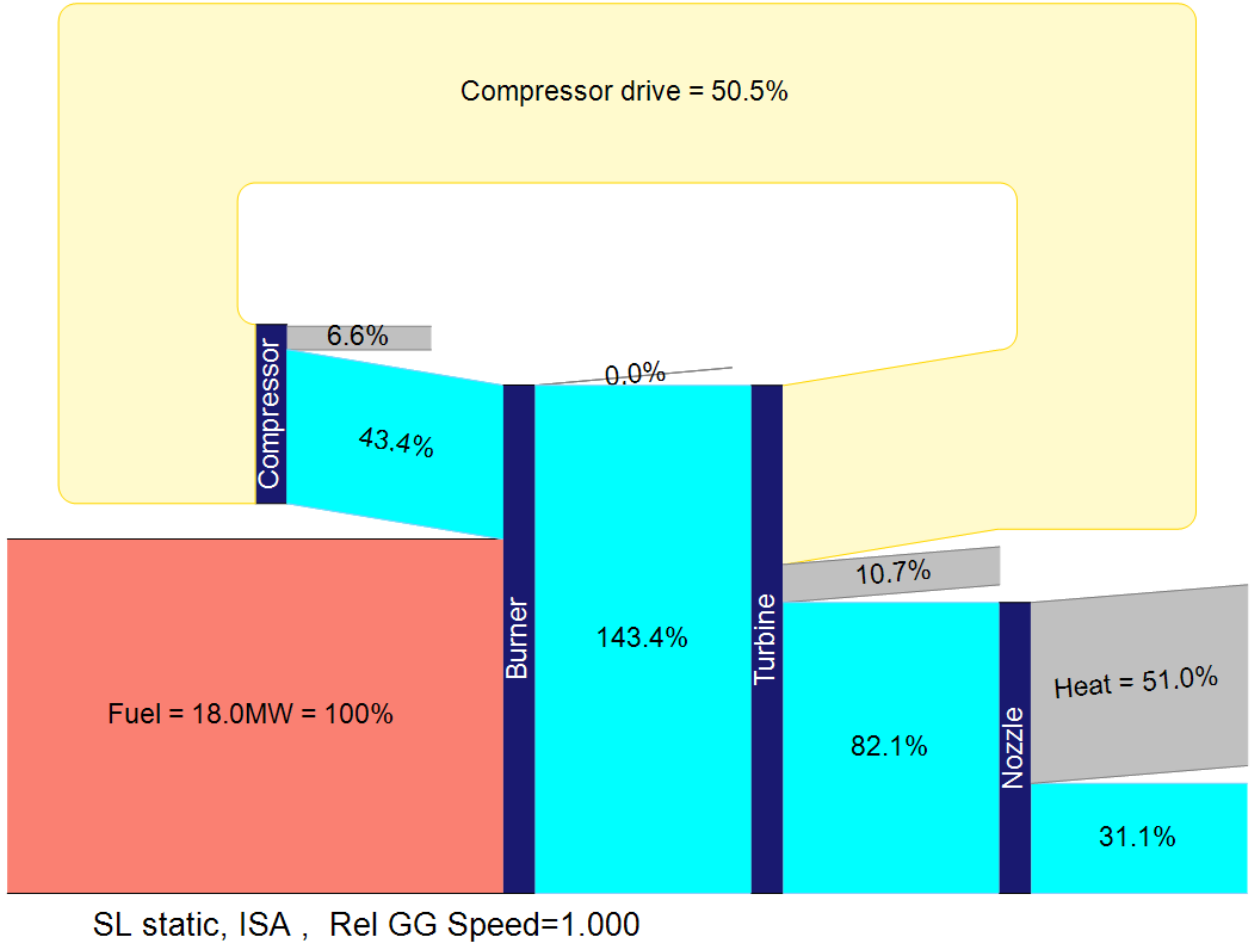
# Sankey Diagram






SL static, ISA , Rel GG Speed=1.000

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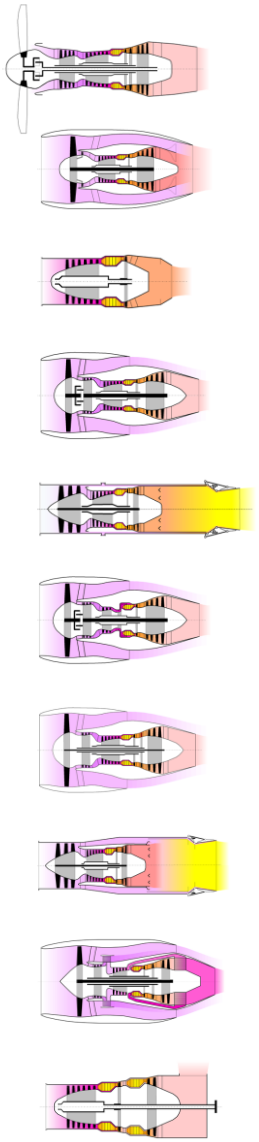

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# Outline

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components

Cooperation of the Components

Gas Generator +

Variable Geometry

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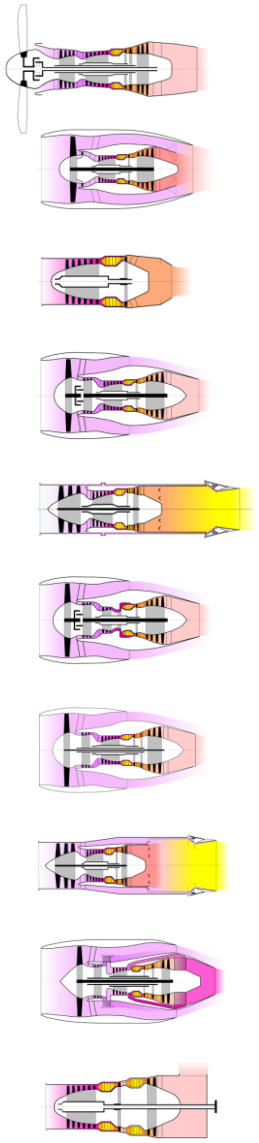
# Total Temperature



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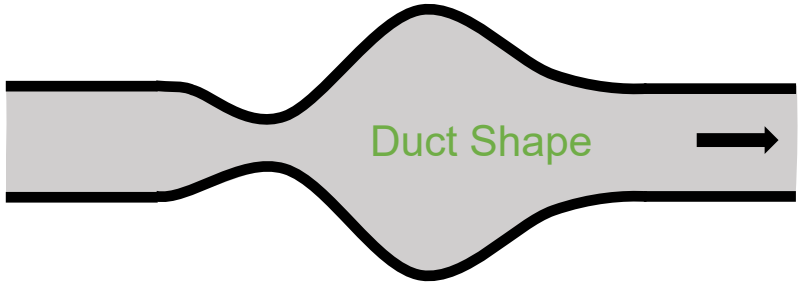


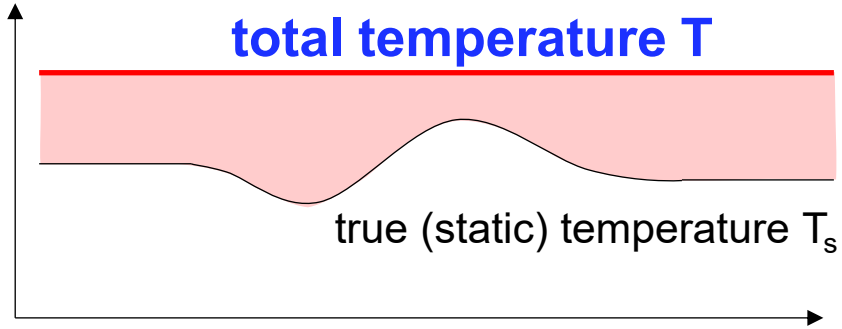

Total Energy = W*H = const

Mass Flow W = const

Total Enthalpy H = const

$H = c_P * T$ = const

Total Temperature **T** = const




Static Temperature $T_s$ varies:

$$c_P * T_s = c_P * T - V^2/2$$

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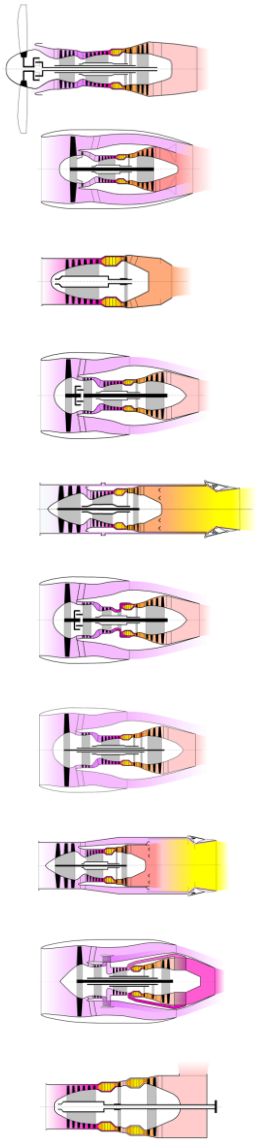
# Total Pressure



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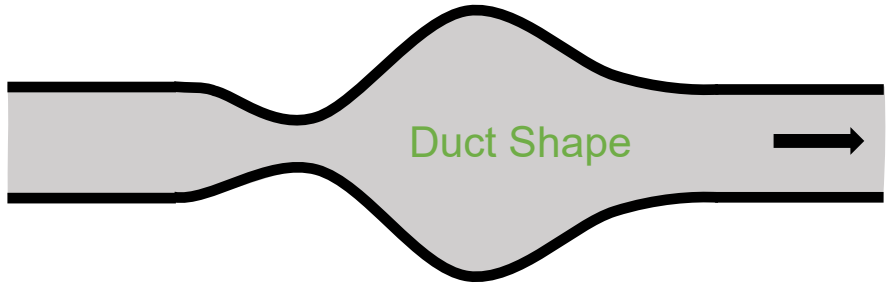
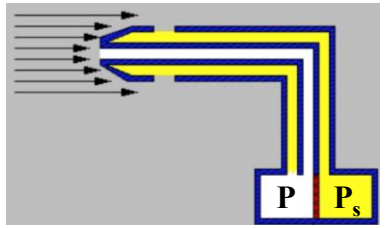
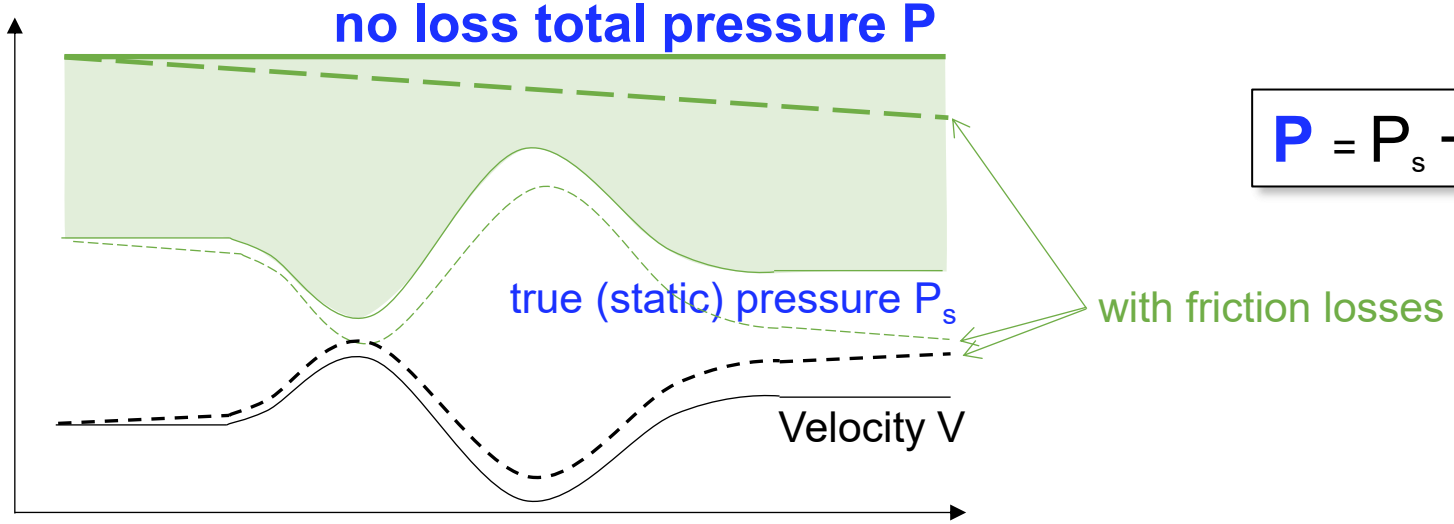



**Energy = W*H = W*$c_P$*T= const**




$$P = P_s + \rho * V^2/2$$

dynamic pressure

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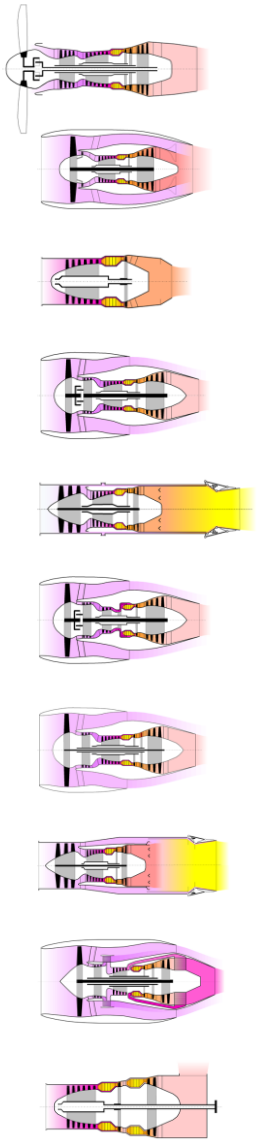

# Correlations Between Static and Total Quantities

Constant Gas Properties:

$$H = c_P * T = c_P * T_s + \frac{V^2}{2}$$

Isentropic Exponent:

$$\gamma = \frac{c_p}{c_p - R}$$

Mach Number:

$$M = \frac{V}{V_{sonic}} = \frac{V}{\sqrt{\gamma * R * T_s}}$$

$$\frac{T}{T_s} = 1 + \frac{\gamma - 1}{2} M^2$$

$$\frac{P}{P_s} = \left(\frac{T}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

R = Gas Constant
$R_{air}$ = 287 J/(kg*K)

$c_P$ = Specific Heat @ Constant Pressure
$c_{P,air}$ = 1004 J/(kg*K)

$\gamma_{air}$ = 1.4

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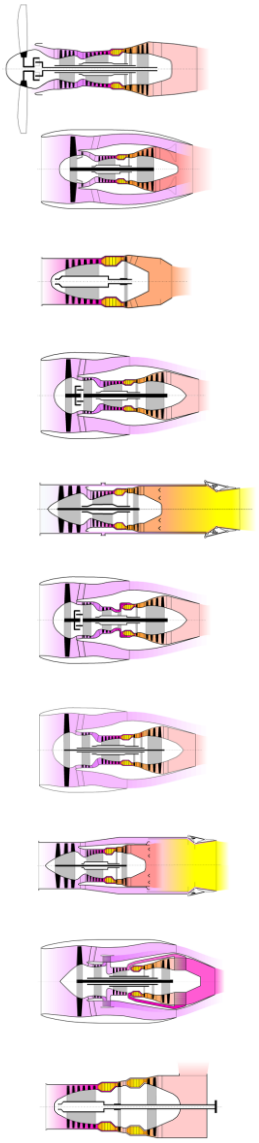
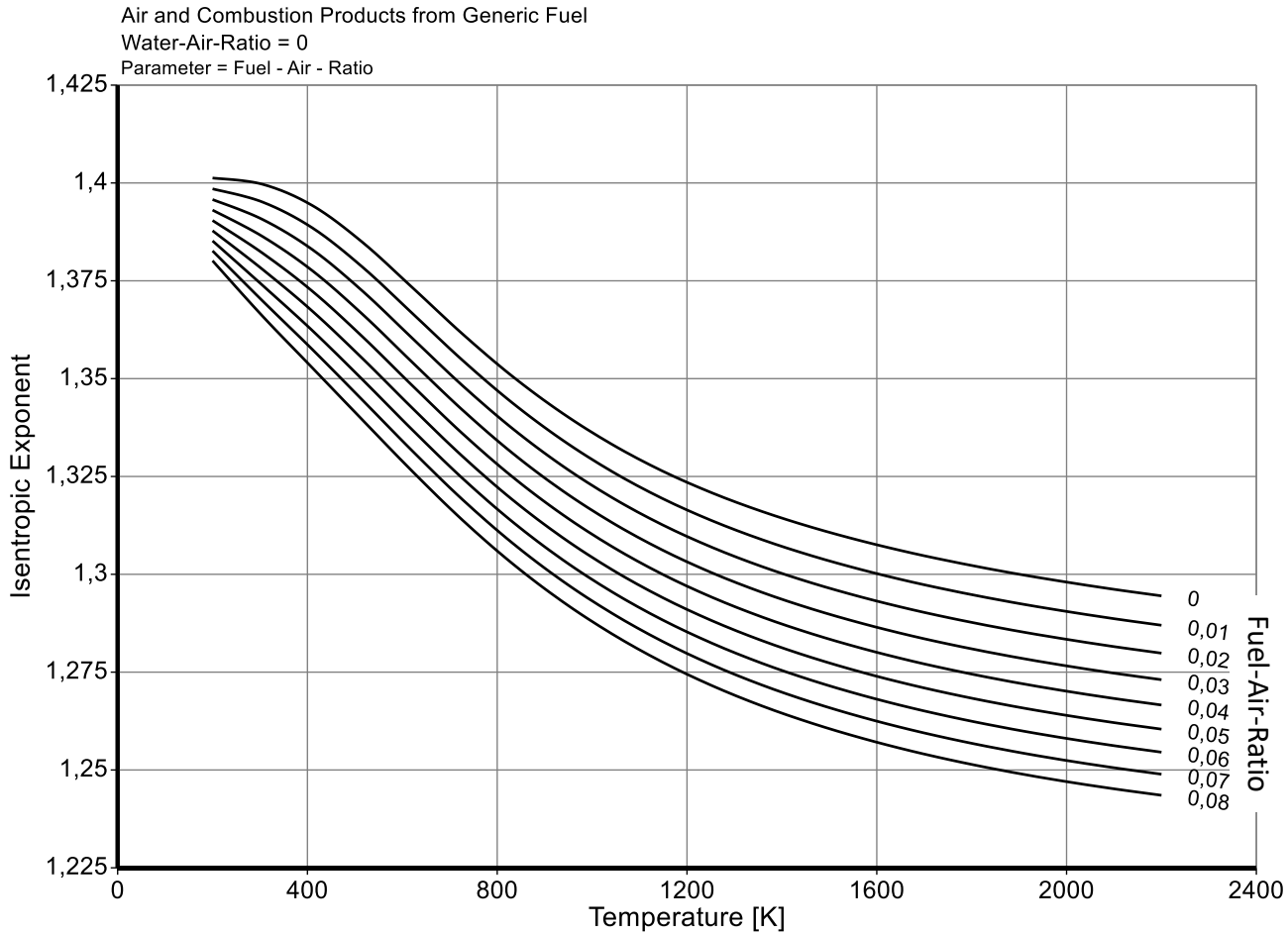
# Gas Properties
# Isentropic Exponent $\gamma = c_p/(c_p-R)$





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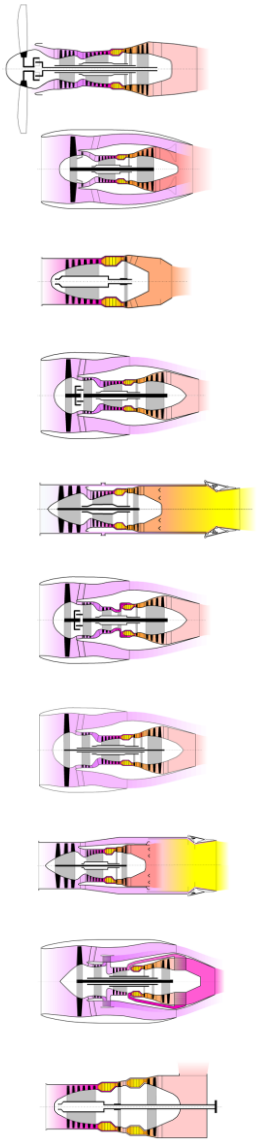
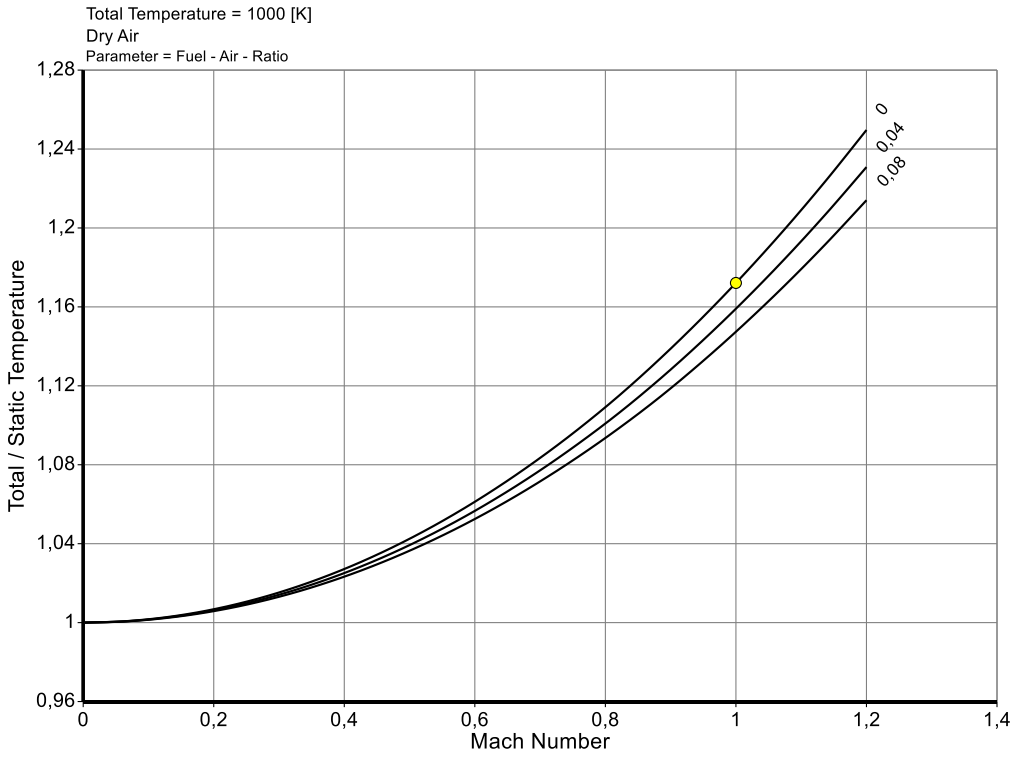
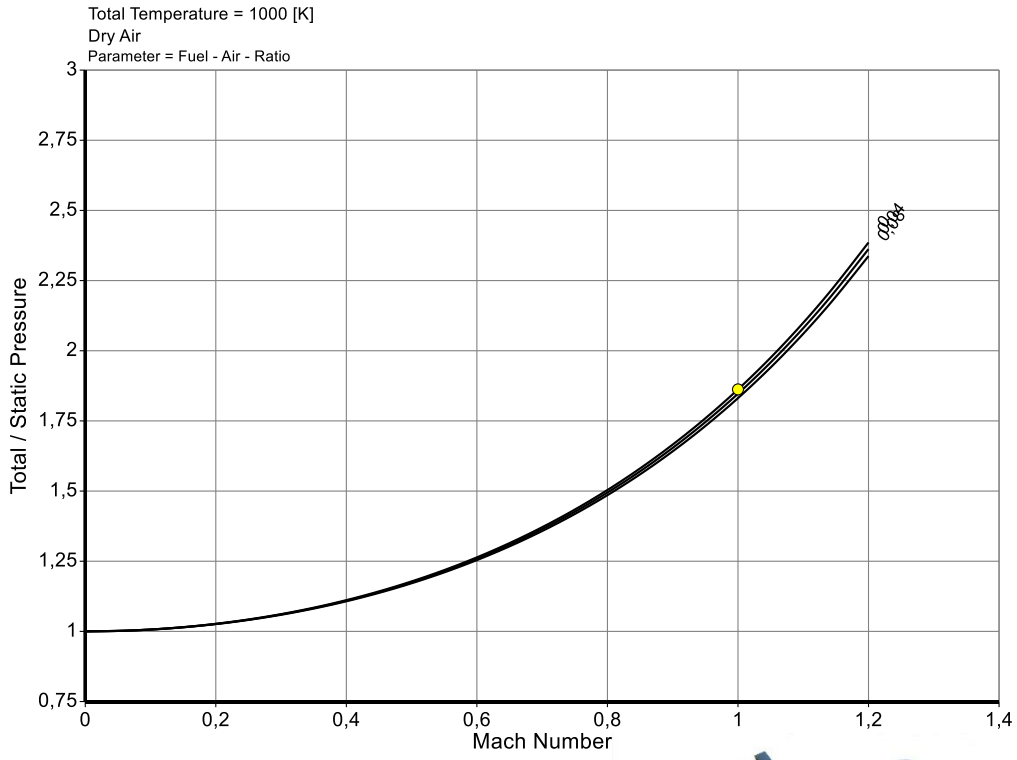
# Total-Static Temperature- and Pressure Ratio



$$\frac{T}{T_s} = 1 + \frac{\gamma - 1}{2} M^2$$

$$\frac{P}{P_s} = \left(\frac{T}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$



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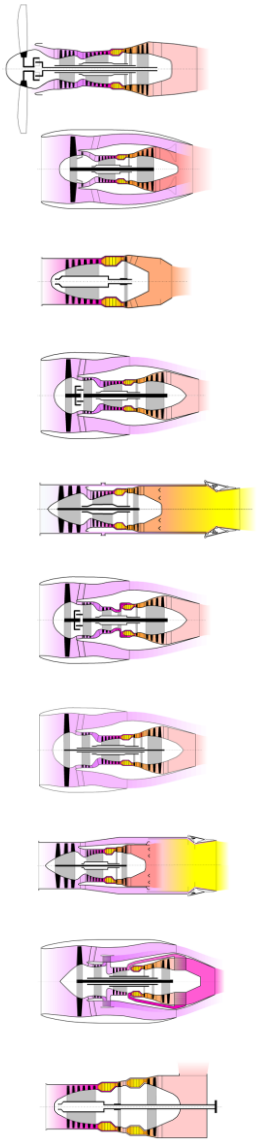
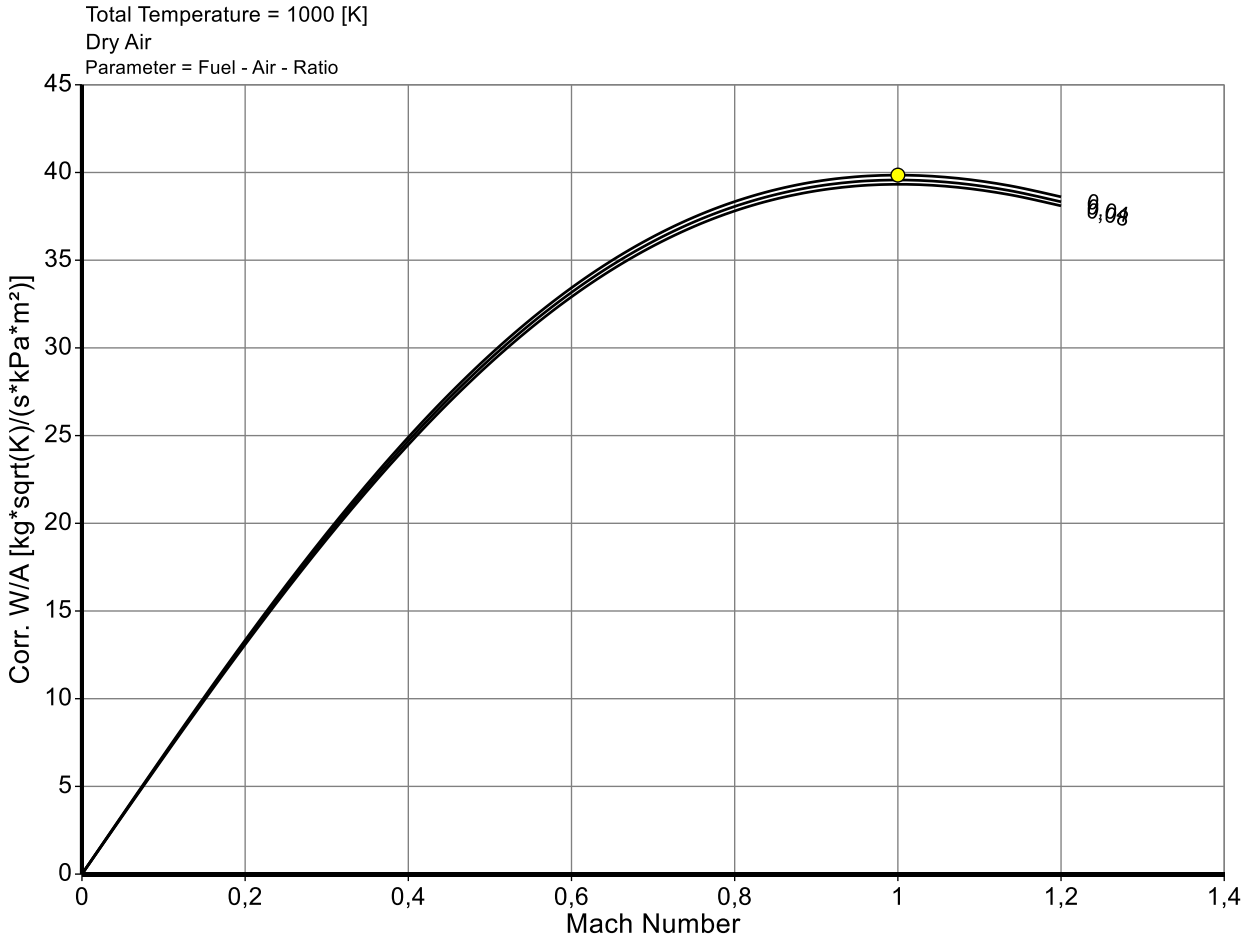
# Corrected Flow per Area



$$\frac{\frac{W\sqrt{T}}{P}}{A} = \frac{M\sqrt{\gamma/R}}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}$$



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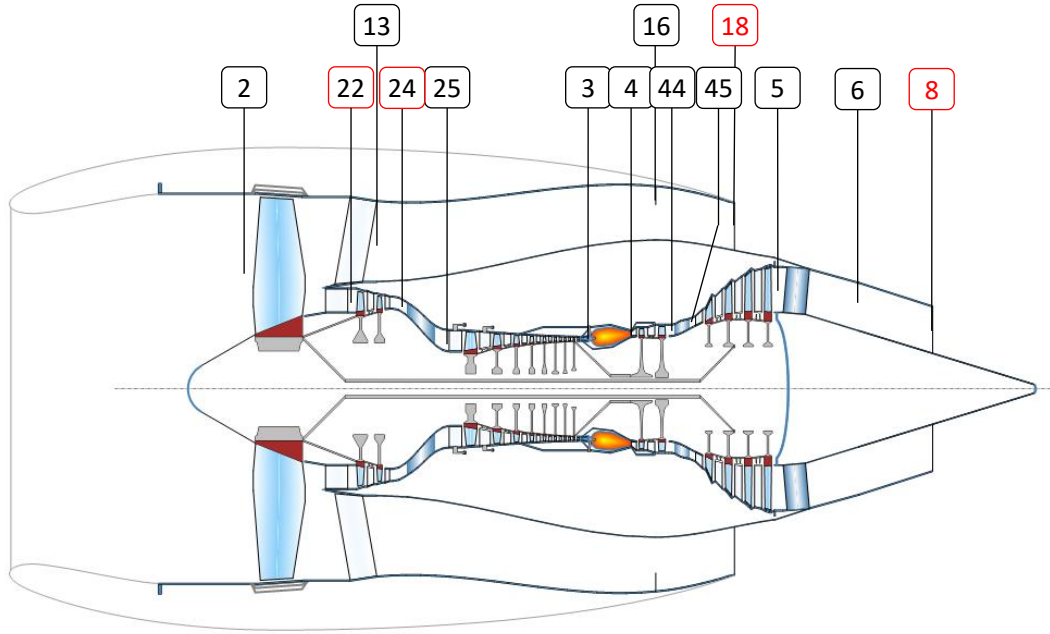
# Nomenclature

## Aerospace Recommended Practice ARP 755




| | | |
|---|---|---|
| a | velocity of sound | [m/s] |
| $c_P$ | specific heat | [J/(kg × K)] |
| A | area | [m²] |
| ΔH | specific work | [J/(kg/s)], [m²/s²] |
| M | Mach number | - |
| N | rotational speed | rpm |
| P | total pressure | [kPa] |
| $P_s$ | static pressure | [kPa] |
| R | gas constant | [J/(kg × K)] |
| T | total temperature [K] | |
| $T_s$ | static temperature [K] | |
| U | circumferential speed | [m/s] |
| V | velocity | [m/s] |
| W | mass flow | [kg/s] |
| | | |
| δ | T/288.15 K | - |
| Θ | P/101.325 kPa | - |
| ϒ | Isentropic exponent | - |
| ρ | density | [kg/m³] |

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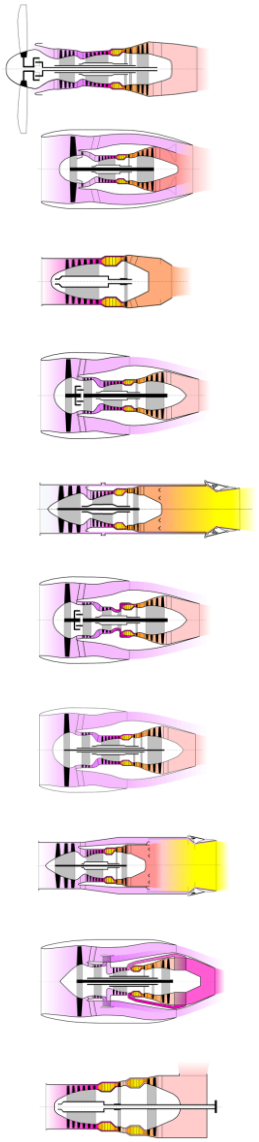
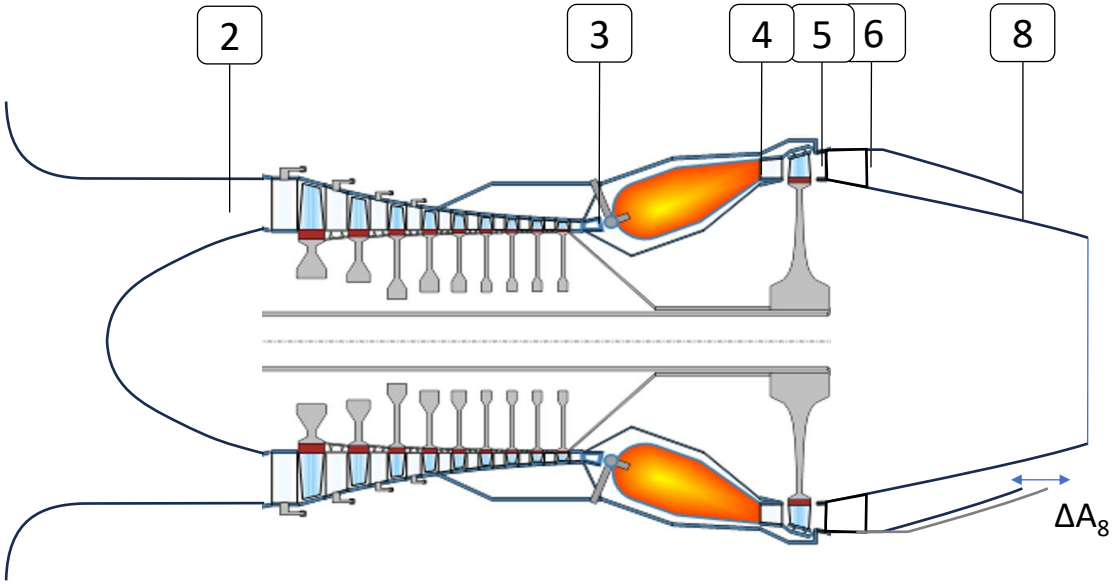
# Nomenclature
## Gas Generator - The Engine Core






https://www.flightglobal.com/snecma-runs-core-of-silvercrest-business-jet-engine/77803.article

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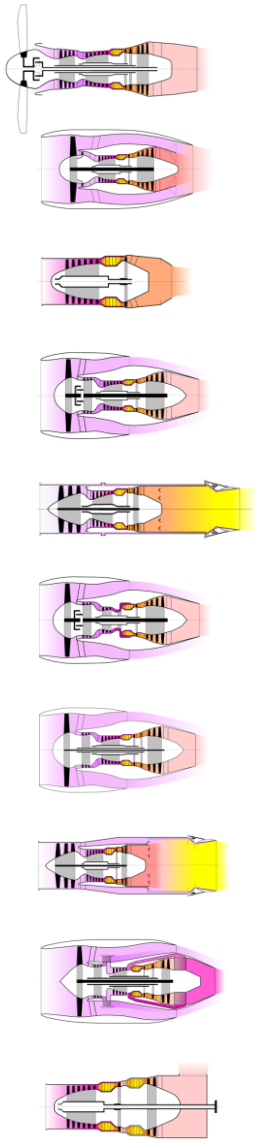

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# Outline

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components
- Compressor
- Burner
- Turbine
- Nozzle

Cooperation of the Components

Gas Generator +

Variable Geometry

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# Compressor Performance Map

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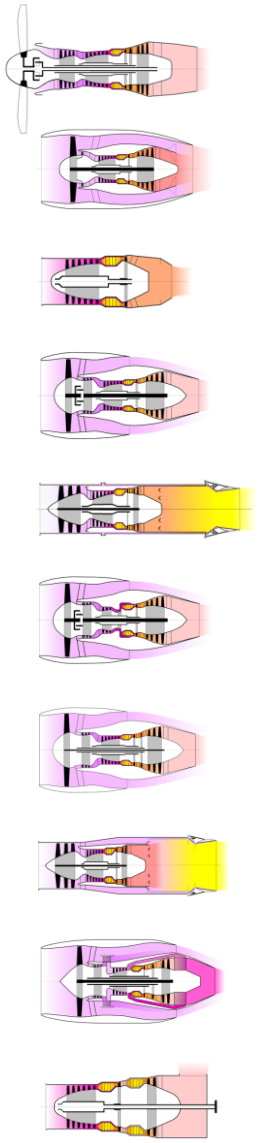

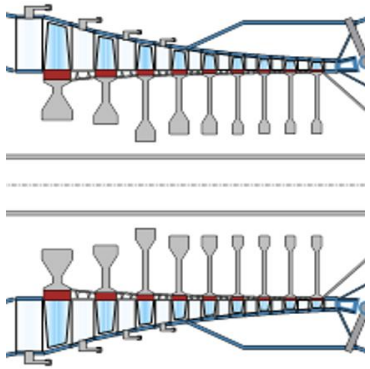

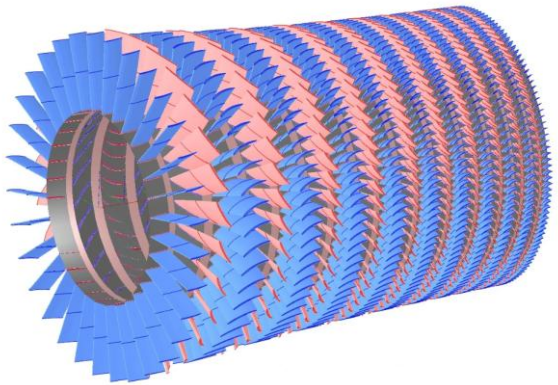

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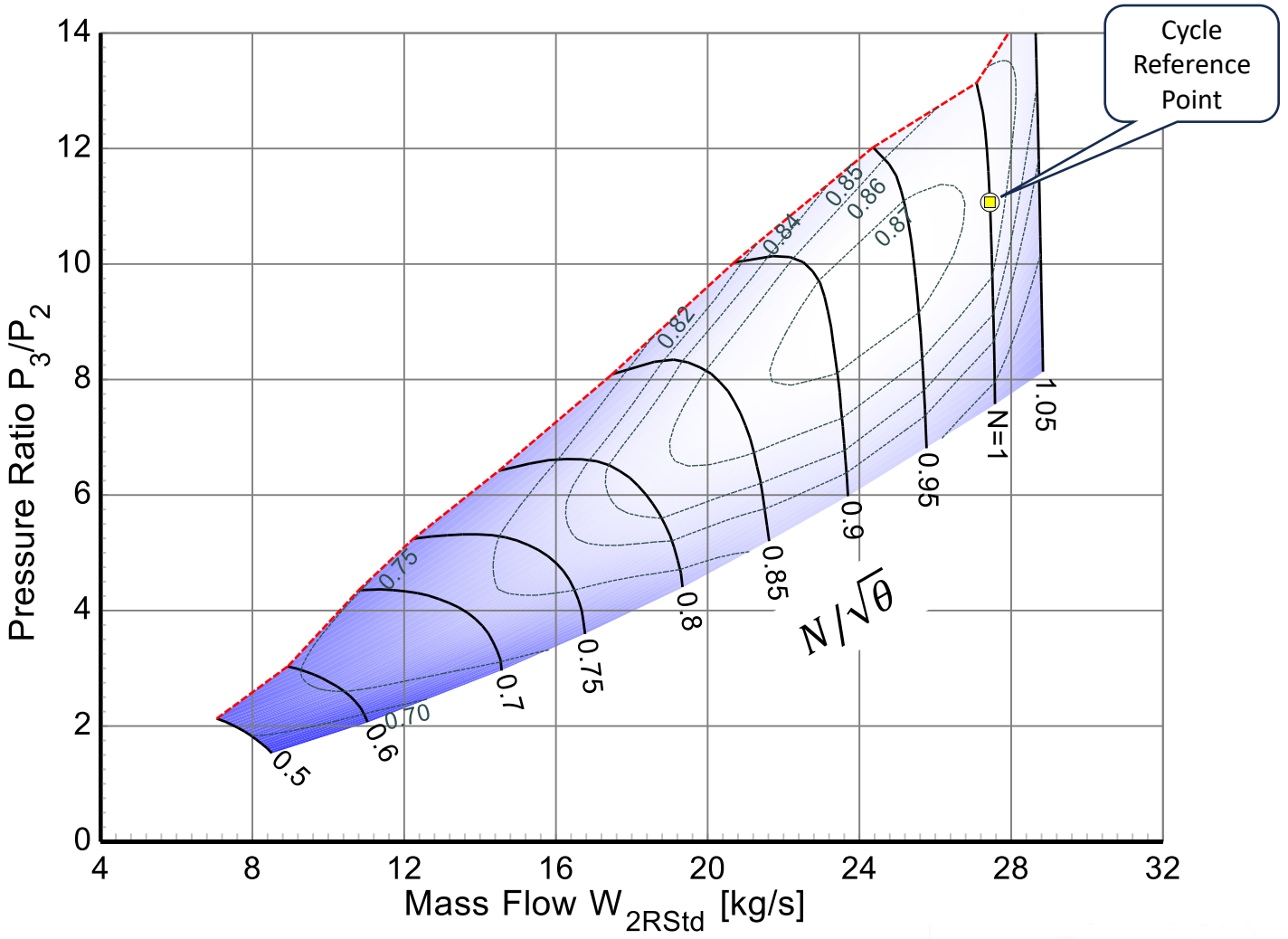

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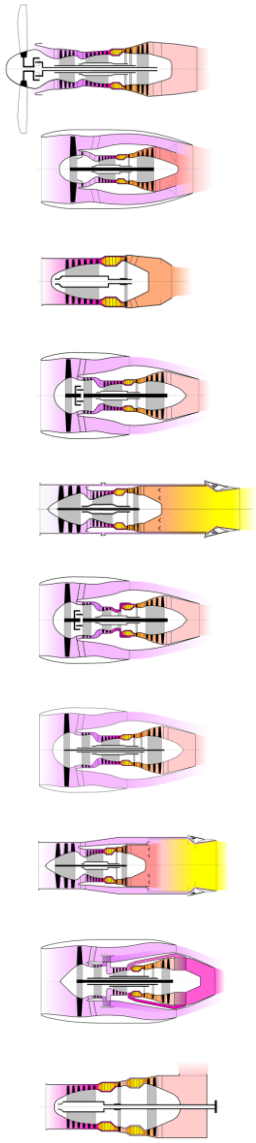
# Compressor Cascade Performance



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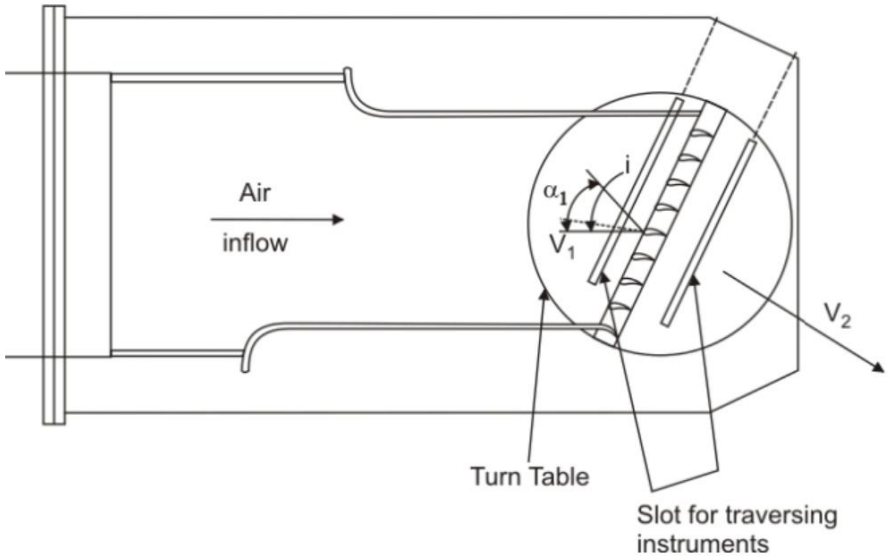


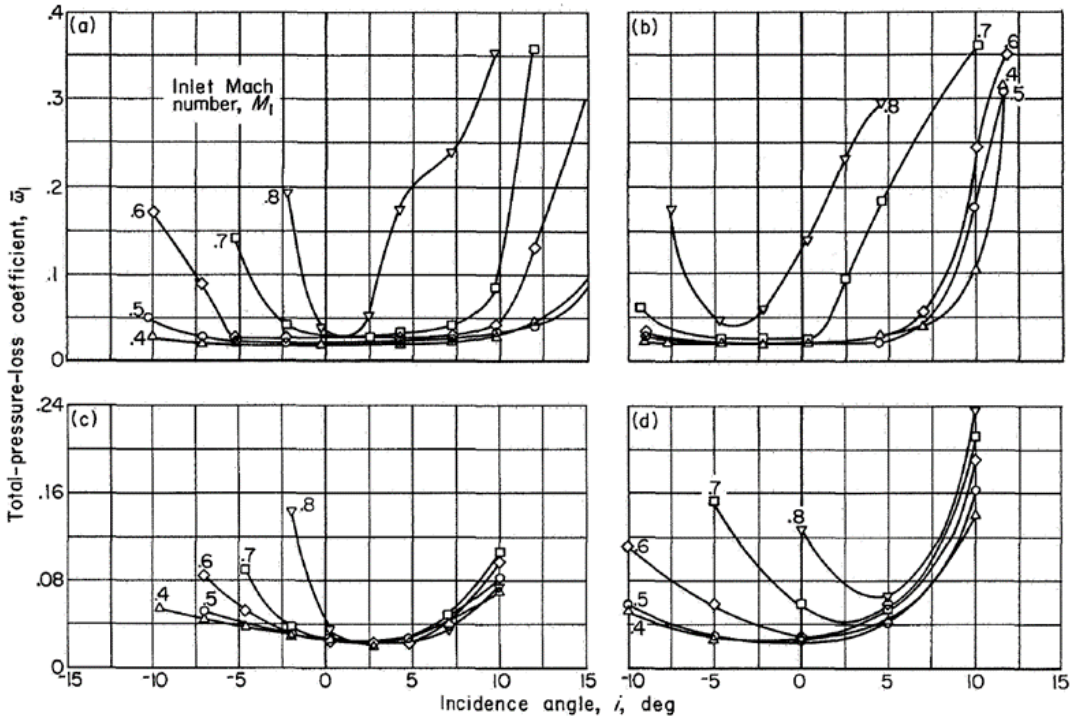


Loss Characteristics of Cascade Blade Sections (Ref. NASA SP-36)
(a) Circular Arc, (b) Parabolic Arc (c) Double Circular Arc (d) Sharp Nose Blade

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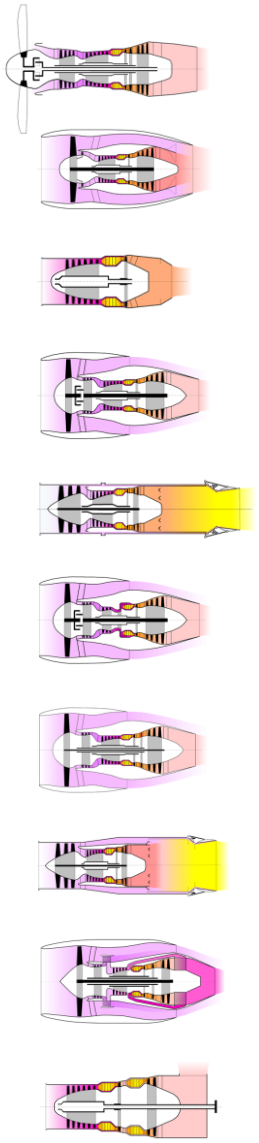

# Mach Number Similarity

## Losses are equal if

- all flow angles are equal
- all Mach numbers are equal

Equal flow angles and equal (absolute) velocities yield equal specific work:

$$\Delta H = U * (V_{u2} - V_{u1})$$

Equal flow angles and equal Mach numbers yield equal corrected specific work:

$$\frac{\Delta H}{\gamma R T_s} = \frac{U}{\sqrt{\gamma R T_s}} \frac{V_{u2} - V_{u1}}{\sqrt{\gamma R T_s}}$$

velocity of sound

| | | |
|---|---|---|
| H | specific work | [m²/s²] |
| M | Mach number | - |
| P | total pressure | [kPa] |
| $P_s$ | static pressure | [kPa] |
| R | gas constant | [J/(kg × K)] |
| T | total temperature | [K] |
| $T_s$ | static temperature | [K] |
| U | circumferential speed | [m/s] |
| V | absolute speed | [m/s] |
| $V_U$ | circumf. speed component | [m/s] |
| Δ | difference | |
| $\Theta$ | T/288.15 K | - |
| γ | isentropic exponent | - |

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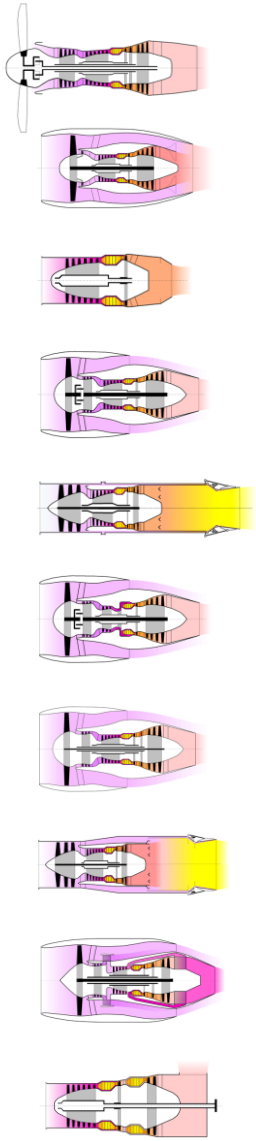
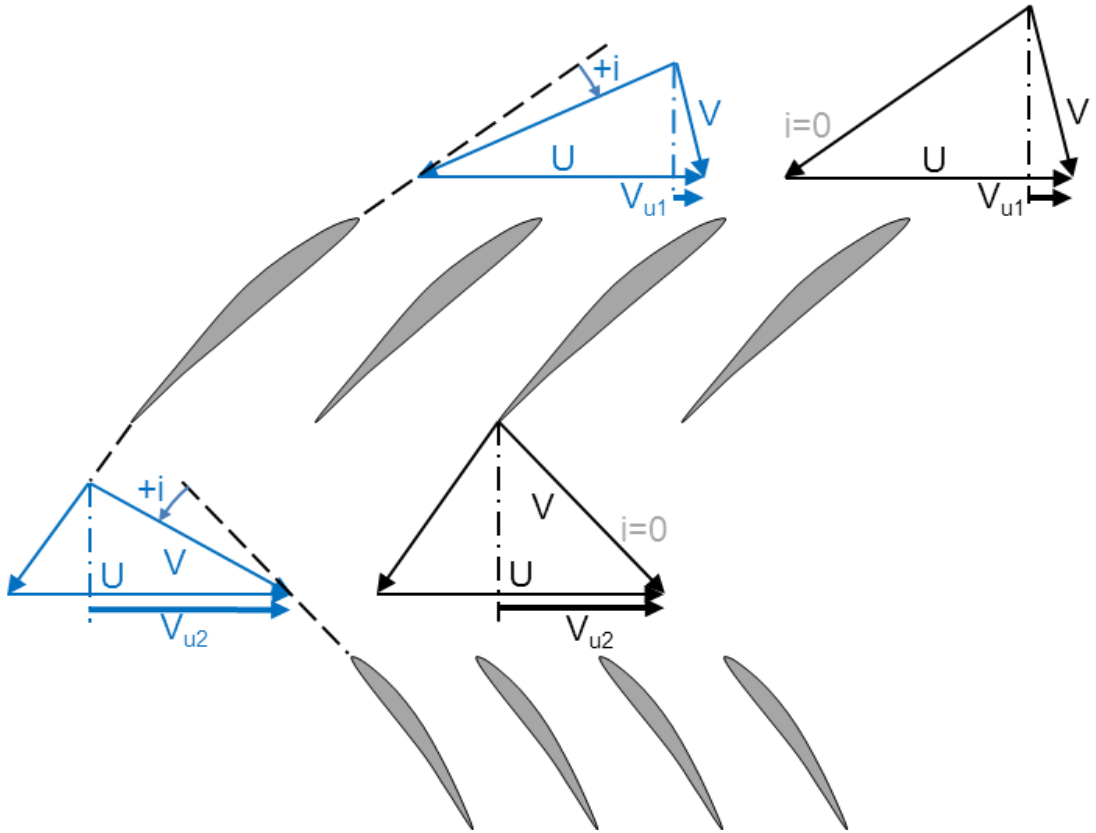
# Compressor Stage Performance






Specific Work:

(Euler's Equation)

$$\Delta H = U*(V_{u2} - V_{u1})$$

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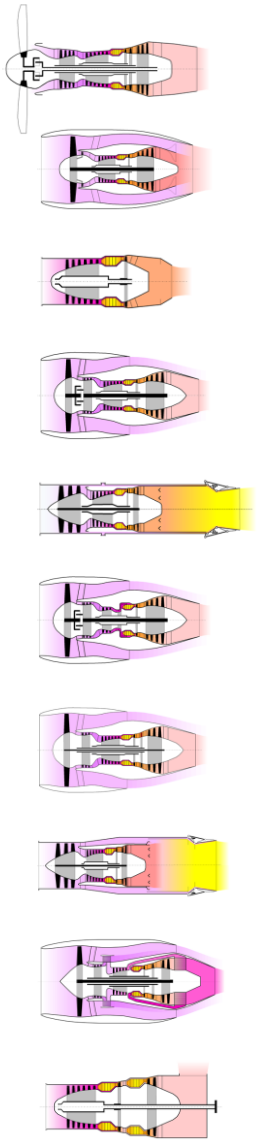
# Compressor Map
## ΔH/T is Correlated With Mach²



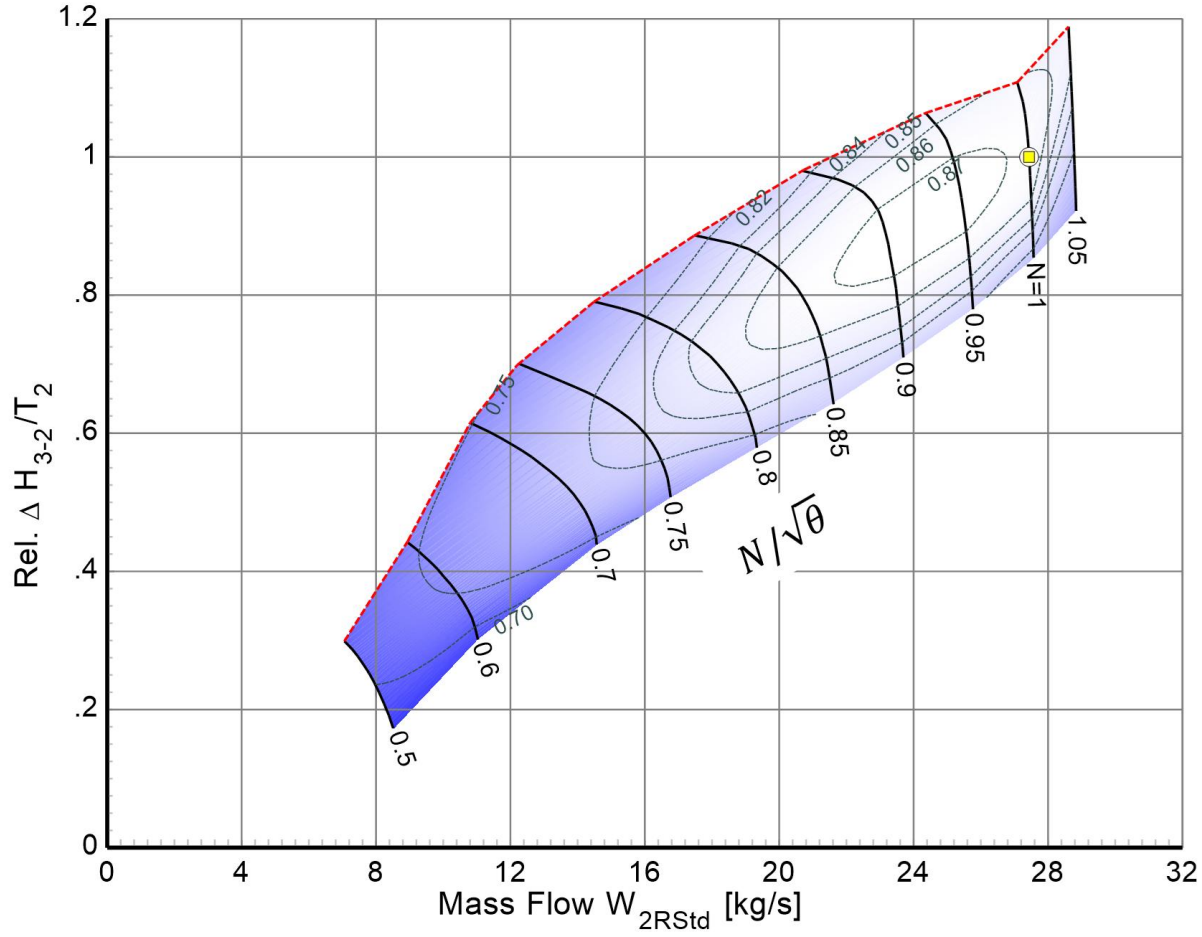
$$\frac{\Delta H}{\gamma R T_s} = \frac{U}{\sqrt{\gamma R T_s}} \times \frac{V_{u2} - V_{u1}}{\sqrt{\gamma R T_s}}$$

velocity of sound

$$\frac{\Delta H/T}{\gamma R\, T_s/T} = \frac{U}{\sqrt{\gamma R\, T_s}} \times \frac{V_{u2} - V_{u1}}{\sqrt{\gamma R\, T_s}}$$

$$T_s/T = \frac{1}{1 + \frac{\gamma - 1}{2} M^2}$$

$$\frac{\Delta H}{T} = \gamma R \frac{M_U\,(M_{Vu2} - M_{Vu1})}{1 + \frac{\gamma - 1}{2} M^2}$$



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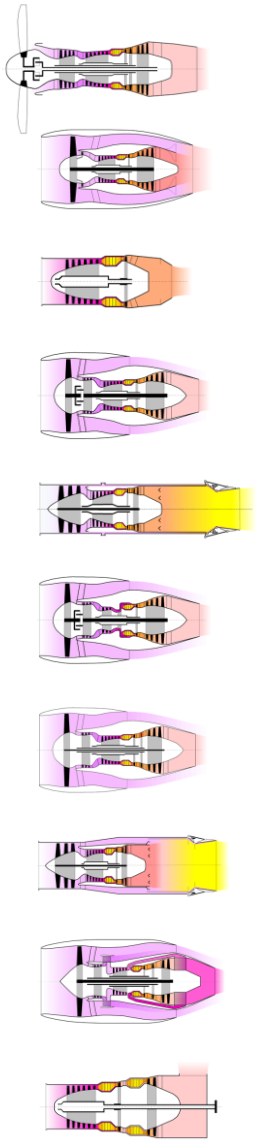
# Compressor Map

## $P_3/P_2$ is Correlated With Mach Number



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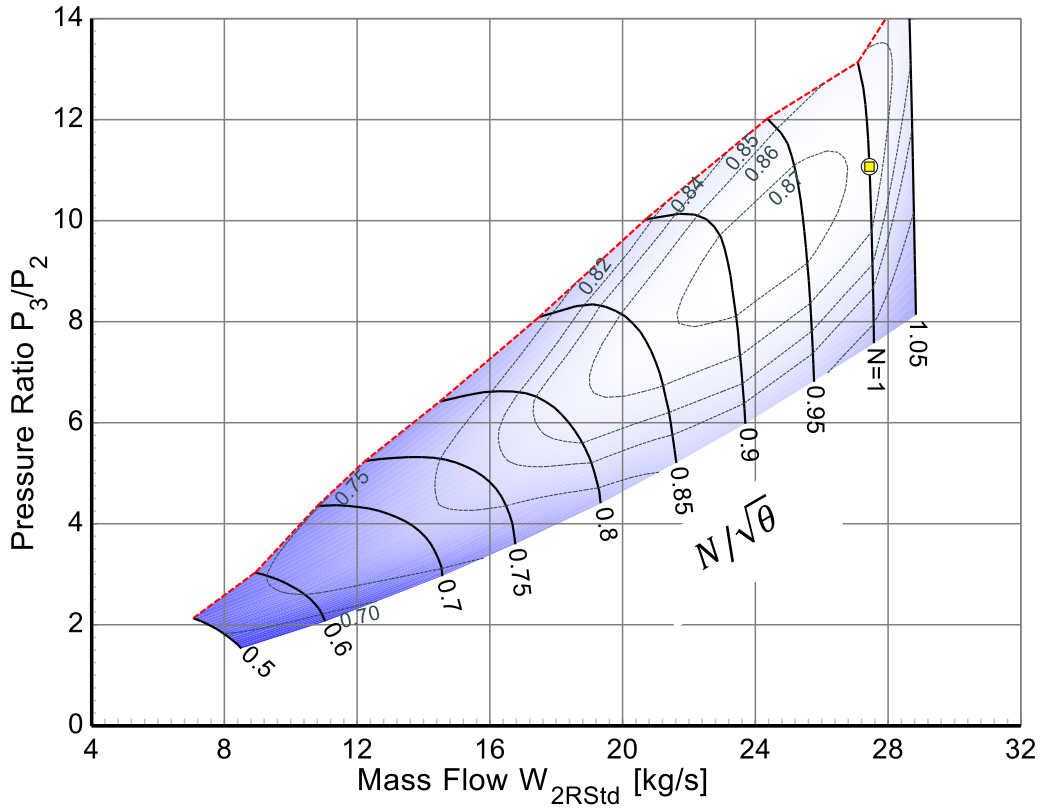
$$\Delta H_{is} = C_p \times T_2 \left( \frac{T_{3\,is}}{T_2} - 1 \right)$$

$$\frac{\Delta H_{3-2}}{T_2} = \frac{\gamma}{\gamma - 1} R \left[ \left( \frac{P_3}{P_2} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right] \Big/ \eta_{is}$$

$$\frac{P_3}{P_2} = \left( 1 + \eta_{is} \frac{\Delta H_{3-2}}{\frac{\gamma}{\gamma - 1} R \times T_2} \right)^{\frac{\gamma}{\gamma-1}}$$



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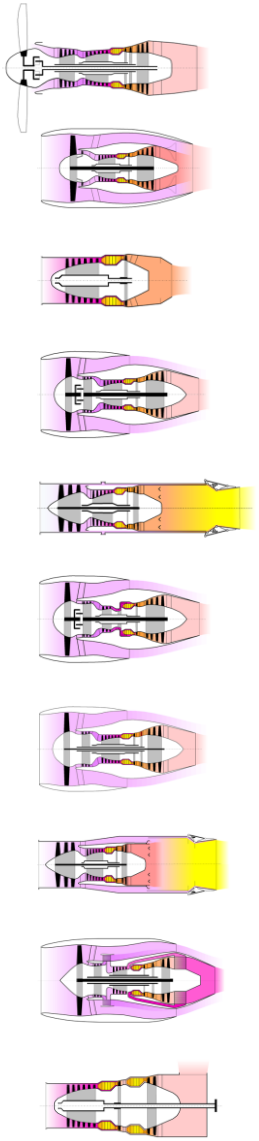
# Mach Number Similarity

## Corrected Mass Flow ↔ Mach Number



$$M = \frac{V}{a} = \frac{W}{A * \rho * \sqrt{\gamma * R * T_s}}$$

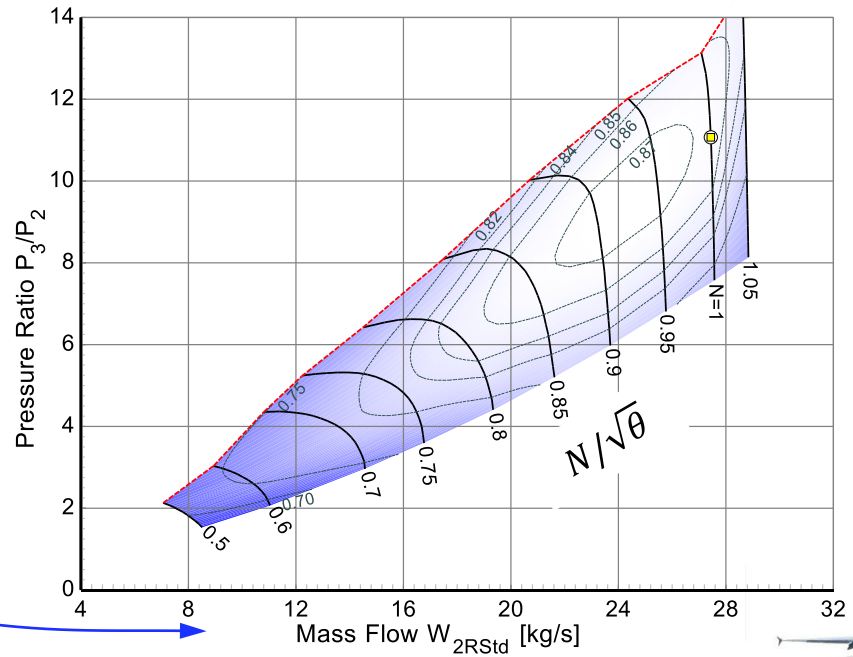
$$= \frac{W * R * T_s}{A * P_s * \sqrt{\gamma * R * T_s}}$$

$$= \frac{W * \sqrt{\frac{R}{\gamma} T} * \sqrt{\frac{T_s}{T}}}{A * P * \frac{P_s}{P}}$$

$$\frac{W*\sqrt{T}}{P} = A*M * \sqrt{\frac{\gamma}{R}} * \sqrt{1 + \frac{\gamma-1}{2} M^2} * \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}}$$

$$\frac{W*\sqrt{\frac{T_2}{288.15K}}}{\frac{P_2}{101.325kPa}} = \frac{W*\sqrt{\Theta}}{\delta} = W_{2Rstd}$$

| | | |
|---|---|---|
| a | velocity of sound | [m/s] |
| A | area | [m²] |
| M | Mach number | - |
| P | total pressure | [kPa] |
| $P_s$ | static pressure | [kPa] |
| R | gas constant | [J/(kg × K)] |
| T | total temperature | [K] |
| $T_s$ | static temperature | [K] |
| V | velocity | [m/s] |
| W | mass flow | [kg/s] |
| | | |
| δ | P/101.325 kPa | - |
| Θ | T/288.15 K | - |
| γ | Isentropic exponent | - |
| ρ | density | [kg/m³] |

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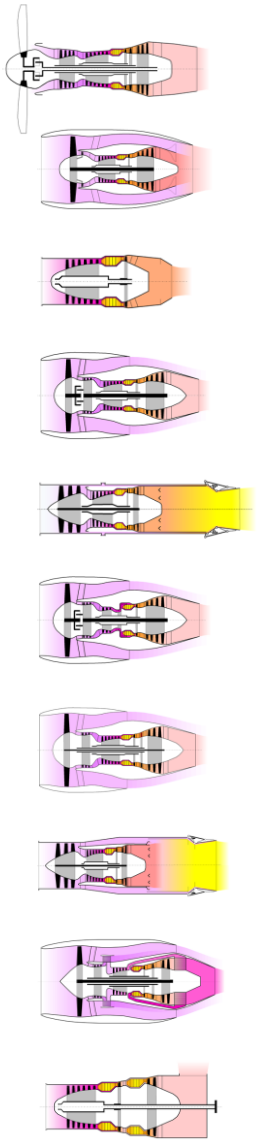
# Mach Number Similarity

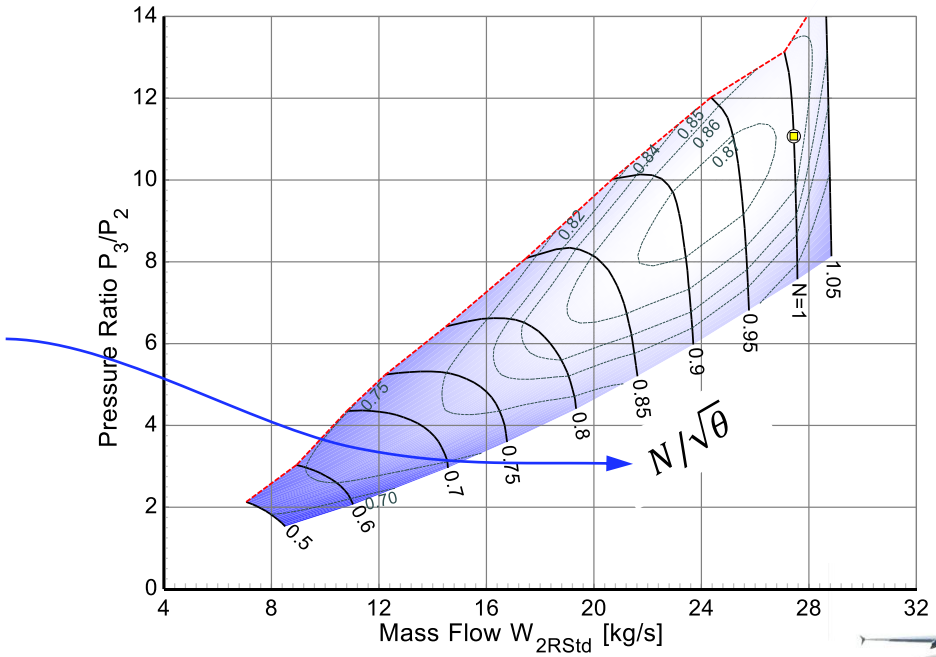
## Corrected Spool Speed ↔ Mach Number



$$M_U = \frac{U}{a} = \frac{const * N}{\sqrt{\gamma * R * T_s}} \cong \frac{N}{\sqrt{\gamma * R * T} * \sqrt{\frac{T_s}{T}}}$$

$$\frac{N}{\sqrt{T}} \cong \frac{\sqrt{\gamma * R}\, M_U}{\sqrt{1 + \frac{\gamma - 1}{2} M^2}}$$

$$\frac{N}{\sqrt{\frac{T}{288.15K}}} = \frac{N}{\sqrt{\Theta}}$$




| | | |
|---|---|---|
| a | velocity of sound | [m/s] |
| M | Mach number | - |
| N | circumferential speed | [rpm] |
| R | gas constant | [J/(kg × K)] |
| T | total temperature | [K] |
| $T_s$ | static temperature | [K] |
| U | circumferial velocity | [m/s] |
| Θ | T/288.15 K | - |
| γ | Isentropic exponent | - |

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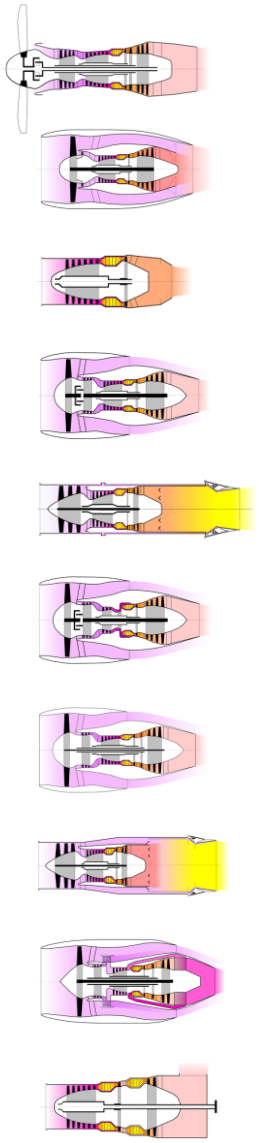

# Mach Number Similarity Parameters

## Corrected specific work

$$\frac{\Delta H}{T} = \gamma R \frac{M_U \left(M_{Vu2} - M_{Vu1}\right)}{1 + \frac{\gamma - 1}{2} M^2} \cong \frac{\Delta H}{\Theta}$$

## Corrected mass flow

$$\frac{W*\sqrt{T}}{P} = A*M * \sqrt{\frac{\gamma}{R}} * \sqrt{1 + \frac{\gamma-1}{2} M^2} * \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \cong \frac{W\sqrt{\theta}}{\delta}$$

## Corrected spool speed

$$\frac{N}{\sqrt{T}} \cong \frac{\sqrt{\gamma * R}\, M_U}{\sqrt{1 + \frac{\gamma-1}{2} M^2}} \cong \frac{N}{\sqrt{\theta}}$$

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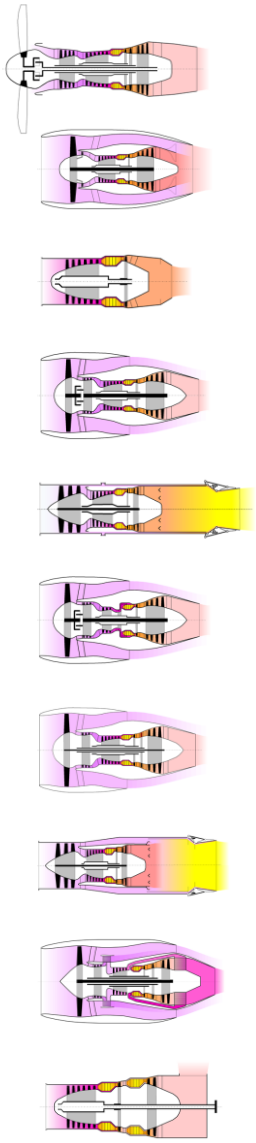
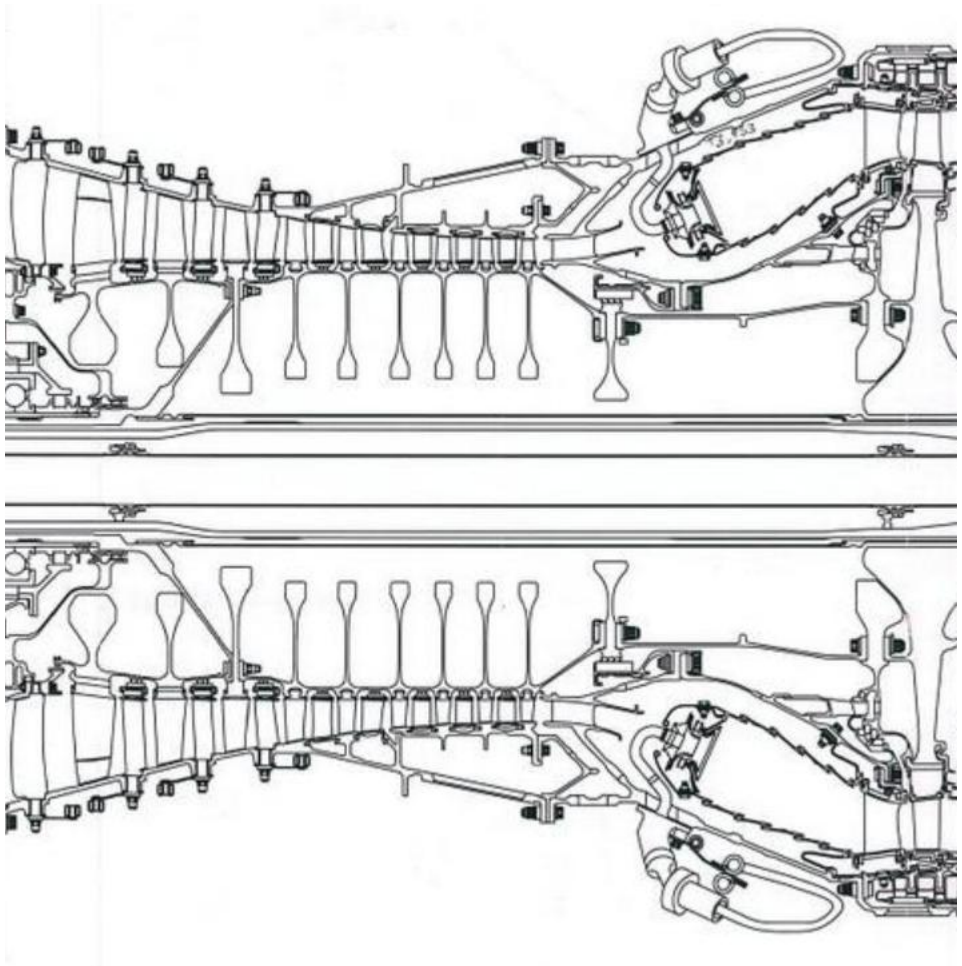
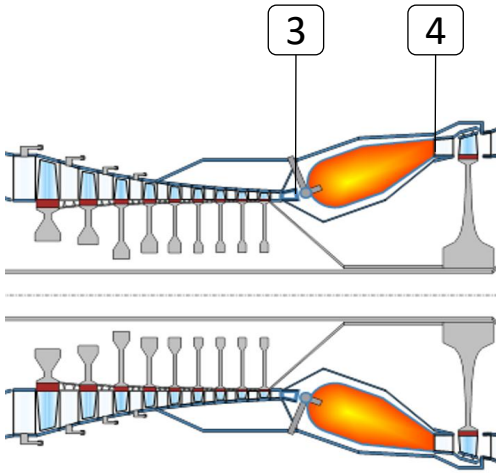
# Combustor








- Pressure Loss
- Temperature Increase
- Efficiency

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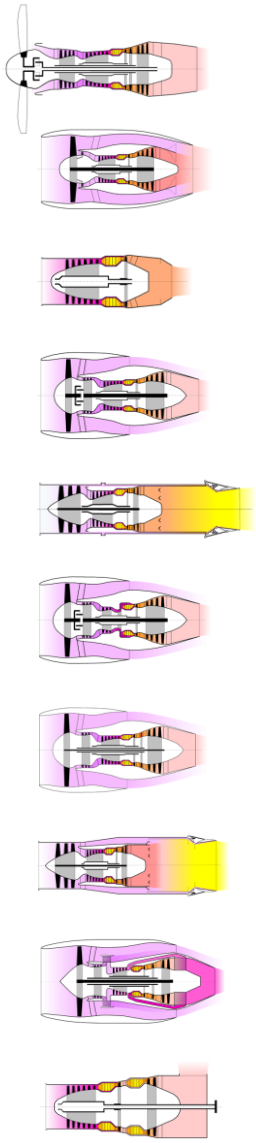


# Combustor Pressure Loss

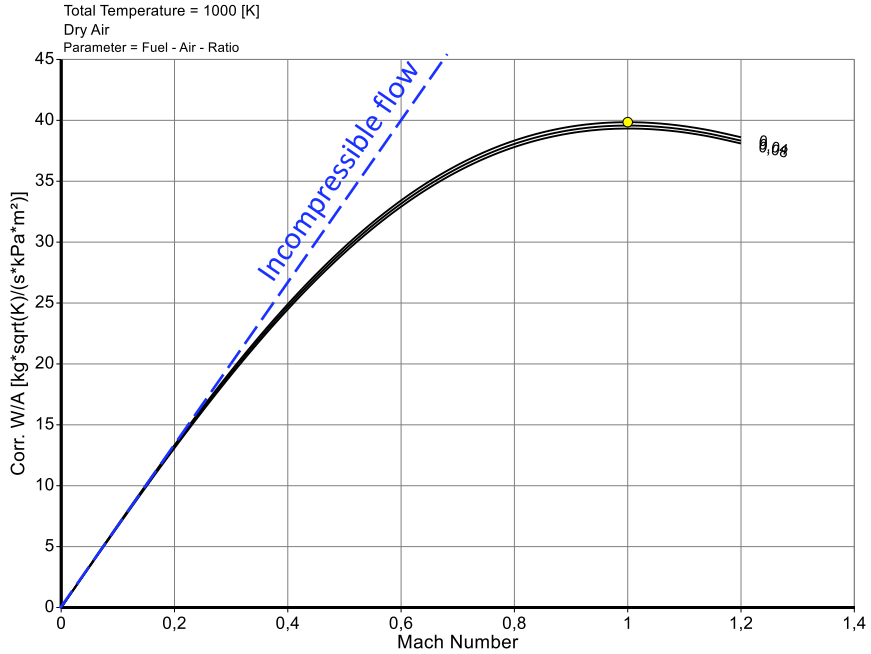
- In incompressible flow - if the Mach number is low – total pressure loss is proportional to dynamic head, i.e. velocity squared:

$$\Delta P \propto \frac{\varrho}{2} V^2$$

- Velocity V is directly proportional to corrected flow per area, therefore

$$\Delta P \propto \left( \frac{W\sqrt{T}}{\frac{P}{A}} \right)^2$$

- We'll see later that the combustor inlet corrected flow varies little.
- So, burner pressure loss stays pretty constant.



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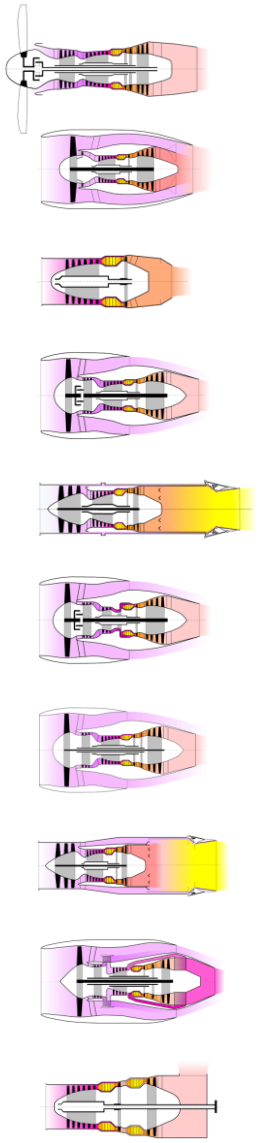
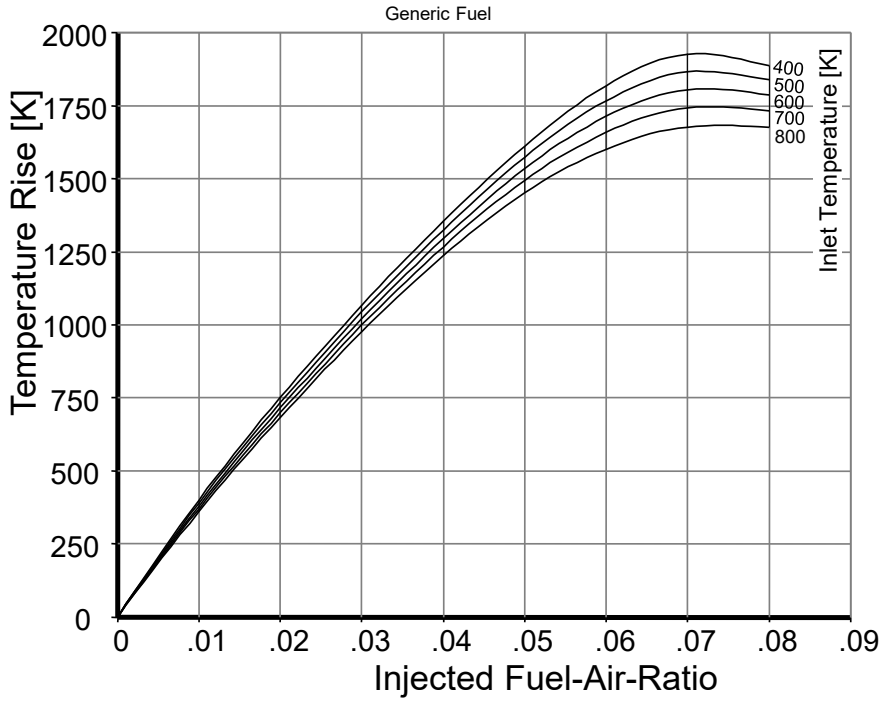
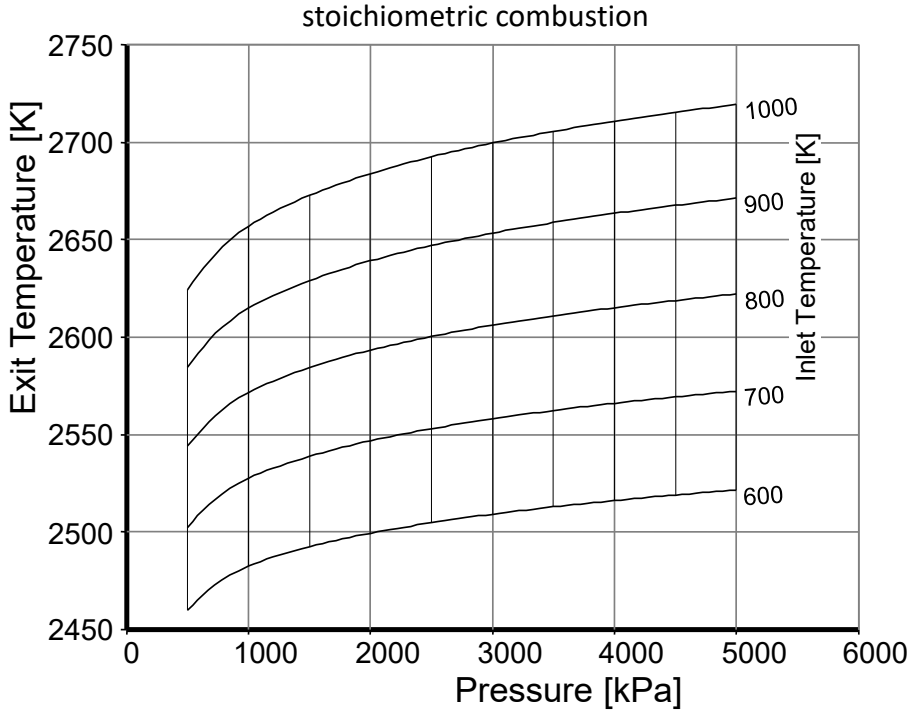
# Ideal Temperature Rise





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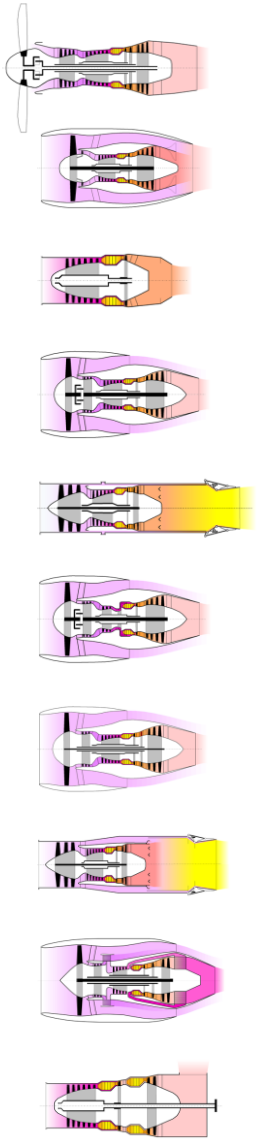
# Combustion Efficiency
## Correlation With Loading Parameter Θ



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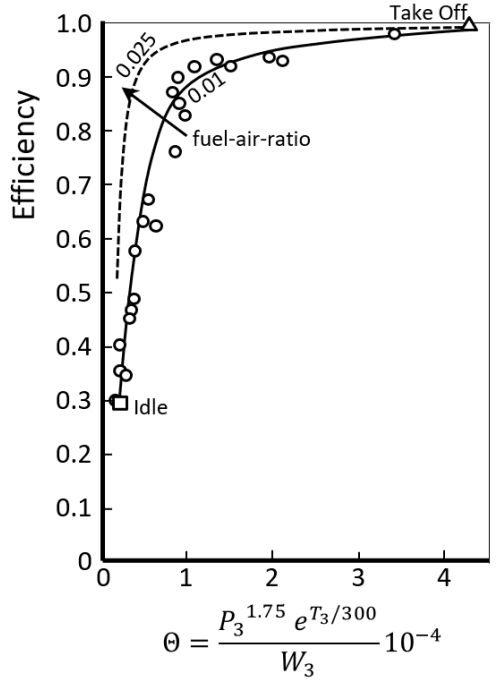


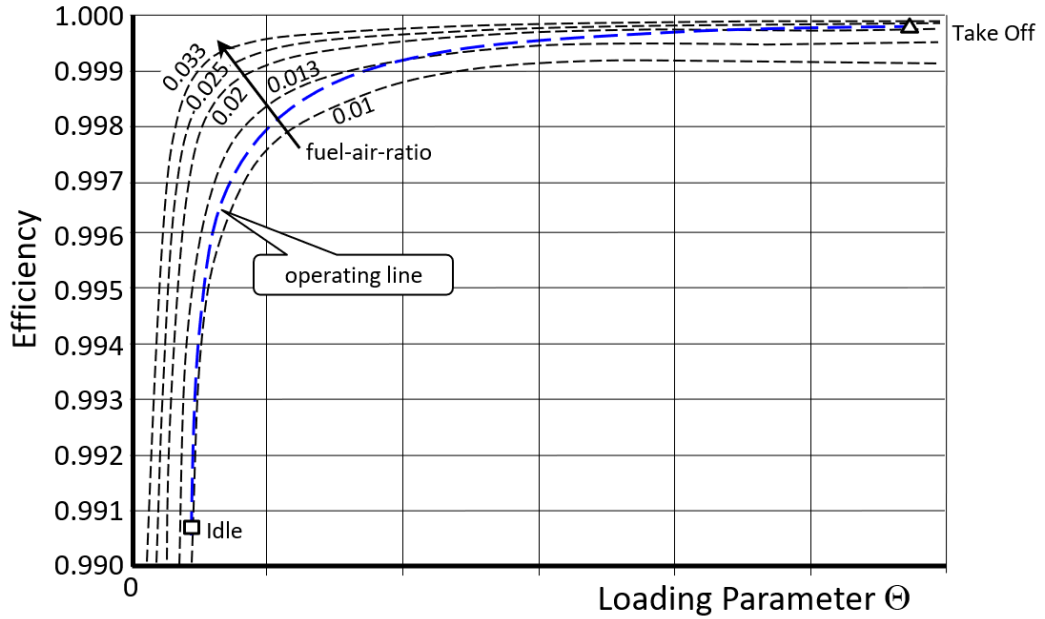


The Loading Parameter Θ represents the ratio between the residence time of the fuel/air mixture in the primary zone and the time required to burn the fuel.

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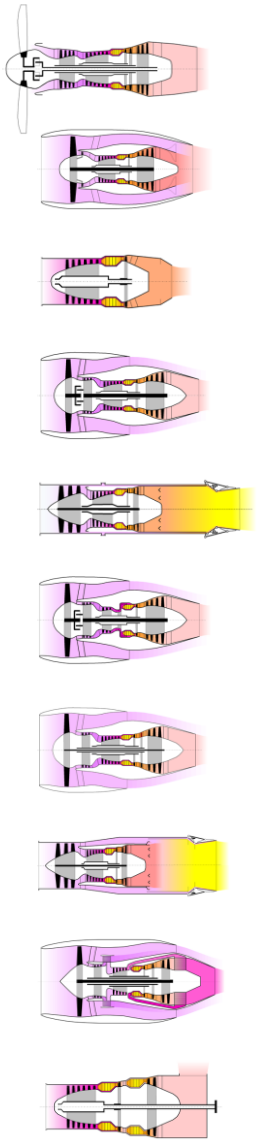
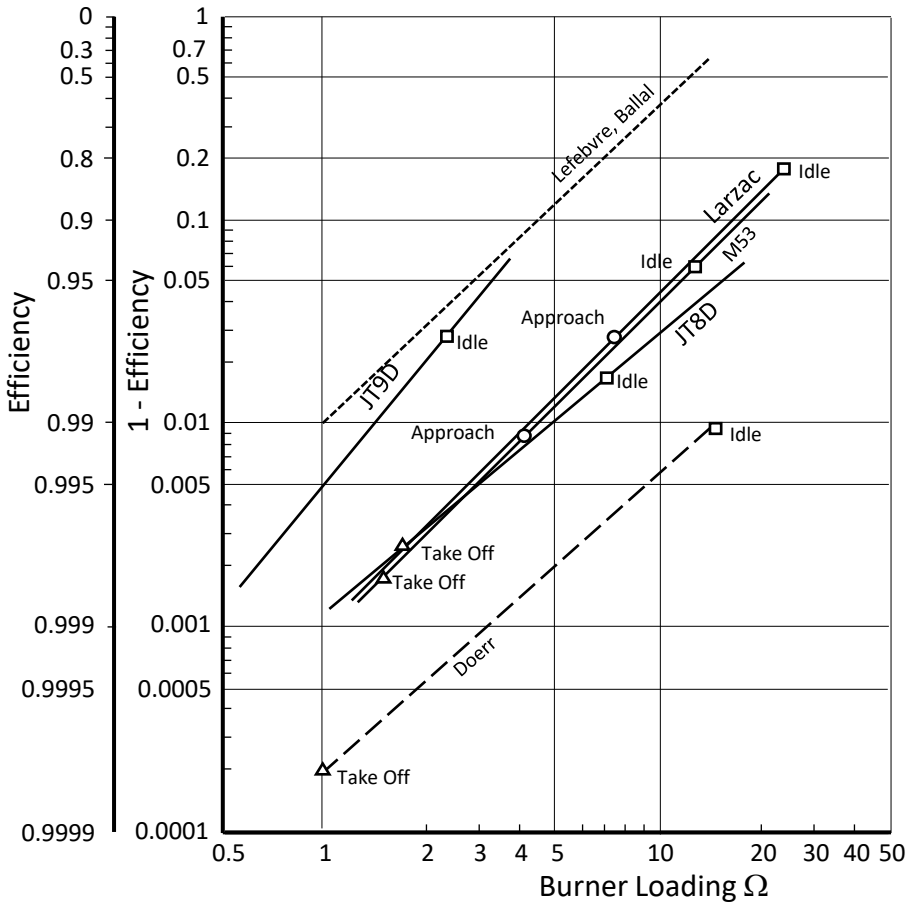
# Combustion Efficiency






Propulsion and Power:

$$\log(1-\eta) = A + B * \log(\Omega / \Omega_{des})$$

Partload Constant

Burner Loading $\Omega = \dfrac{W_{31}}{P_3^{1.8} * e^{T_3/300K} * Vol}$

Attention:
$P_3$ is measured in bar !

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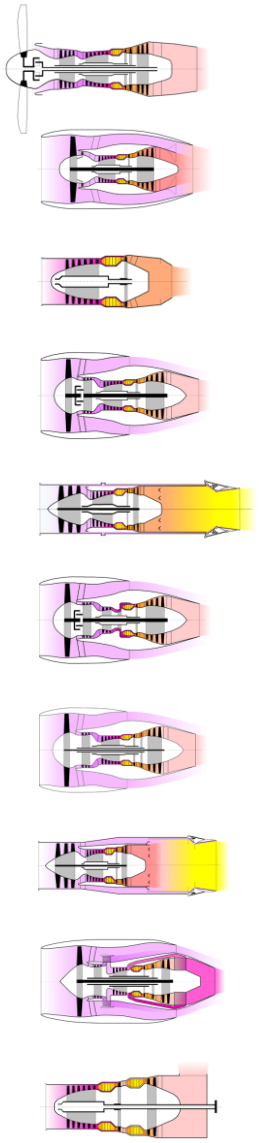
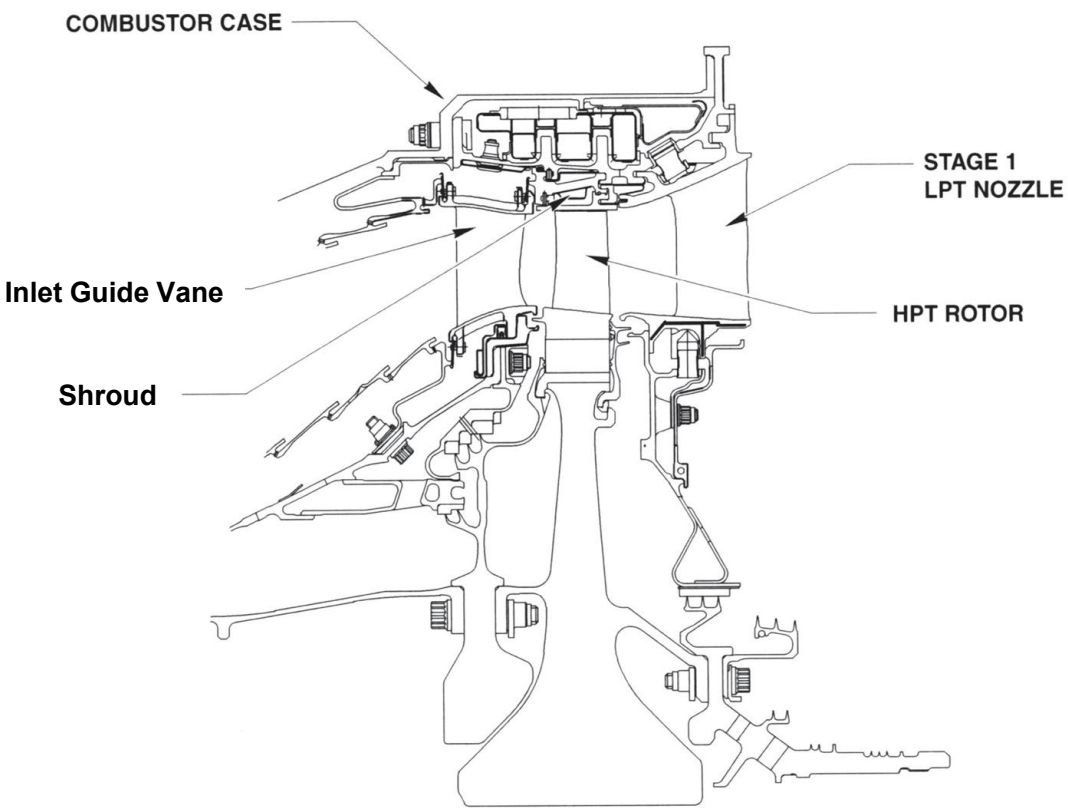
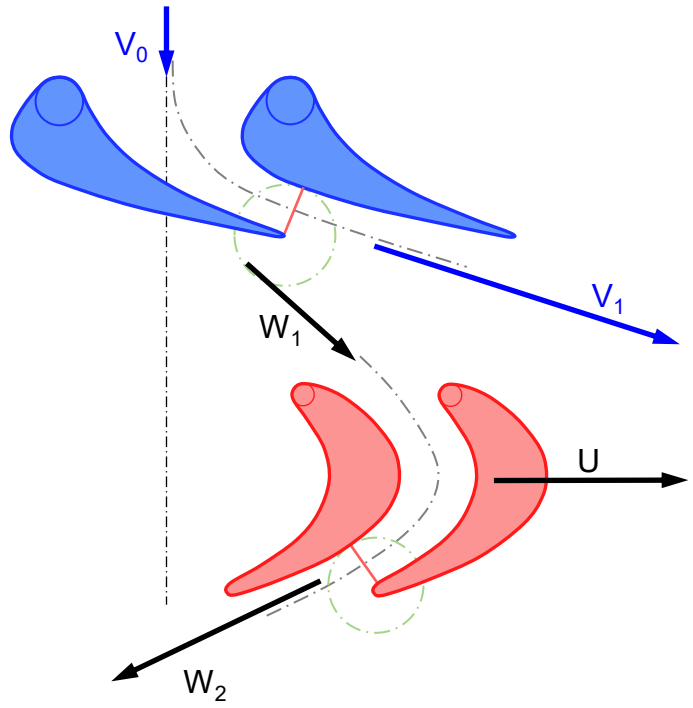
# Turbine
## The Inlet Guide Vane is a Nozzle !





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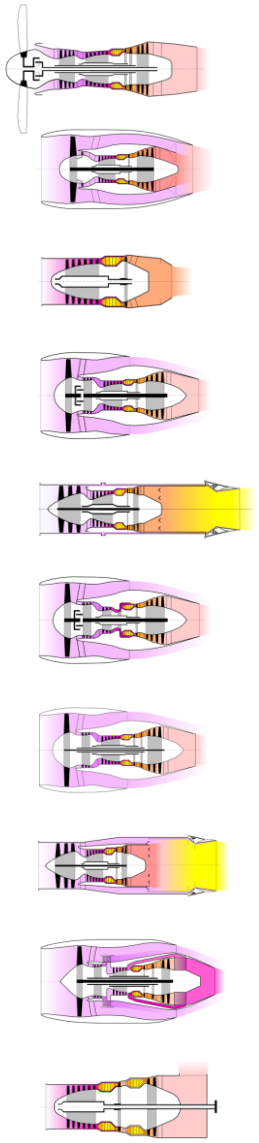
# Turbine Stage Performance



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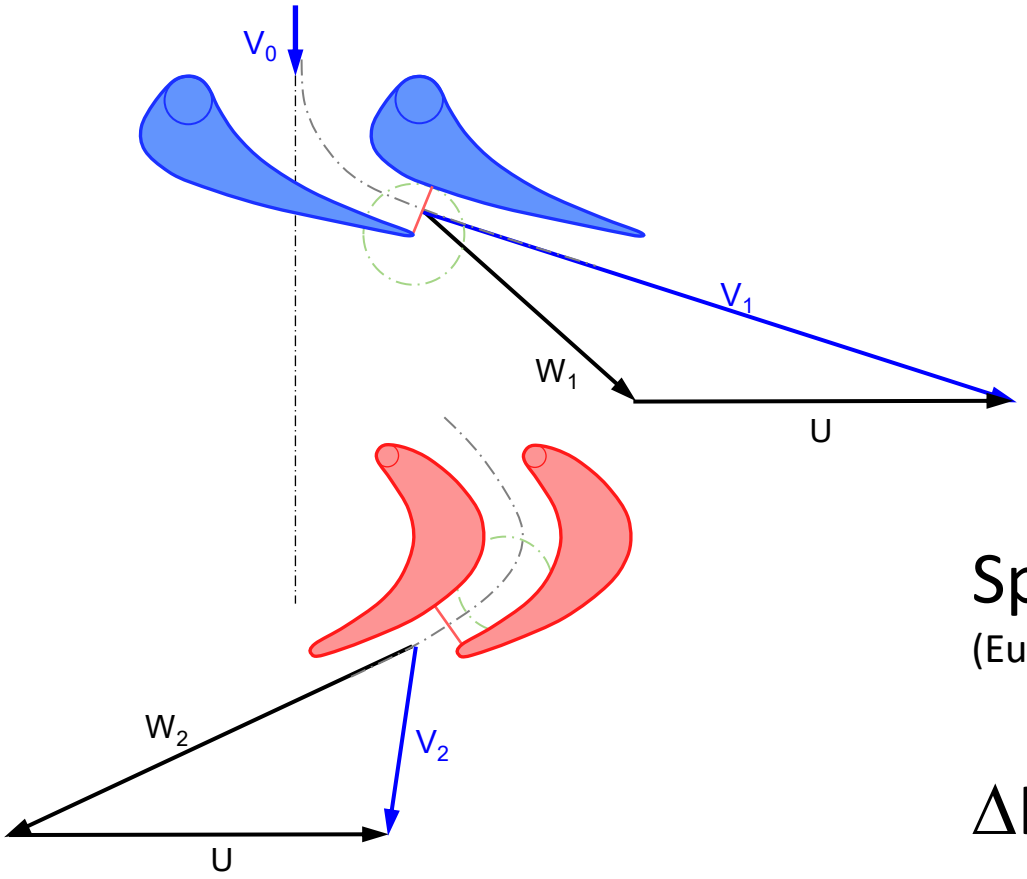


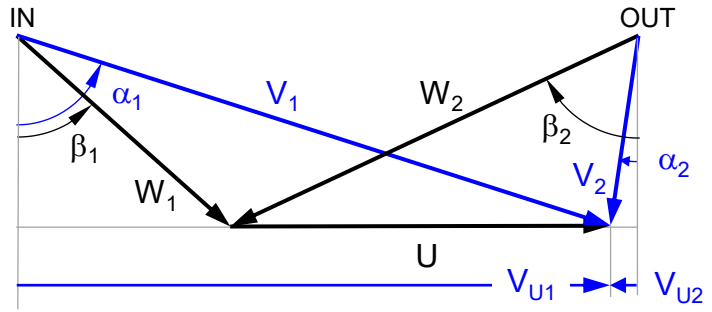


## Specific Work:

(Euler's Equation)

$$\Delta H = U*(V_{u2} - V_{u1})$$

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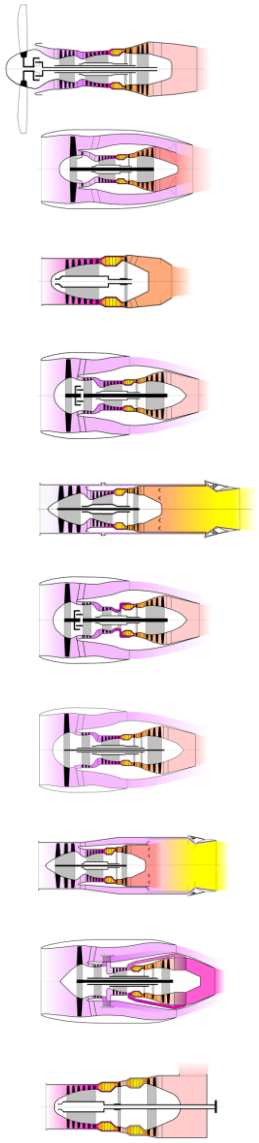
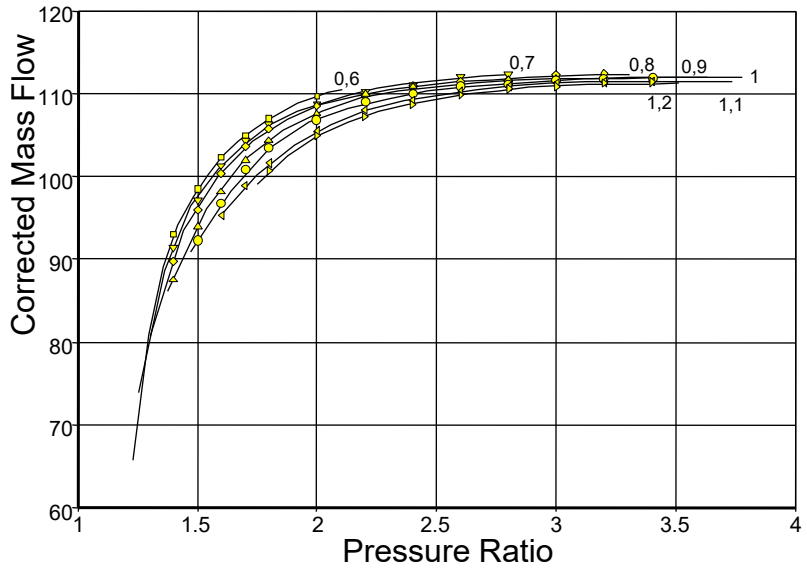
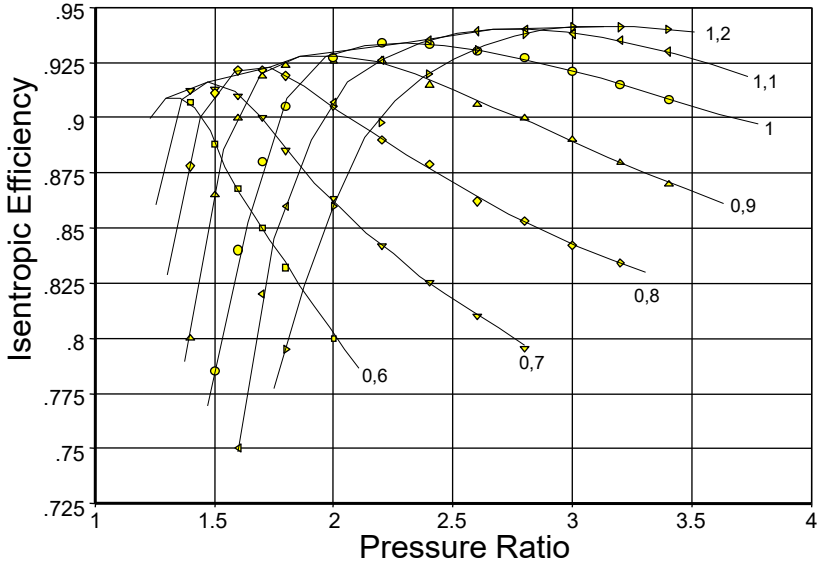
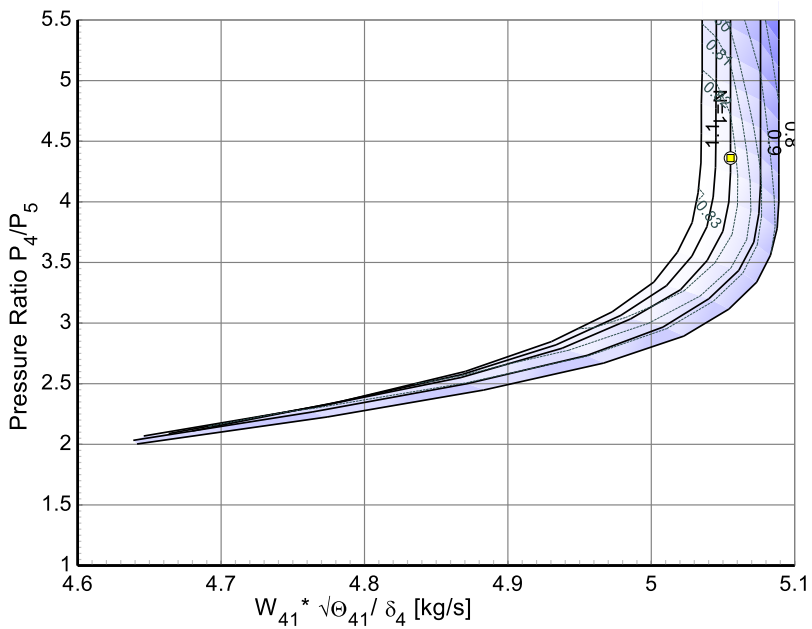
# Turbine Performance Map






Plotted like a compressor map:



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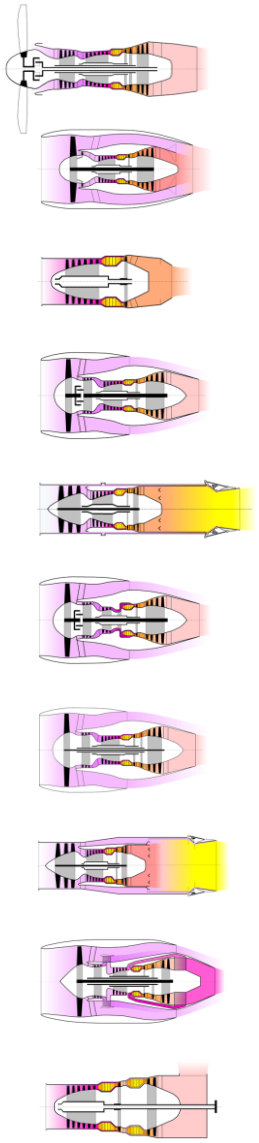

# Mach Number Similarity Parameters

## Corrected specific work

$$\frac{\Delta H}{T} = \gamma R \frac{M_U \left(M_{Vu2} - M_{Vu1}\right)}{1 + \frac{\gamma - 1}{2} M^2} \cong \frac{\Delta H}{\Theta}$$

## Corrected mass flow

$$\frac{W*\sqrt{T}}{P} = A*M * \sqrt{\frac{\gamma}{R}} * \sqrt{1 + \frac{\gamma-1}{2} M^2} * \left(1 + \frac{\gamma-1}{2} M^2\right)^{\frac{\gamma}{\gamma-1}} \cong \frac{W\sqrt{\theta}}{\delta}$$

## Corrected spool speed

$$\frac{N}{\sqrt{T}} \cong \frac{\sqrt{\gamma*R}\, M_U}{\sqrt{1+\frac{\gamma-1}{2}M^2}} \cong \frac{N}{\sqrt{\theta}}$$

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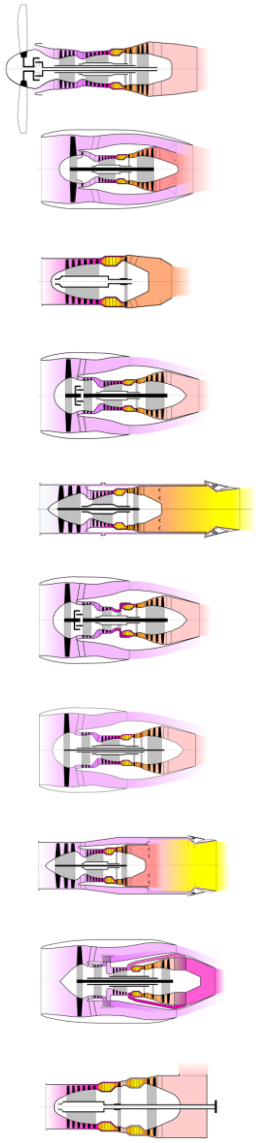
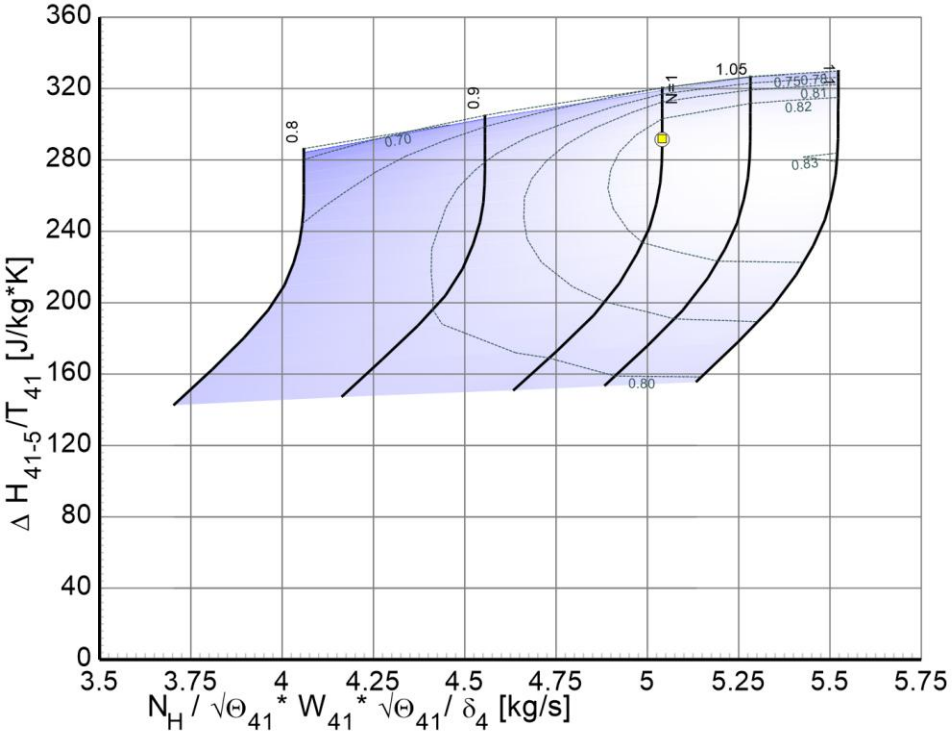
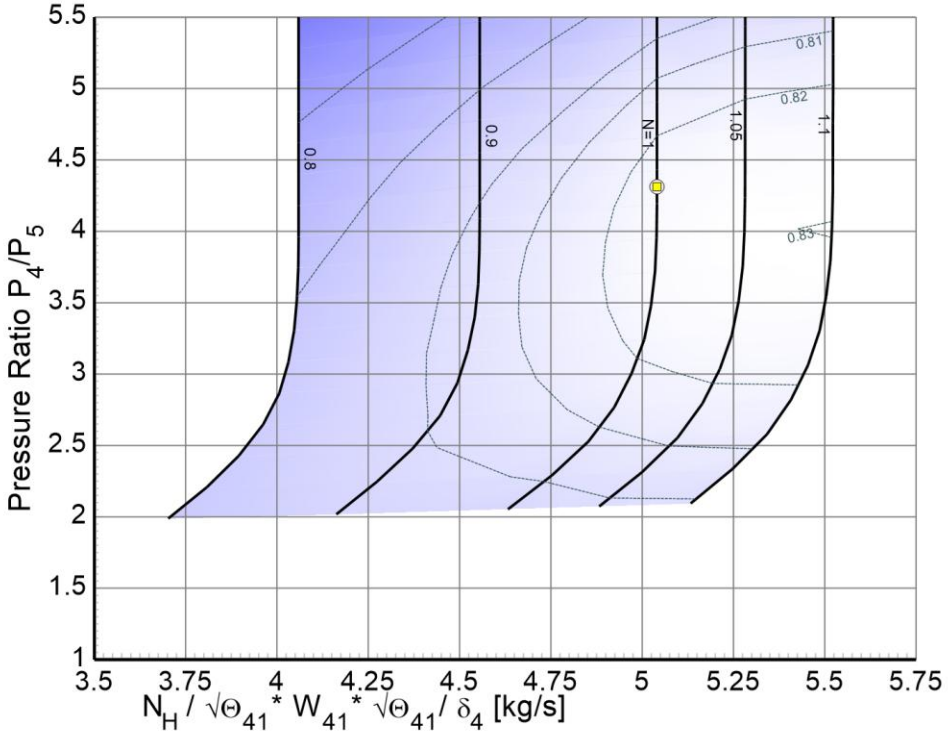
# Alternative Turbine Map Formats





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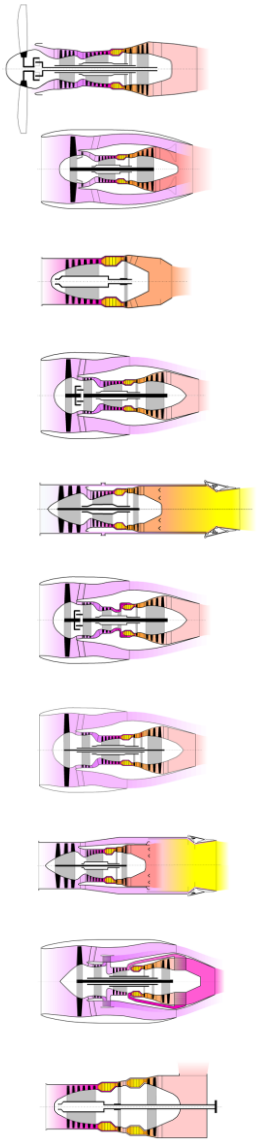
# Corrected Flow per Area Through a Nozzle

## Ideal Case – no Pressure Loss



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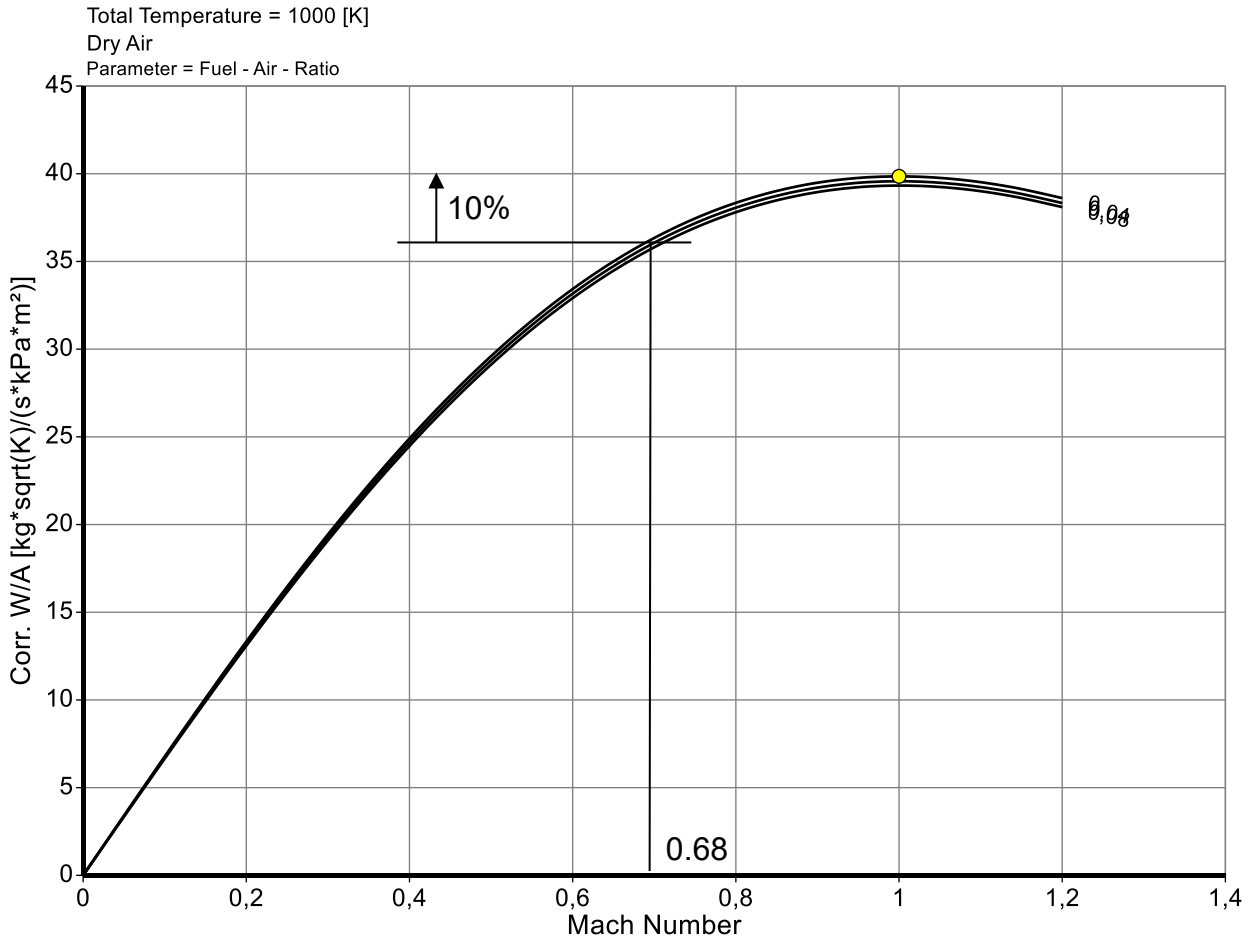
$$\frac{W\sqrt{T}}{P} = \frac{A * M\sqrt{\gamma/R}}{\left(1+\frac{\gamma-1}{2}M^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}$$



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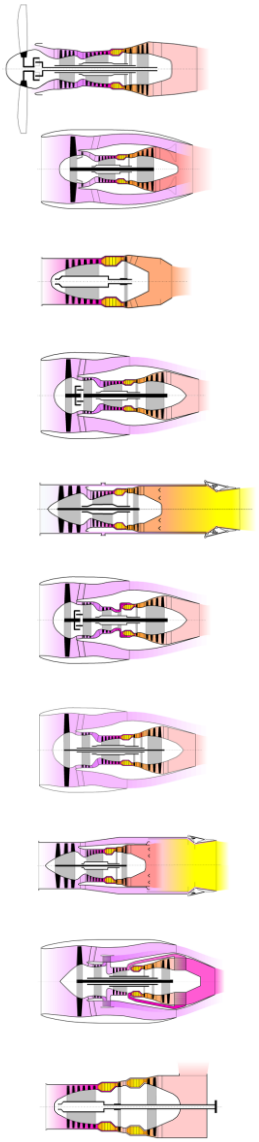

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# Outline

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components

Cooperation of the Components
- Nominal Performance
- Modifiers

Gas Generator +

Variable Geometry

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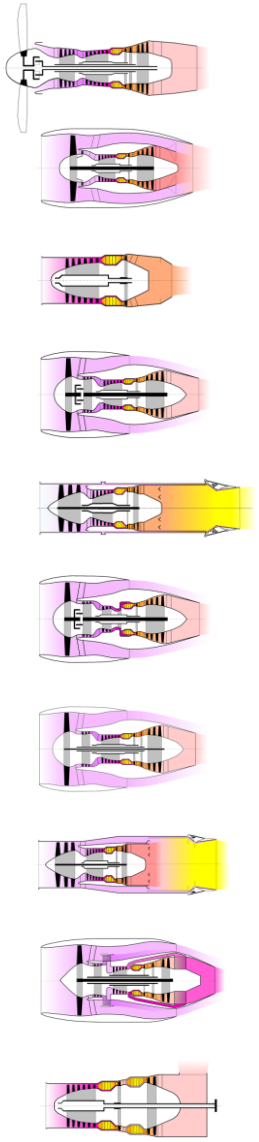
# The Engine Core
## Nomenclature



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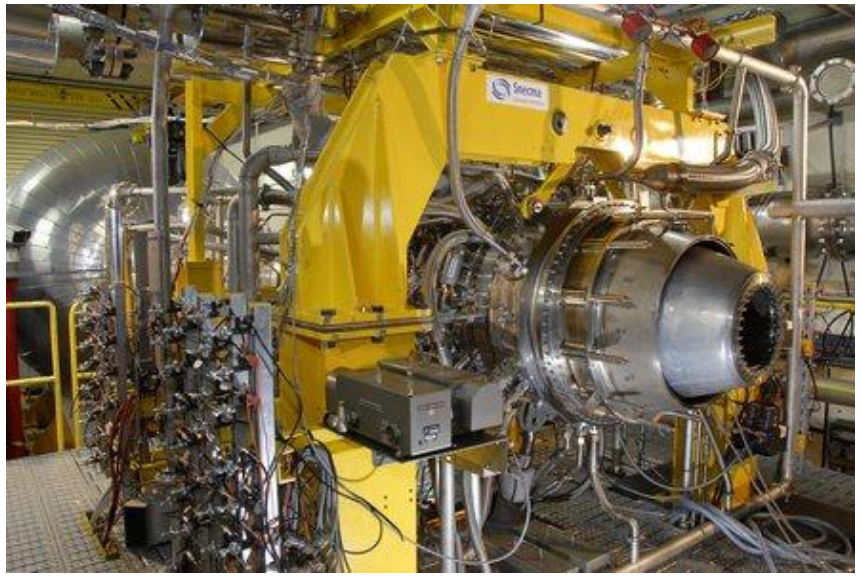
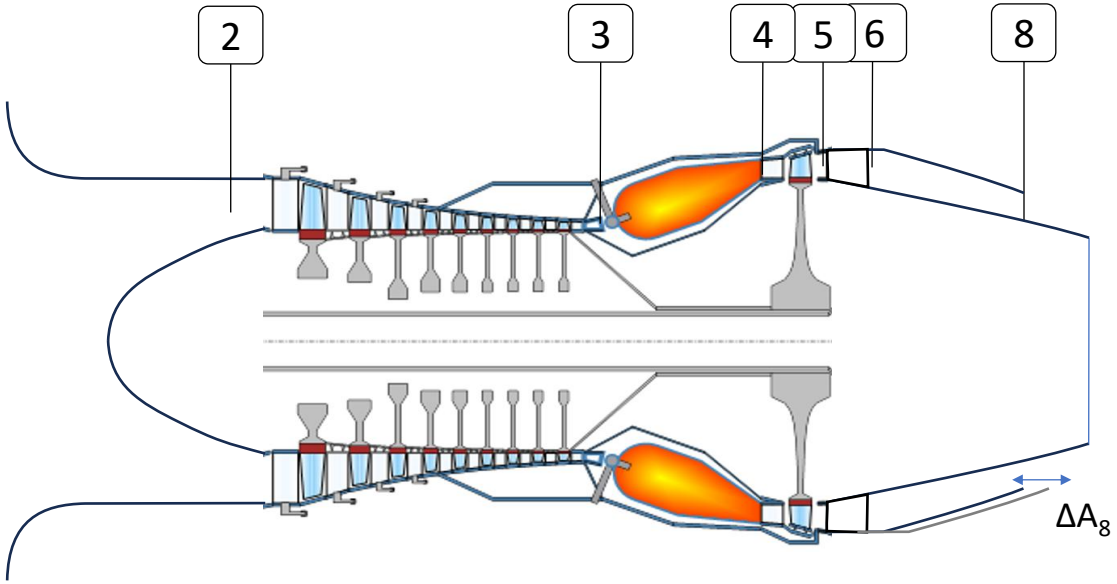


Core test of the SNECMA Silvercrest business jet engine




https://www.flightglobal.com/snecma-runs-core-of-silvercrest-business-jet-engine/77803.article

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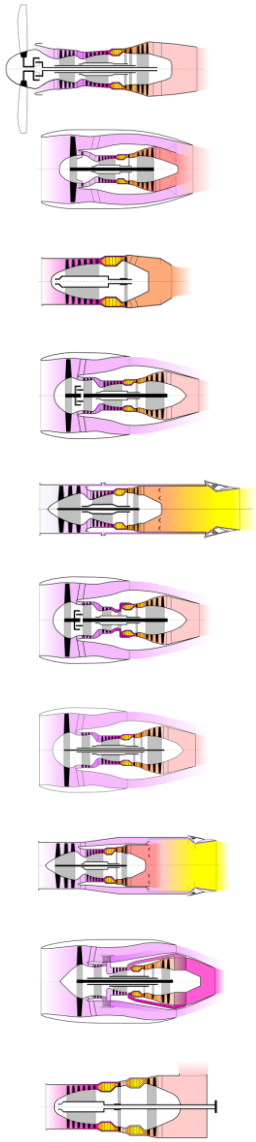
# Mass Flow Continuity
## Compressor and Turbine Inlet



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$$\frac{W_2 * \sqrt{T_2}}{P_2} = \frac{W_4 * \sqrt{T_4}}{A_4 * P_4} * A_4 * \frac{P_4}{P_3} * \frac{W_2}{W_4} * \frac{P_3}{P_2} * \sqrt{\frac{T_2}{T_4}}$$

This is the equation for a linear array in the compressor map.

- The array consists of $T_4/T_2$ lines.
- The array passes through the origin.

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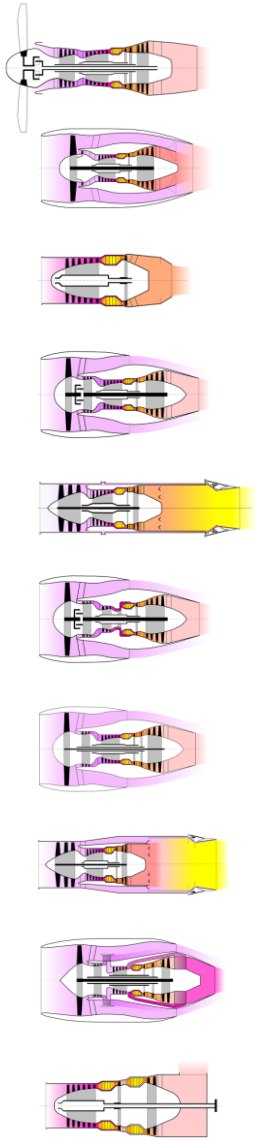
# What factors influence the position of the $T_4/T_2$ lines in the gas generator compressor map?



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$$\text{const}_A$$

$$\frac{W_2 * \sqrt{T_2}}{P_2} = \frac{W_4 * \sqrt{T_4}}{A_4 * P_4} * A_4 * \frac{P_4}{P_3} * \frac{W_2}{W_4} * \frac{P_3}{P_2} * \sqrt{\frac{T_2}{T_4}}$$

The Corrected Flow per Area is always the same because the Mach number is (almost) 1

The turbine throat area $A_4$ does not change

The burner pressure loss is in the order of 5% and does change only little

The mass flow ratio is affected by

- the fuel-air-ratio which varies little
- the turbine cooling air is a constant fraction of $W_2$
- **the amount of bleed air** which may be used
  - for controlling the surge margin
  - for customer purposes

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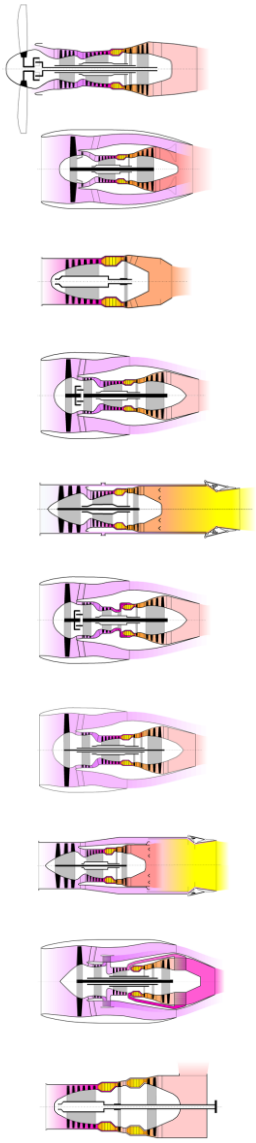
# $T_4/T_2$ Lines
## Full Cycle Calculation



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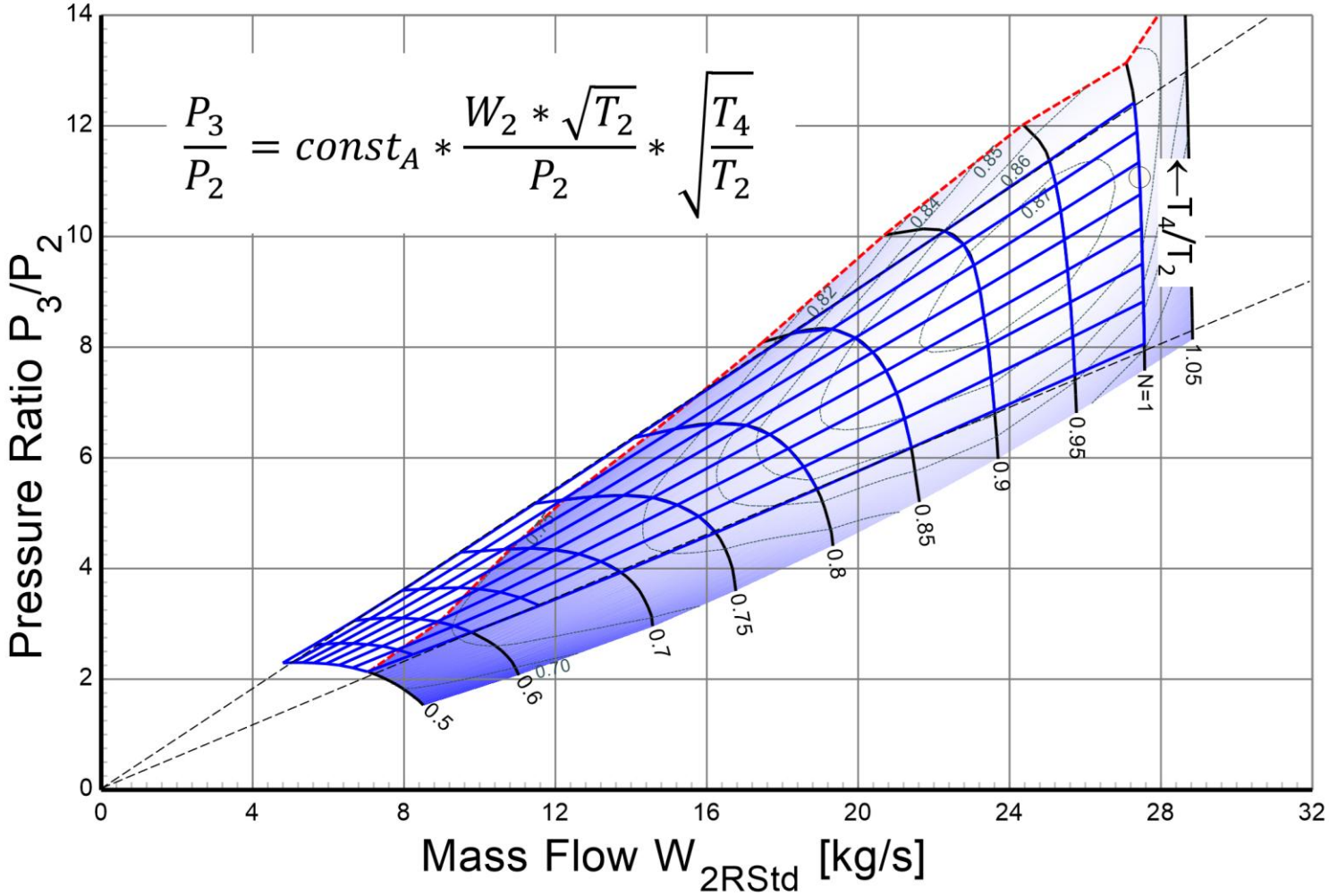


Calculation mode:
PWx iterated so that $T_4/T_2$=const

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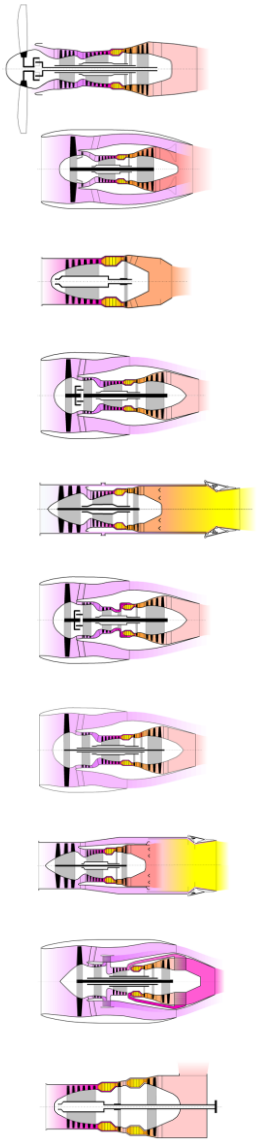
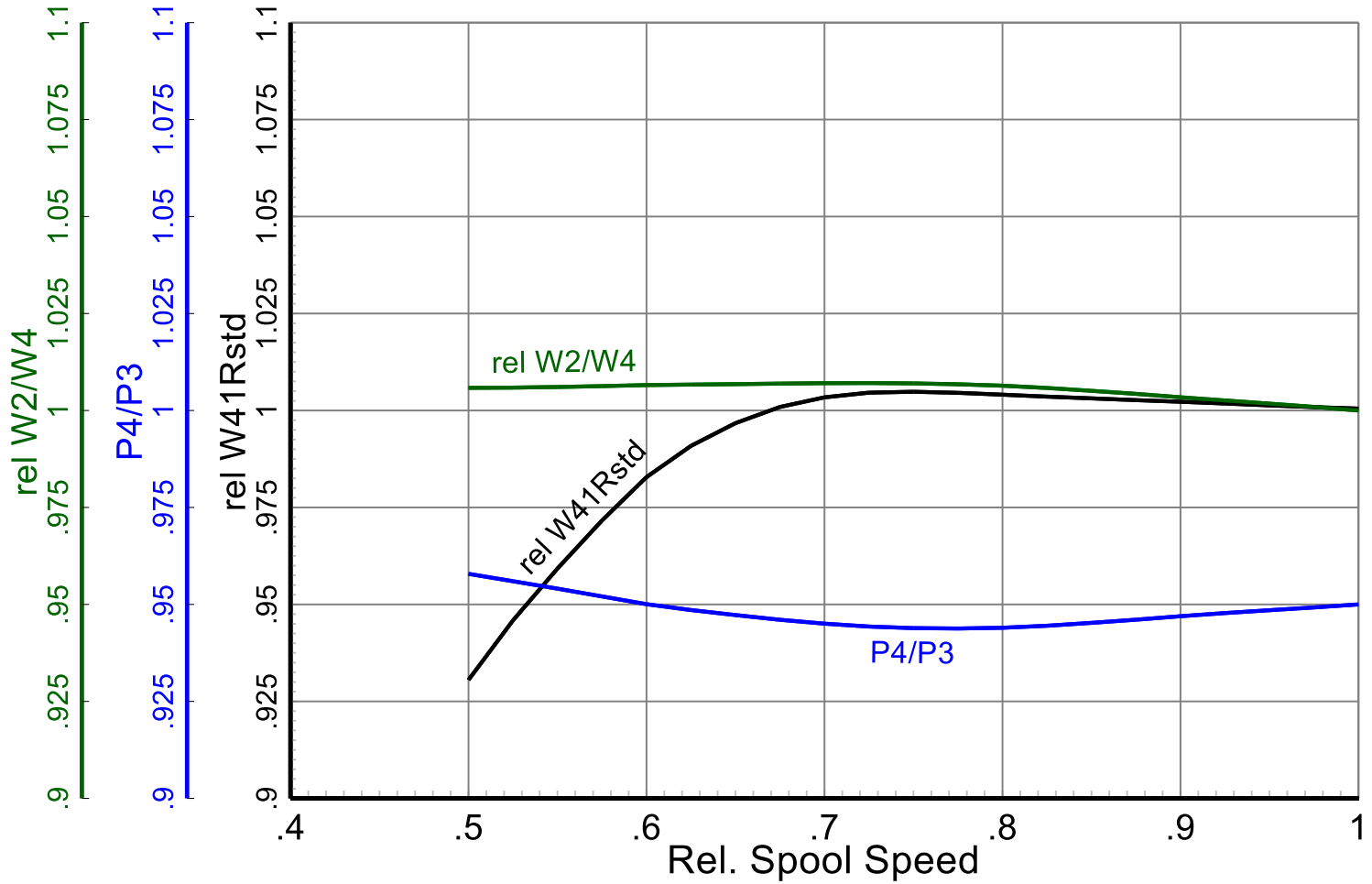
# Is const$_A$ Really Constant?
## Check With a Full Cycle Calculation





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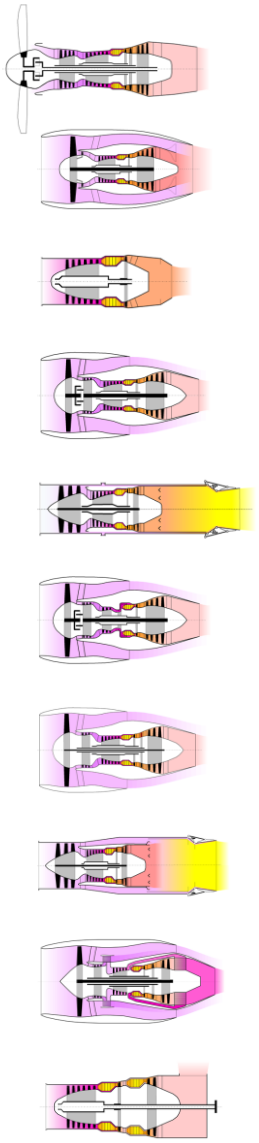
# Mass Flow Continuity 2
## Compressor Exit and Turbine Inlet



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$$\frac{W_3\sqrt{T_3}}{P_3} = \overbrace{\boxed{\frac{W_4\sqrt{T_4}}{P_4 * A_4} * A_4 * \frac{P_4}{P_3} * \frac{W_3}{W_3 + W_f}}}^{\text{const}_B} * \sqrt{\frac{T_3}{T_4}}$$

$$W_4 = W_3 + W_f$$

$$\frac{W_3\sqrt{T_3}}{P_3}\sqrt{\frac{T_4}{T_3}} = const_B$$

Lines of constant compressor exit flow $W_3\sqrt{T_3}/P_3$ are lines of constant $T_4/T_3$

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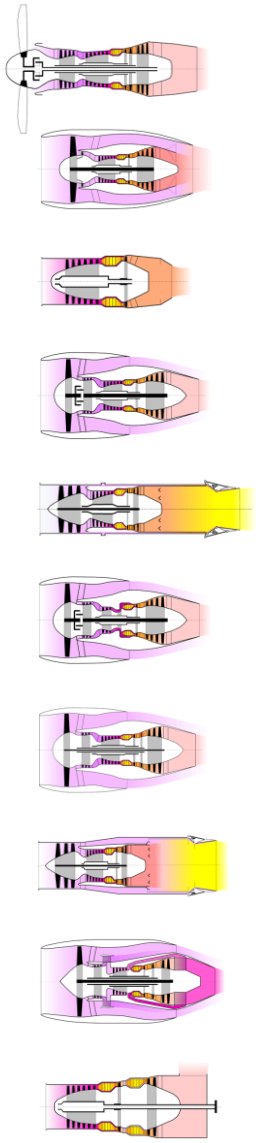
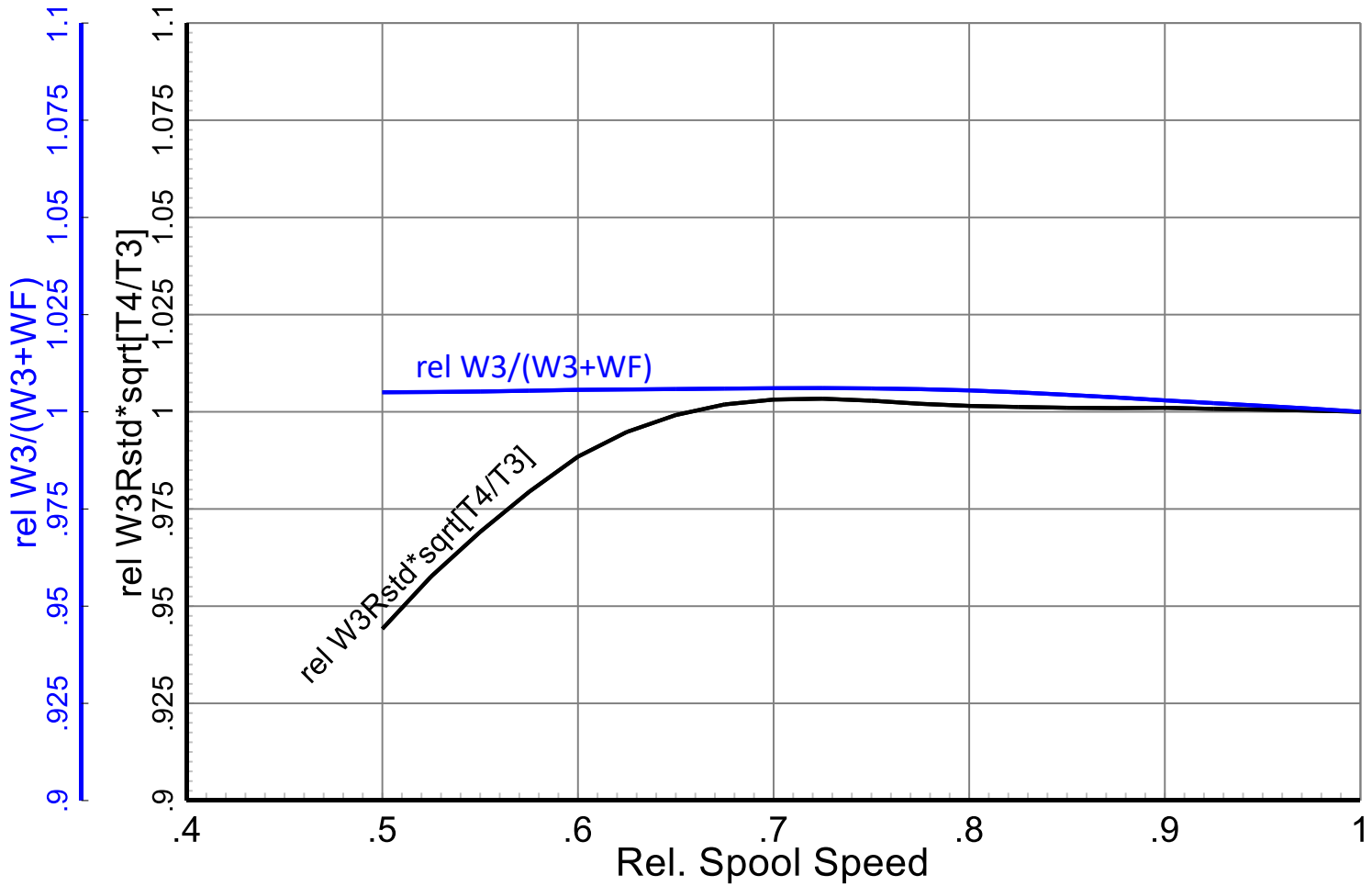
# Is $const_B$ Really Constant?
## Check With a Full Cycle Calculation





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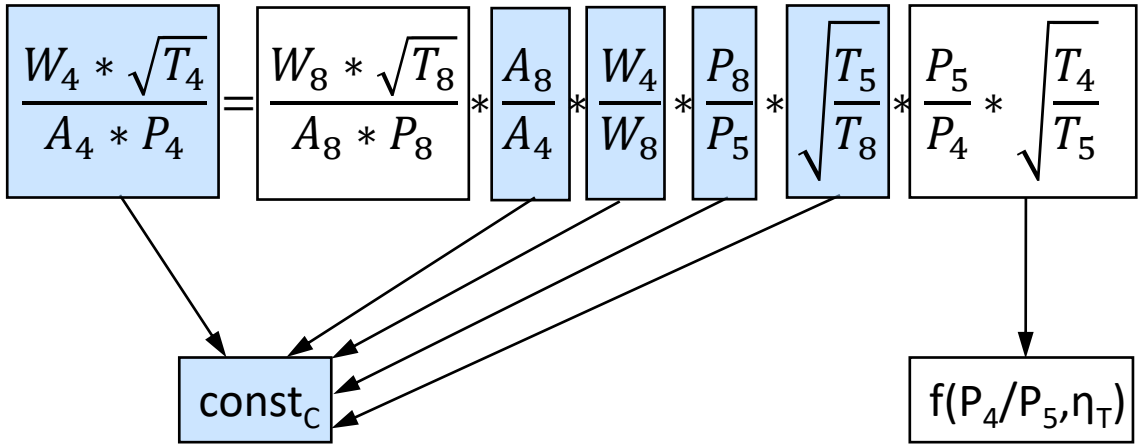
# Mass flow Continuity 3
## Turbine and Nozzle




$$\frac{P_4}{P_5} = const_c \frac{W_8 * \sqrt{T_8}}{A_8 * P_8}$$

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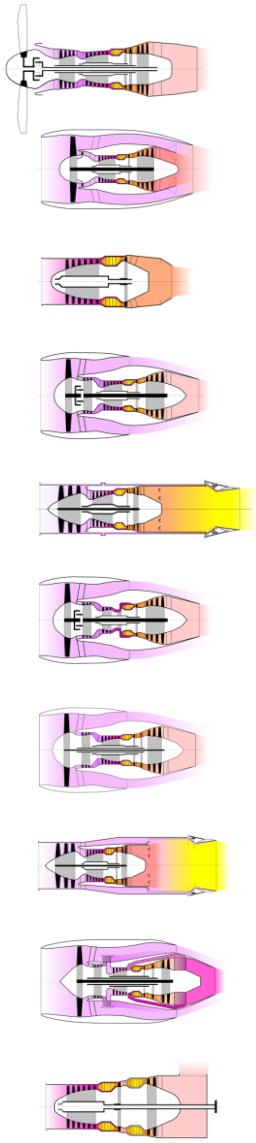
# Is $const_c$ Really Constant?
## Check With a Full Cycle Calculation



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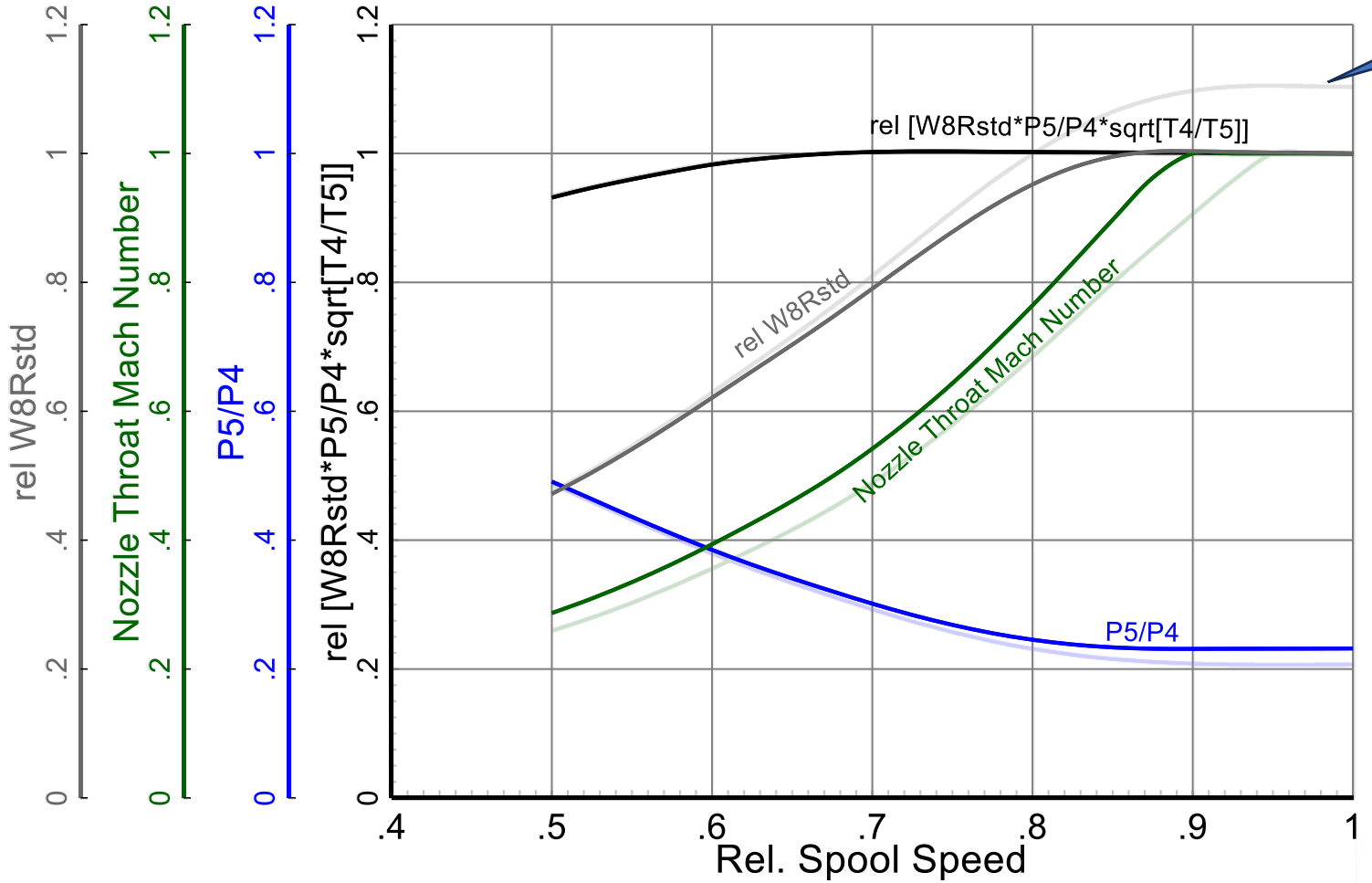


ΔA8=10%

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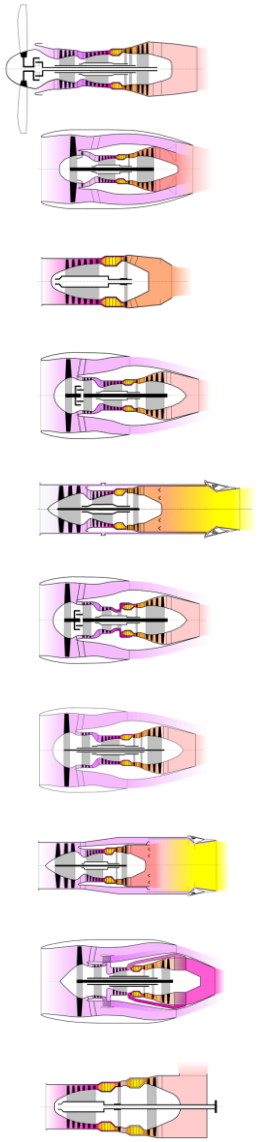
# Take Away
## From Mass Flow Continuity Considerations



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Compressor

$$\frac{P_3}{P_2} = const_A * \frac{W_2 * \sqrt{T_2}}{P_2} * \sqrt{\frac{T_2}{T_4}}$$

Lines of constant $T_4/T_2$ in the compressor map are linear lines that pass through the origin

Burner

$$\frac{W_3\sqrt{T_3}}{P_3}\sqrt{\frac{T_4}{T_3}} = const_B$$

Lines of constant corrected compressor exit flow $W_3\sqrt{T_3}/P_3$ in the compressor map are lines of constant $T_4/T_3$

Turbine

$$\frac{W_4\sqrt{T_4}}{P_4} = constant$$

Corrected turbine inlet flow $W_4\sqrt{T_4}/P_4$ is constant above idle

$$\frac{P_4}{P_5} = const_C \frac{W_8 * \sqrt{T_8}}{A_8 * P_8}$$

Turbine pressure ratio $P_4/P_5$ remains constant as long as the nozzle flow remains sonic.

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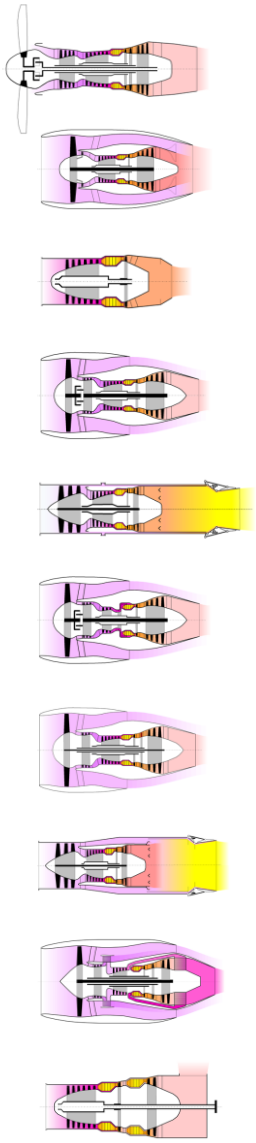

# Power Balance Compressor – Turbine

Turbine power equals compressor power plus power offtake:

$$PW_T = PW_C + PW_x$$

$$W_2 * H_C = W_4 * H_T - PW_x$$

$$\frac{H_{is,C}}{\eta_C} = \frac{W_4}{W_2} H_{is,T} * \eta_T - \frac{PW_x}{W_2}$$

$$\frac{H_{is,C}}{T_2 * \eta_C} = \frac{W_4}{W_2} * \frac{H_{is,T}}{T_4} * \frac{T_4}{T_2} * \eta_T - \frac{PW_x}{W_2 * T_2}$$

| | | |
|---|---|---|
| $C_P$ | specific heat | [J/(kg×K)] |
| H | specific work | [J/kg] |
| P | total pressure | [kPa] |
| $PW_x$ | shaft power offtake | [kW] |
| R | gas constant | [J/(kg×K)] |
| T | total temperature | [K] |
| W | mass flow | [kg/s] |

Indices

| | |
|---|---|
| C | compressor |
| T | turbine |
| is | isentropic |

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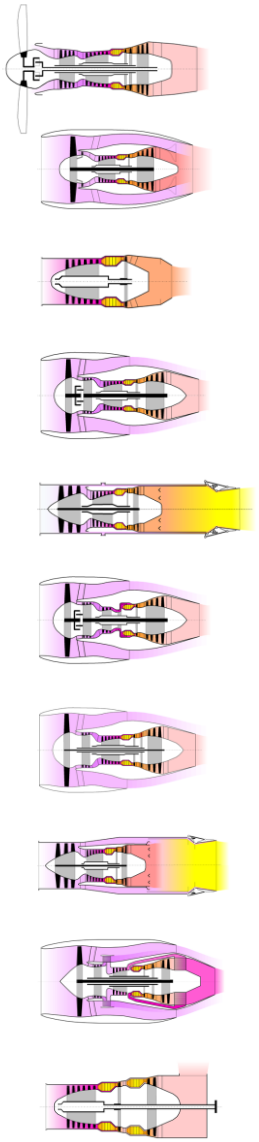
# Power Balance Compressor – Turbine



$$\frac{H_{is,C}}{T_2 * \eta_C} = \overbrace{\boxed{\frac{W_4}{W_2} * \frac{H_{is,T}}{T_4}}}^{const_D} * \eta_T * \frac{T_4}{T_2} - \frac{PW_x}{W_2 * T_2}$$

| | | |
|---|---|---|
| $C_P$ | specific heat | [J/(kg×K)] |
| H | specific work | [J/kg] |
| $H_{is}$ | isentropic specific work | [J/kg] |
| P | total pressure | [kPa] |
| $PW_x$ | shaft power offtake | [kW] |
| R | gas constant | [J/(kg×K)] |
| T | total temperature | [K] |
| W | mass flow | [kg/s] |

$$\frac{C_{p,C} * \left[\left(\frac{P_3}{P_2}\right)^{R/c_{p,C}} - 1\right]}{T_2 * \eta_C} = const_D * \frac{T_4}{T_2} * \eta_T - \frac{\frac{PW_x}{P_2\sqrt{T_2}}}{\frac{W_2\sqrt{T_2}}{P_2}}$$

$$\frac{PW_x}{W_2 * T_2} = \frac{\frac{PW_x}{P_2}}{\frac{W_2\sqrt{T_2}\sqrt{T_2}}{P_2}} = \frac{\frac{PW_x}{P_2\sqrt{T_2}}}{\frac{W_2\sqrt{T_2}}{P_2}}$$

$$\frac{C_{p,C} * \left[\left(\frac{P_3}{P_2}\right)^{R/c_{p,C}} - 1\right]}{T_2} = const_D * \frac{T_4}{T_2} * \eta_T * \eta_C$$

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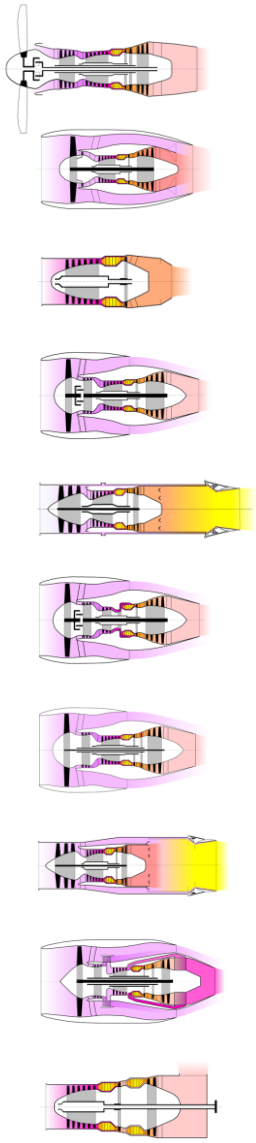
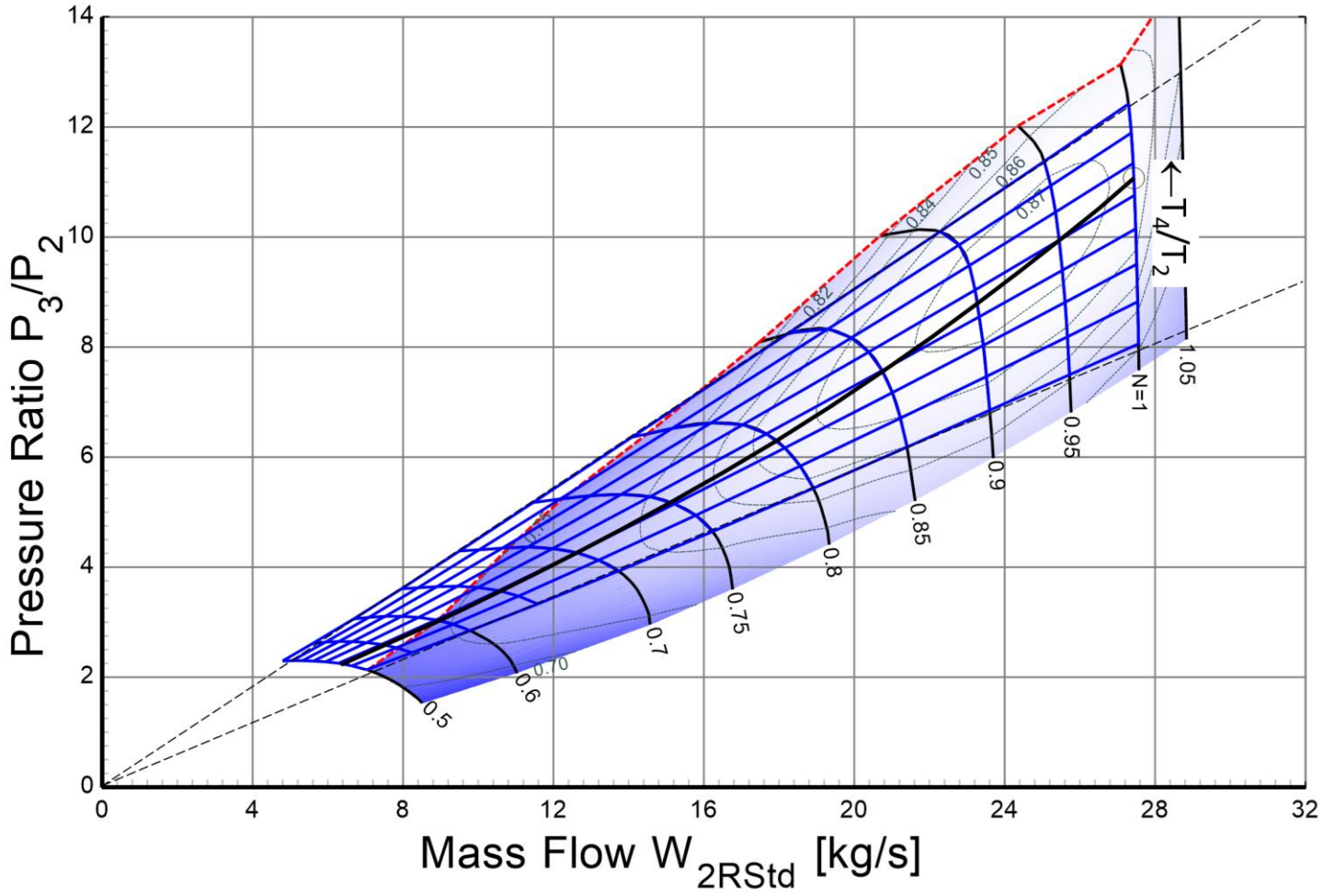
# Compressor Operating Line

## Steeper Than the $T_4/T_2$ Lines While $M_8$=1





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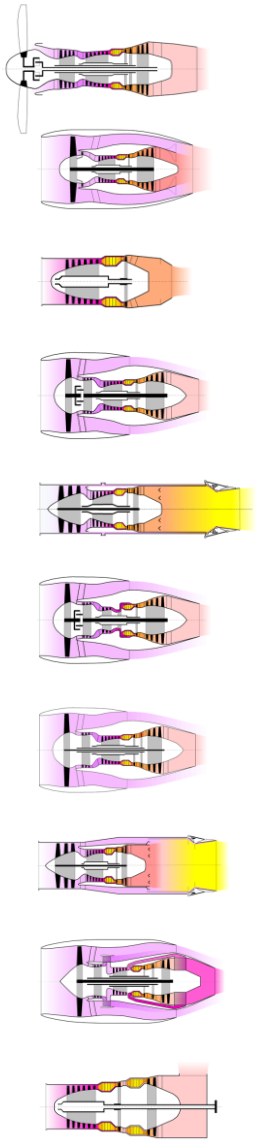
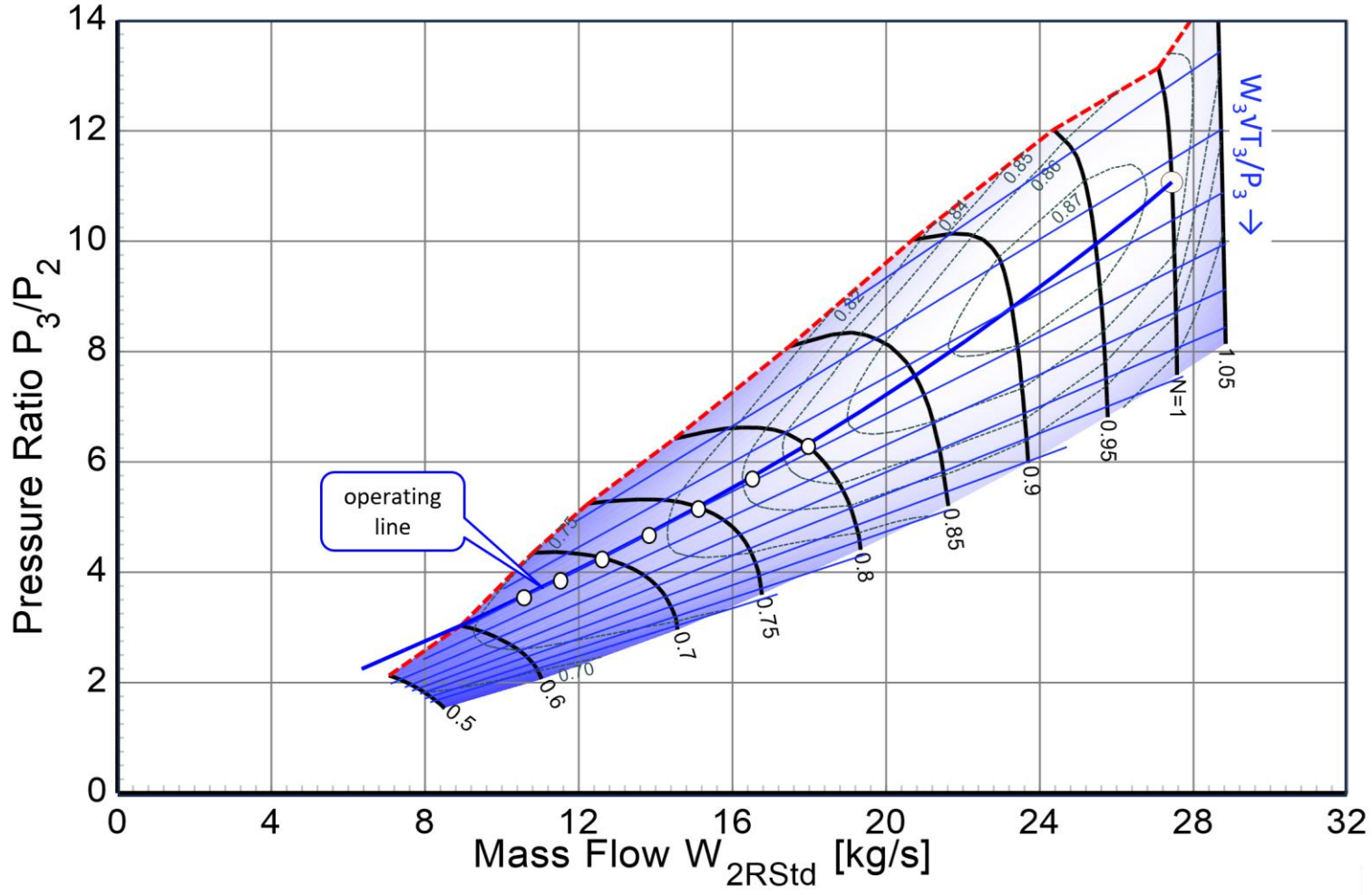
# Compressor Operating Line
## Steeper Than the $W_3\sqrt{T_3}/P_3$ Lines While $M_8$=1





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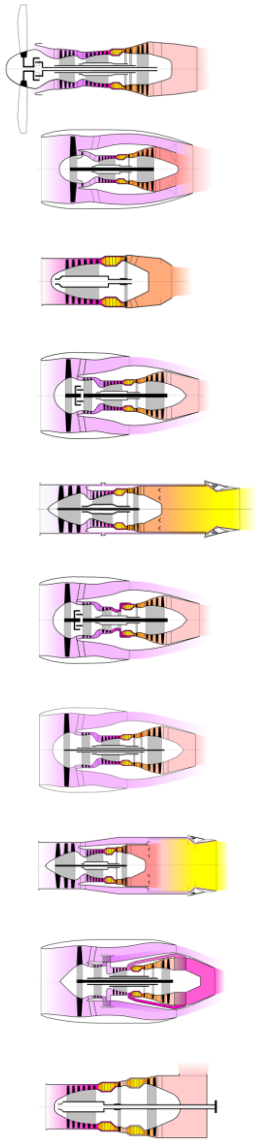
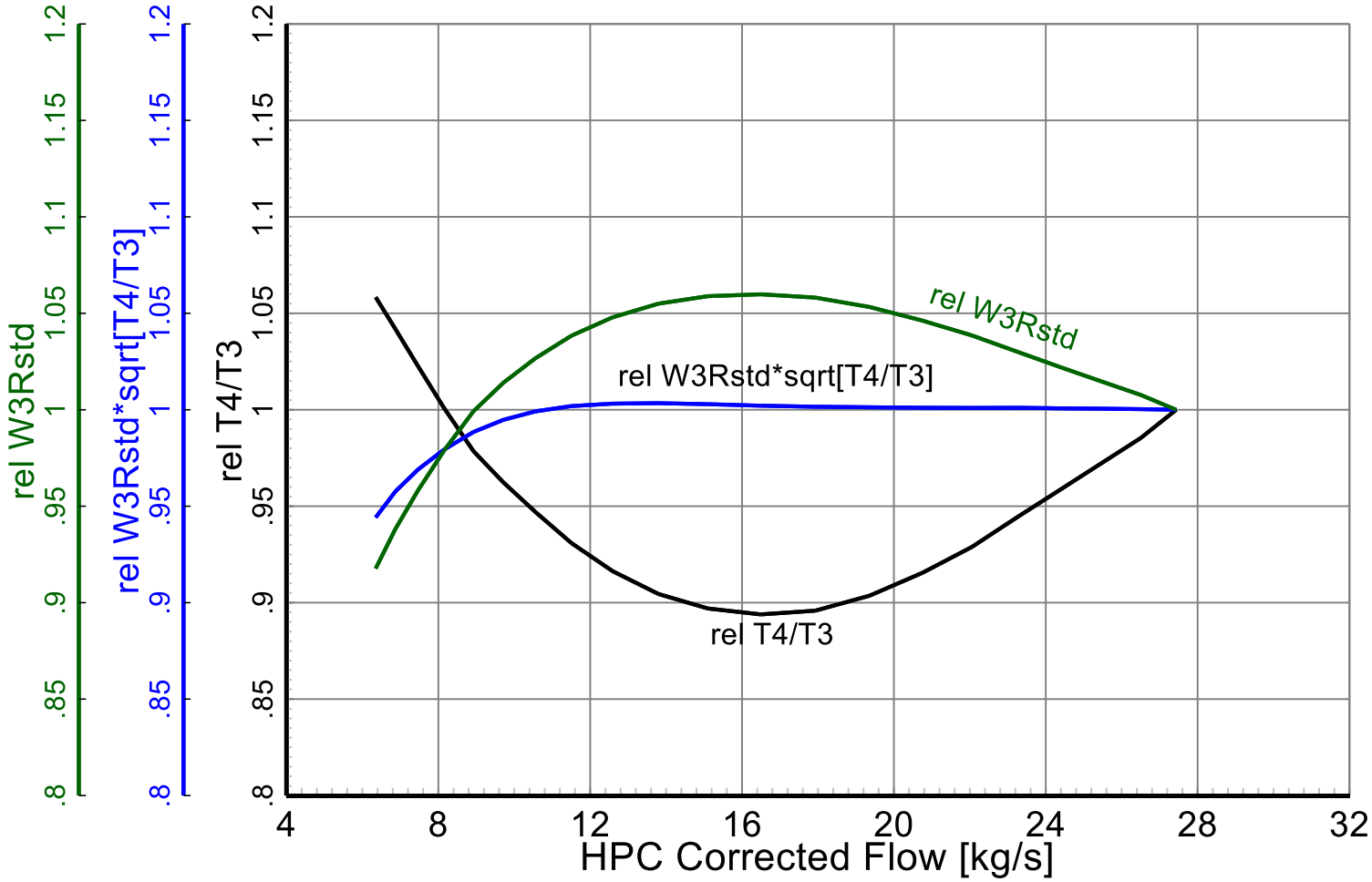
# Combustor Operating Line





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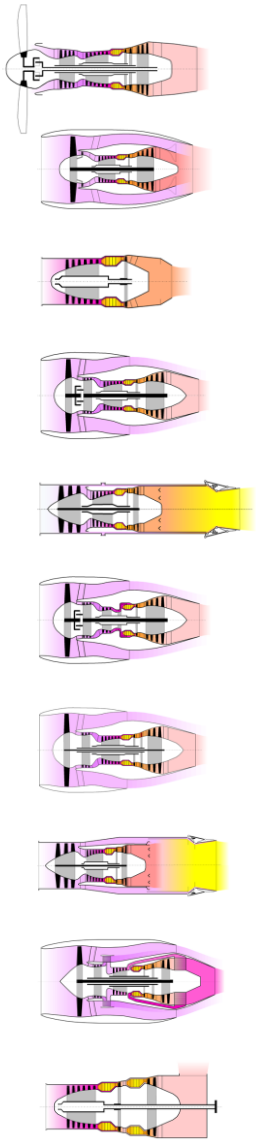
# Turbine and Nozzle Operating Lines
## Full Cycle Calculation



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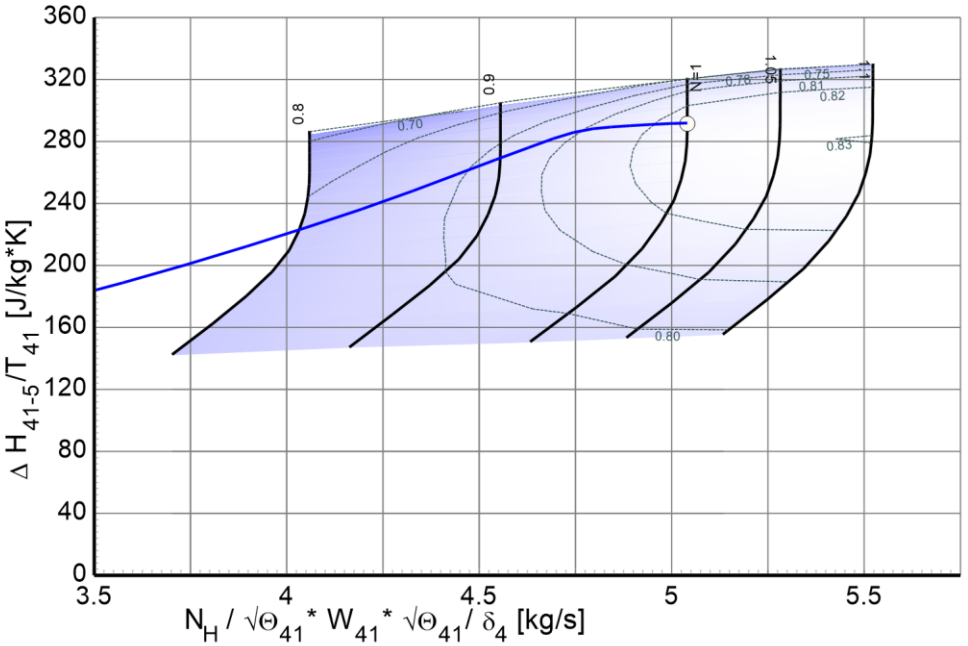


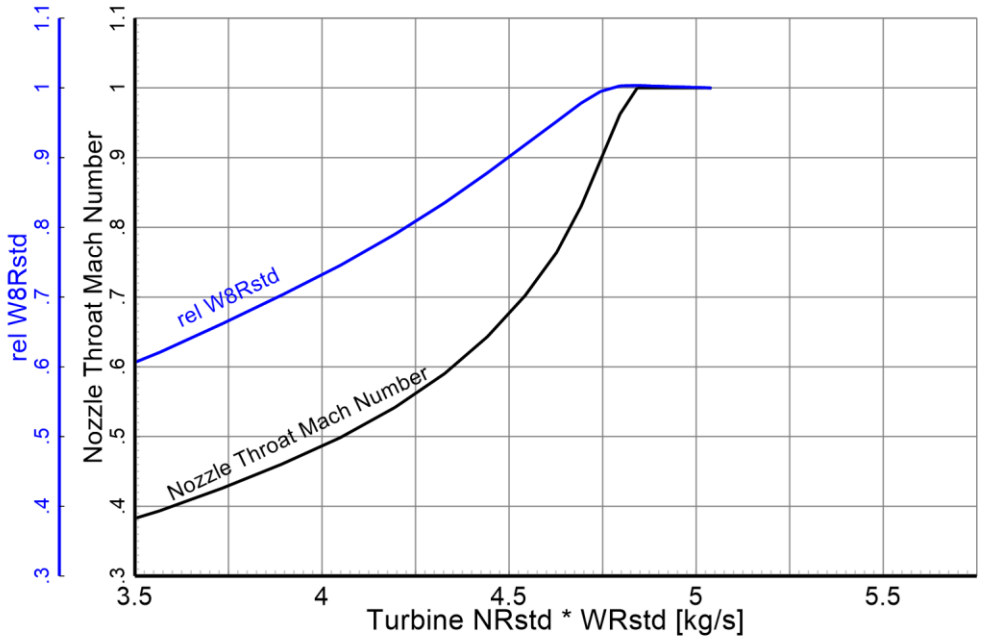


The turbine pressure ratio remains constant as long as the nozzle throat Mach number is 1

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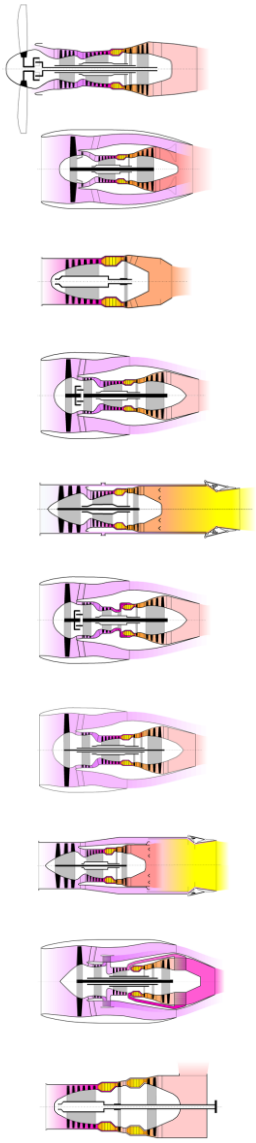
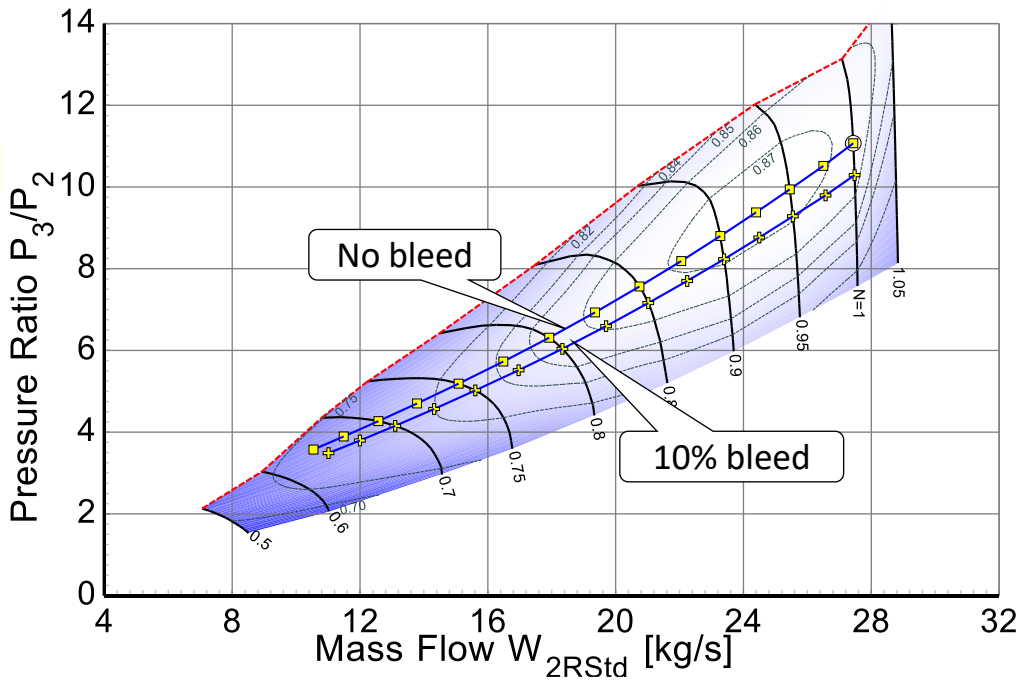
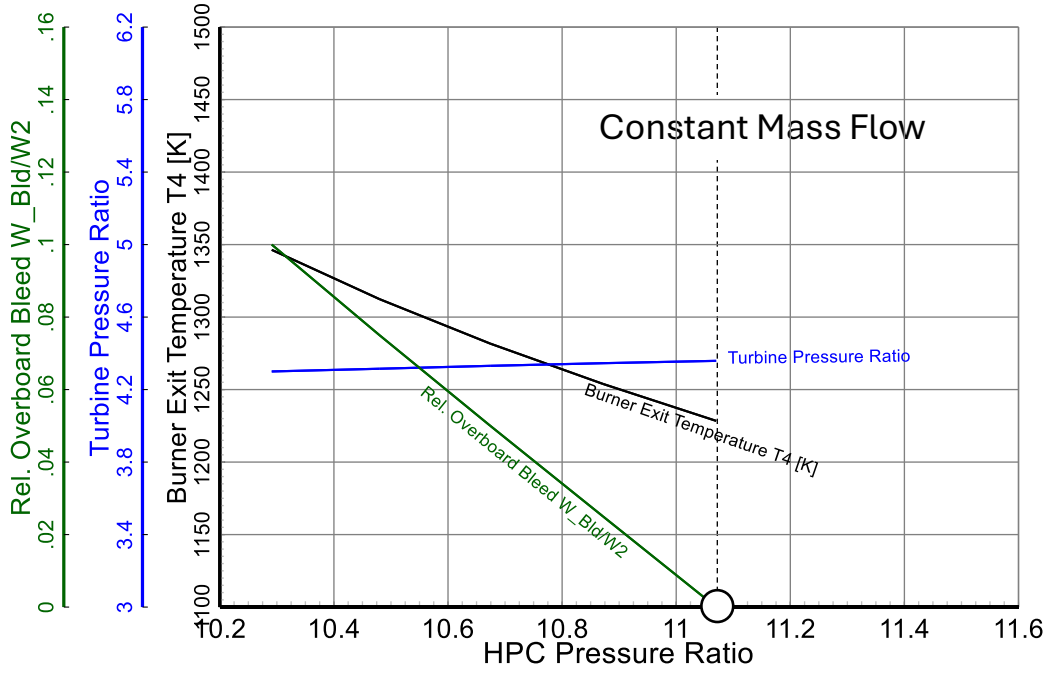
# Modifiers
## Compressor Exit Bleed





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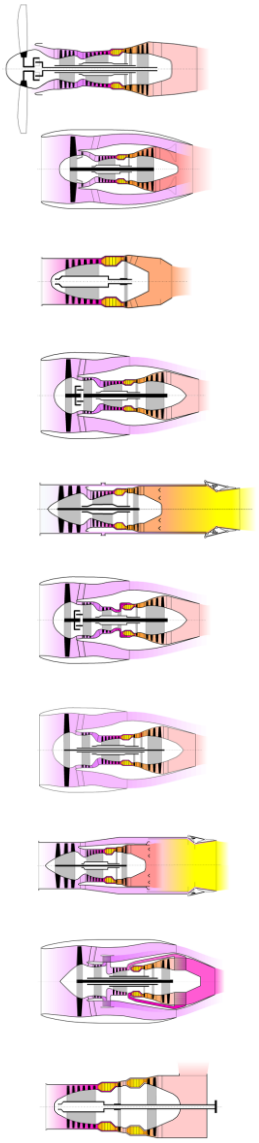
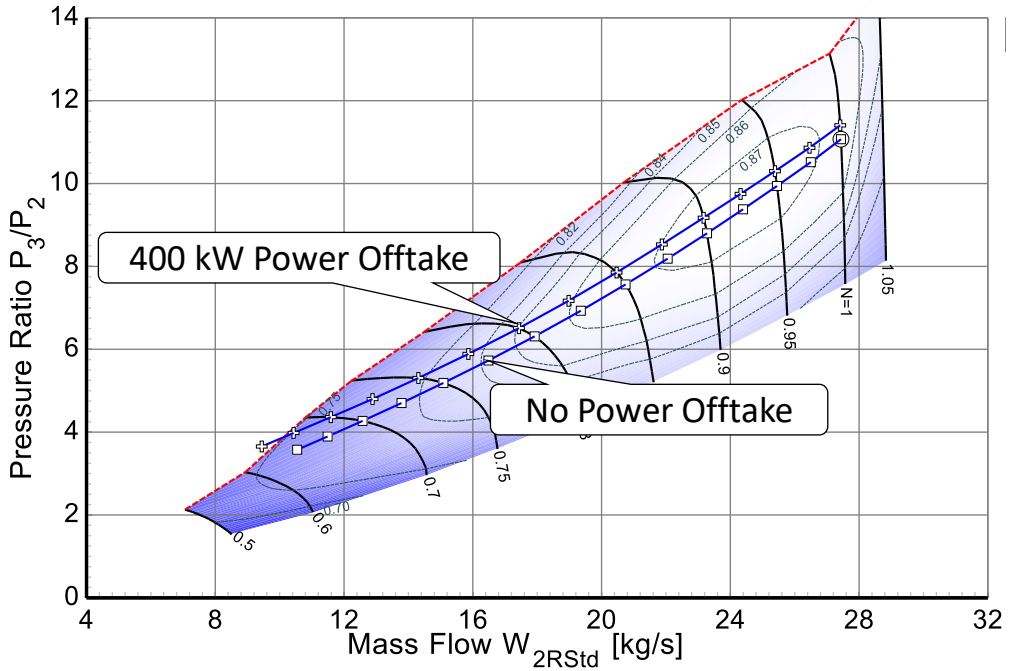
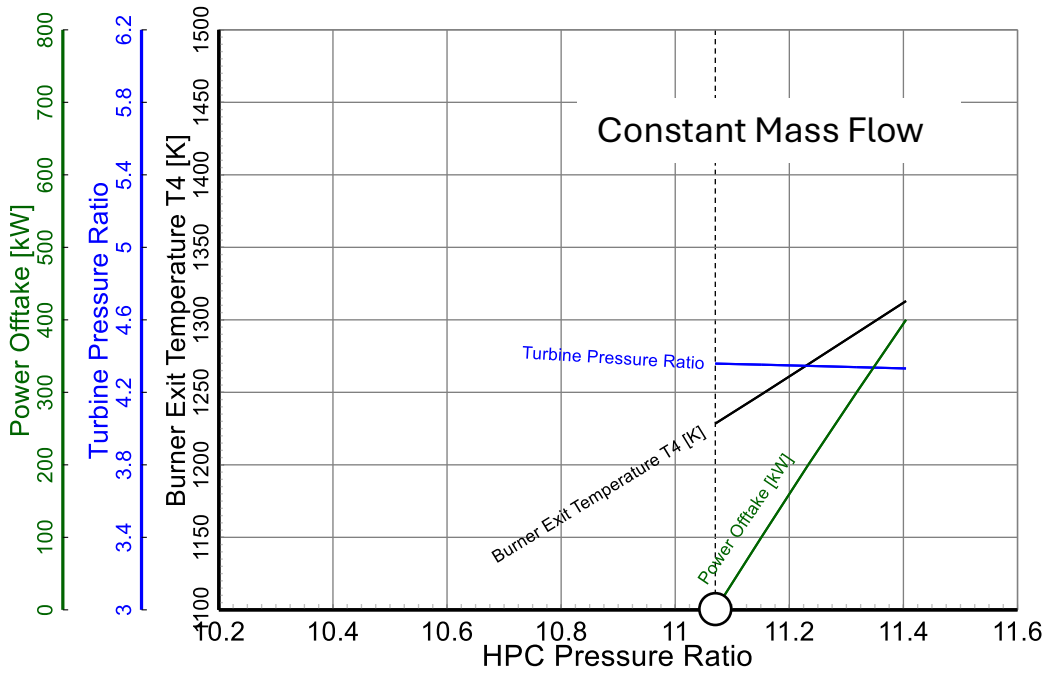
# Modifiers
## Power Offtake





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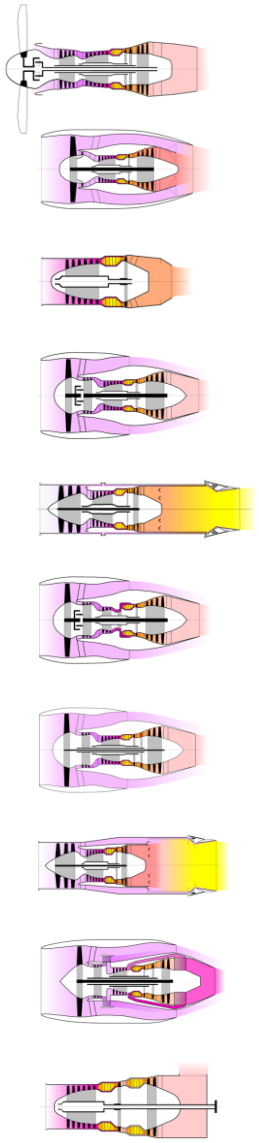
# Modifier
## Nozzle Area



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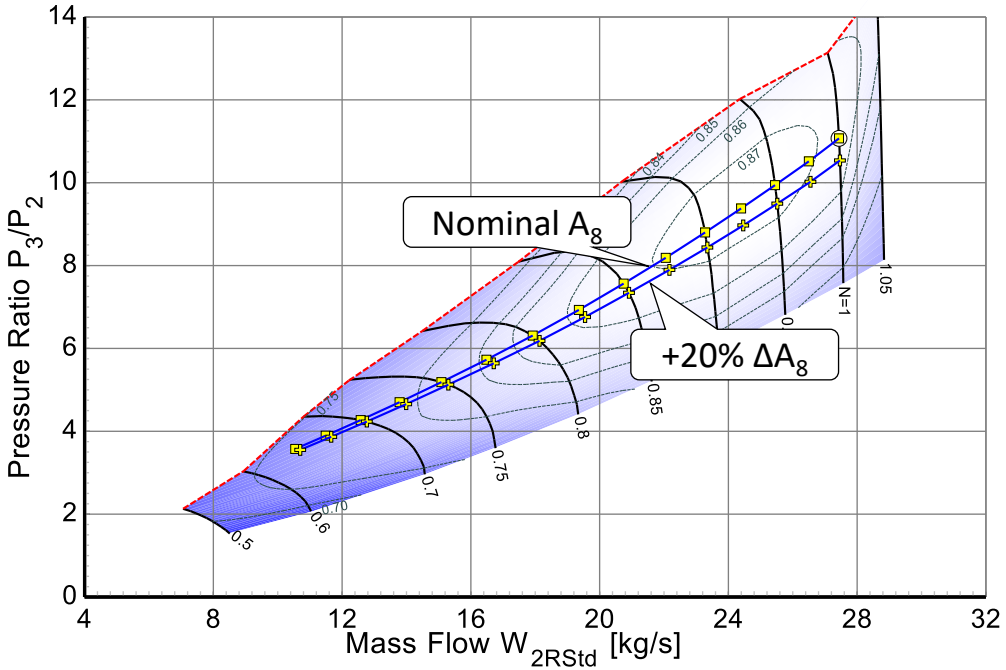


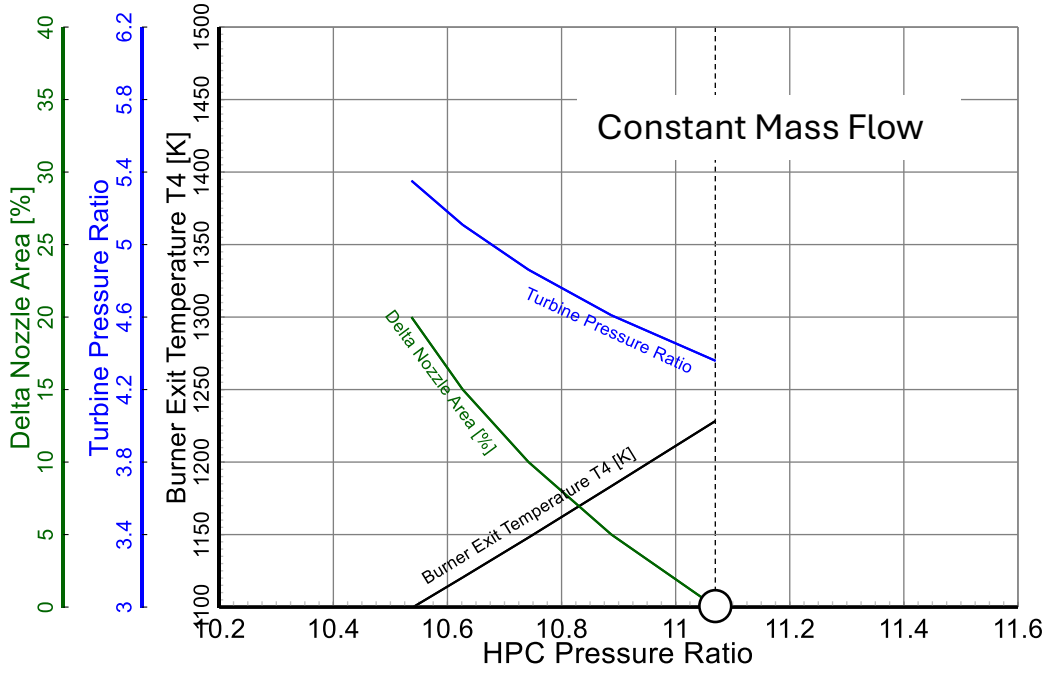

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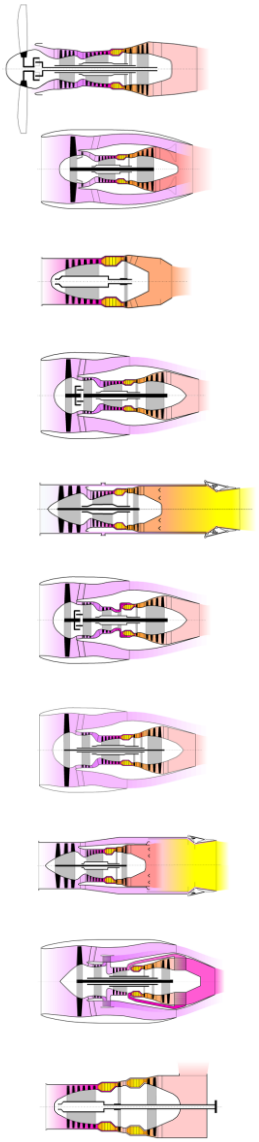
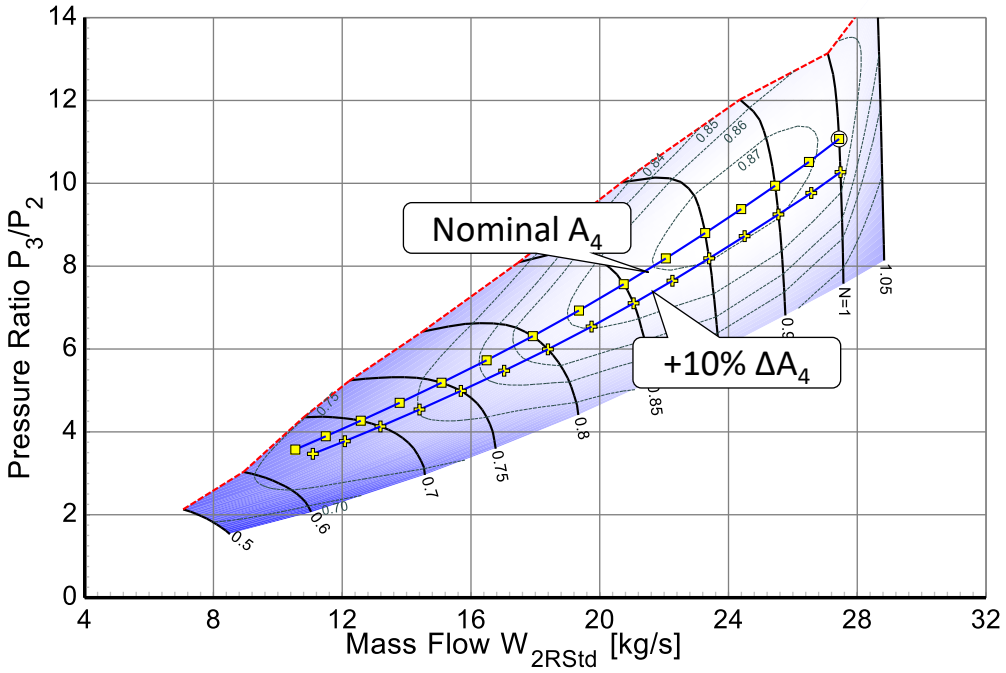
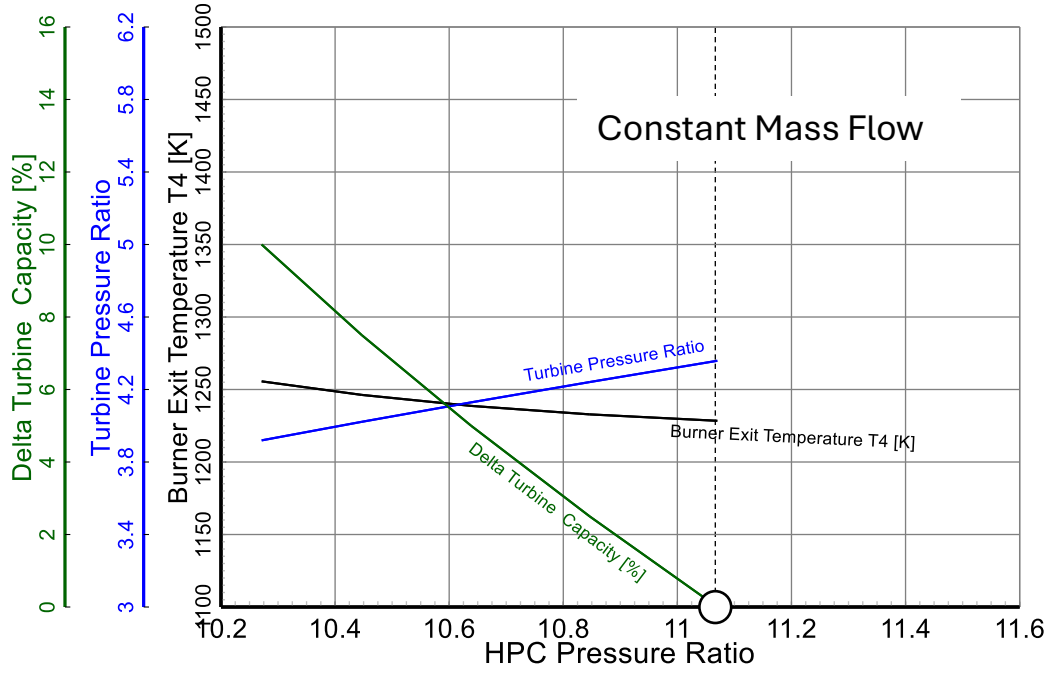
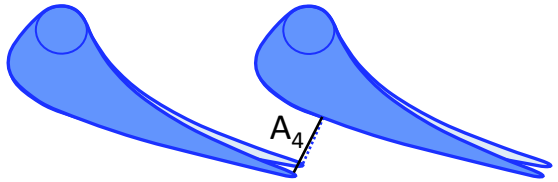
# Modifier
## Turbine Flow Capacity






A simple method for adapting $A_4$ (the turbine flow capacity):



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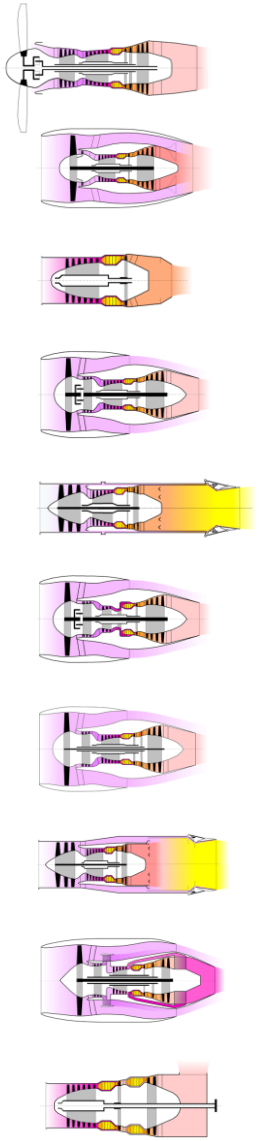
# Non-Dimensional Component Performance Parameters

## Mach Numbers in Disguise



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Compressor

$$\frac{P_3}{P_2} = const_A * \frac{W_2 * \sqrt{T_2}}{P_2} * \sqrt{\frac{T_2}{T_4}}$$

$T_4/T_2$ lines are straight lines through the origin of the compressor map

Burner

$$\frac{W_3\sqrt{T_3}}{P_3}\sqrt{\frac{T_4}{T_3}} = const_B$$

Compressor exit corrected flow decreases when $T_4/T_3$ increases.

Turbine

$$\frac{W_4\sqrt{T_4}}{P_4} = const \qquad \frac{P_4}{P_5} = const_C \frac{W_8 * \sqrt{T_8}}{A_8 * P_8}$$

Turbine pressure ratio is constant while the nozzle flow is sonic

Power Balance

$$\frac{C_{p,C} * \left[\left(\frac{P_3}{P_2}\right)^{R/c_{p,C}} - 1\right]}{T_2 * \eta_C} = const_D * \frac{T_4}{T_2} * \eta_T + \frac{\frac{PW_x}{P_2 * \sqrt{T_2}}}{\frac{W_2\sqrt{T_2}}{P_2}}$$

Compressor pressure ratio increases if the product of $\eta_C$ and $\eta_T$ decreases or $PW_x$ increases

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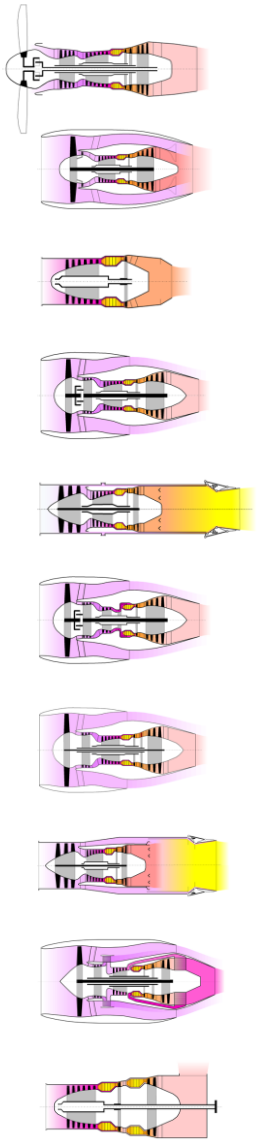

# Non-Dimensional Engine Performance Parameters

$$F_N = W * (V_9 - V_0) = \frac{W\sqrt{T}}{P}\frac{(V_9 - V_0)}{\sqrt{T}} \times P$$

$$\delta_2 = \frac{P_2}{101.325kPa} \qquad \Theta_2 = \frac{T_2}{288.15K}$$

$$F_{N,corr} = \frac{F_N}{\delta_2} = \frac{W\sqrt{\Theta_2}}{\delta_2}\left(\frac{V_9}{\sqrt{\Theta_2}} - \frac{V_0}{\sqrt{\Theta_2}}\right)$$

Corrected net thrust

$\frac{V_0}{\sqrt{\Theta_2}}$ is proportional to the flight Mach number

$$PW_{x,corr} = \frac{PW_x}{\delta_2 * \sqrt{\Theta_2}}$$

Corrected shaft power

$$W_{F,corr} = \frac{W_F * FHV}{\delta_2 * \sqrt{\Theta_2}} = \frac{W_F}{\delta_2 * \sqrt{\Theta_2}}$$

Corrected fuel flow

An energy stream, not a mass flow!

$$TSFC_{corr} = \frac{\frac{W_F}{\delta_2 * \sqrt{\Theta_2}}}{\frac{F_N}{\delta_2}} = \frac{W_F}{F_N * \sqrt{\Theta_2}} = \frac{SFC}{\sqrt{\Theta_2}}$$

Corrected thrust specific fuel consumption

Changes with flight Mach number

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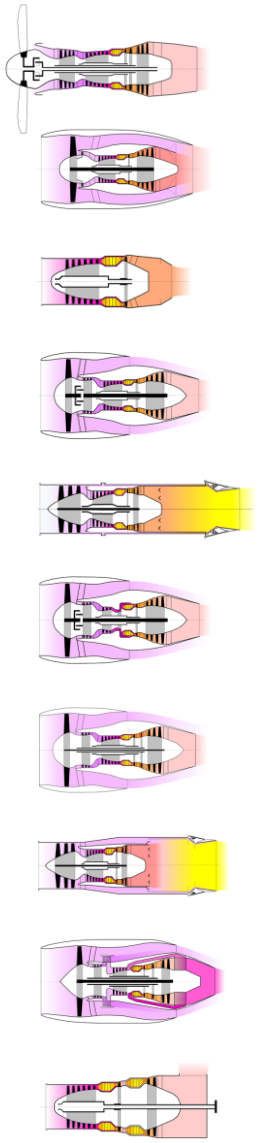
# Non-Dimensional Performance
## Some Numbers



| case | ambient T | alt [ft] | M | T2 | P2 | Θ | δ | P3/P2 | W2Rstd | rel N/√Θ | % N | FN | FN/δ | rel FN/δ | SFC | SFC√Θ | rel SFC√Θ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ISA SLS | 0 | 0 | 288.15 | 101.325 | 1.0000 | 1.0000 | 9 | 23.67 | 1.000 | 90.90 | 12.62 | 12.62 | 1.0000 | 23.71 | 23.71 | 1.0000 |
| 2 | ISA+15 SLS | 0 | 0 | 303.15 | 101.325 | 1.0521 | 1.0000 | 9 | 23.66 | 1.000 | 93.20 | 12.67 | 12.67 | 1.0040 | 24.50 | 23.89 | 1.0076 |
| 3 | ISA-15 SLS | 0 | 0 | 273.15 | 101.325 | 0.9479 | 1.0000 | 9 | 23.66 | 0.999 | 88.40 | 12.57 | 12.57 | 0.9960 | 22.94 | 23.56 | 0.9940 |
| | | | | | | | | | | | | | | | | | |
| 4 | ISA-36.44 | 0 | 0.85 | 288.15 | 162.5 | 1.0000 | 1.6038 | 9 | 23.67 | 0.999 | 90.80 | 15.1 | 9.42 | 0.7461 | 31.76 | 31.76 | 1.3397 |
| 5 | ISA+3.2 | 20000 | 0.85 | 288.15 | 74.69 | 1.0000 | 0.7371 | 9 | 23.58 | 0.999 | 90.80 | 6.97 | 9.46 | 0.7493 | 31.98 | 31.98 | 1.3491 |
| 6 | ISA+33 | 35000 | 0.85 | 288.15 | 38.25 | 1.0000 | 0.3775 | 9 | 23.17 | 0.994 | 90.40 | 3.62 | 9.60 | 0.7607 | 32.89 | 32.89 | 1.3874 |
| 7 | ISA | 35000 | 0.85 | 250.5 | 38.25 | 0.8693 | 0.3775 | 9 | 23.28 | 0.996 | 84.40 | 3.56 | 9.44 | 0.7480 | 30.09 | 32.28 | 1.3617 |
| | | | | | | | | | | | | | | | | | |
| 8 | ISA-3.644 | 0 | 0.25 | 288.15 | 105.83 | 1.0000 | 1.0445 | 9 | 23.67 | 1.000 | 90.90 | 11.47 | 10.98 | 0.8700 | 27.25 | 27.25 | 1.1495 |
| 9 | ISA+15 | 0 | 0.25 | 306.9 | 105.83 | 1.0651 | 1.0445 | 9 | 23.67 | 1.000 | 93.80 | 11.53 | 11.04 | 0.8748 | 28.34 | 27.46 | 1.1583 |
| 10 | ISA-15 | 0 | 0.25 | 276.6 | 105.83 | 0.9599 | 1.0445 | 9 | 23.66 | 0.999 | 89.00 | 11.43 | 10.94 | 0.8669 | 26.58 | 27.13 | 1.1444 |

Corrected Thrust

Corrected SFC

Flight Conditions

Compressor Operating Point

Changes with Mach number and $P_2$

Changes with Mach number and Θ

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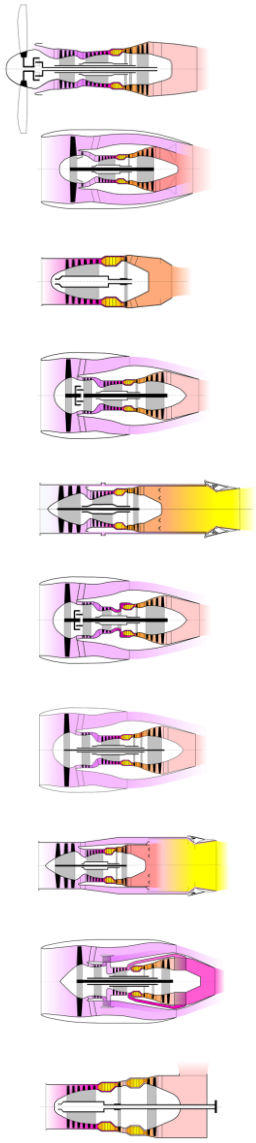

# Take Away

At a given point in the compressor map:

- All Mach numbers in the compressor are fixed
- The non-dimensionals describe what happens in the engine.
- True thrust and fuel consumption change very much within the flight envelope.
- Corrected thrust changes with Mach number and $\delta_2$ ($P_2$)
- Corrected SFC changes with Mach number and $\Theta_2$ ($T_2$)
- Altitude is not the decisive parameter, $T_2$, $P_2$ and flight Mach number are!

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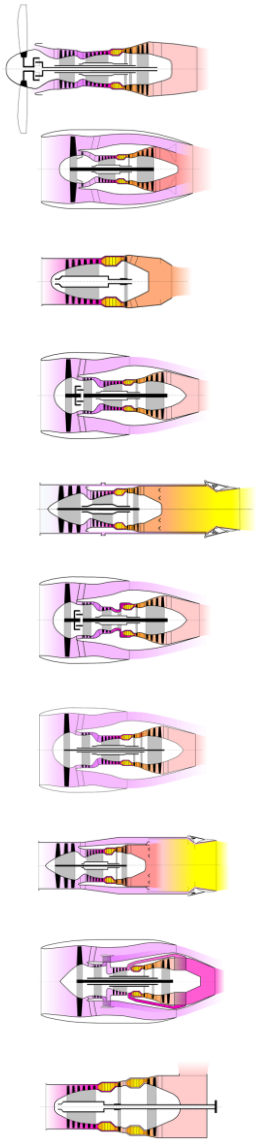

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# Outline

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components

Cooperation of the Components

Gas Generator +
- Power Turbine = 2 Spool Turboshaft
- Booster and Low Pressure Turbine = 2 Spool Turbojet
- Fan, Booster and Low Pressure Turbine = 2 Spool Turbofan

Variable Geometry

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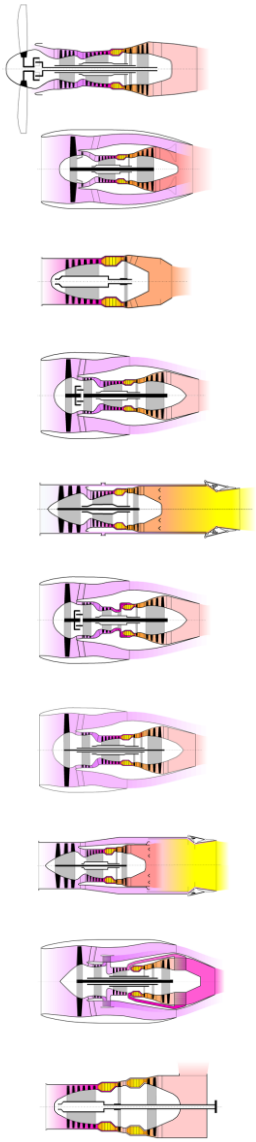
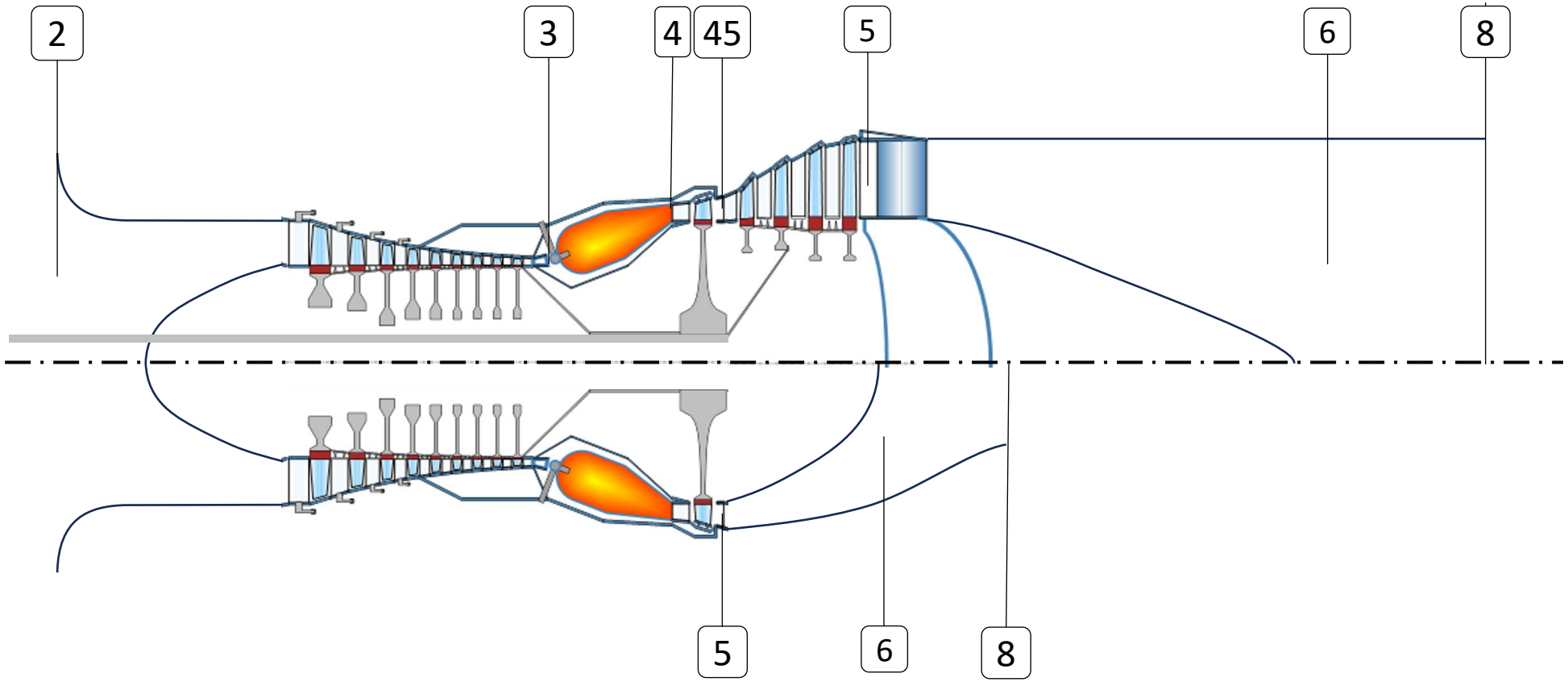
# From Gas Generator to Turboshaft





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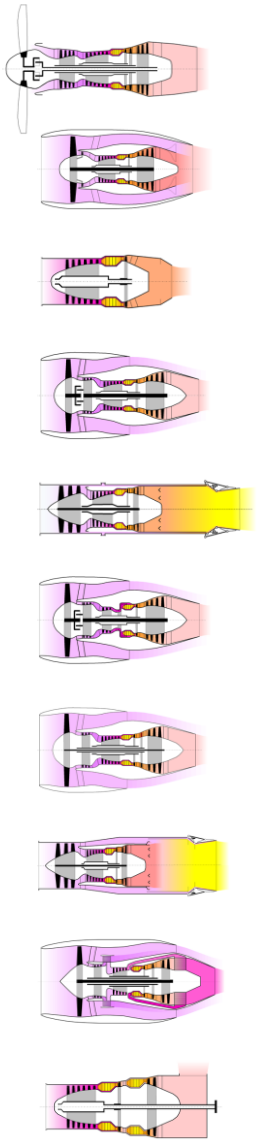
# Turboshaft Reference Cycle
## CFM56-3 Gas Generator plus Power Turbine



| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 1 | 27.436 | 288.15 | 101.325 | |
| 2 | 27.436 | 288.15 | 101.325 | **27.436** |
| 3 | 27.436 | 609.27 | 1121.668 | 3.604 |
| 31 | 23.568 | 609.27 | 1121.668 | |
| 4 | 23.989 | 1250.00 | 1065.584 | 4.751 |
| 41 | 25.910 | 1206.10 | 1065.584 | **5.040** |
| 43 | 25.910 | 908.46 | 247.090 | |
| 44 | 27.556 | 891.50 | 247.090 | |
| 45 | 27.556 | 891.50 | 247.090 | **19.876** |
| 49 | 27.556 | 738.16 | 106.495 | |
| 5 | 27.857 | 736.81 | 106.495 | 42.384 |
| 6 | 27.857 | 736.81 | 104.365 | |
| 8 | 27.857 | 736.81 | 104.365 | 43.249 |
| Bleed | 0.000 | 609.26 | 1121.665 | |

| Efficiencies: | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Compressor | **0.8677** | 0.9033 | 1.000 | **11.070** |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | **0.8250** | 0.7969 | 1.964 | **4.313** |
| LP Turbine | 0.8900 | 0.8789 | 0.645 | 2.320 |
| Generator | 1.0000 | | | |

HP Spool mech Eff 0.9900 Nom Spd 38000 rpm
PT Spool mech Eff 0.9780 Nom Spd 20000 rpm

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | | |
|---|---|---|---|
| PWSD = | 4650.9 | kW | Shaft Power Delivered |
| PSFC = | 0.32624 | kg/(kW*h) | Power Specific Fuel Consumption |
| Heat Rate= | 13953.0 | kJ/(kW*h) | Fuel Flow * Fuel Heating Value / Shaft Power Delivered |
| V0 = | 0.00 | m/s | Flight Velocity |
| FN res = | 3.11 | kN | Residual Net Thrust |
| WF = | 0.42148 | kg/s | Fuel Flow |
| Therm Eff= | 0.25801 | | Thermal Efficiency |
| P2/P1 = | 1.00000 | | Inlet Pressure Ratio |
| TRQ = | 100.0 | % | Torque Delivered Relative to the Cycle Design Point Value |
| P45/P44 = | 1.00000 | | Interturbine Duct Pressure Ratio |
| Incidence= | 0.00000 | deg | Flow Incidence Angle @ Turbine Exit Guide Vanes |
| P6/P5 = | 0.98000 | | Turbine Exit Duct Pressure Ratio |
| PWX = | 0.0 | kW | Power Offtake |
| P8/Pamb = | 1.03000 | | Nozzle Pressure Ratio |
| WBld/W2 = | 0.00000 | | Bleed Air Flow/Mass Flow W2 |
| A8 = | 0.51693 | m² | Geometric Nozzle Throat Area |
| WCHN/W2 = | **0.07000** | | HPT Nozzle Guide Vane Cooling Air / W2 |
| WCHR/W2 = | **0.06000** | | HPT Rotor Cooling Air / W2 |
| Loading = | 100.00 | % | Burner Loading in % of the Cycle Design Point Value |
| WCLN/W2 = | 0.00000 | | LPT Nozzle Guide Vane Cooling Air / W2 |
| WCLR/W2 = | 0.00000 | | LPT Rotor Cooling Air / W2 |
| PW_gen = | 4650.9 | kW | Electric Power |
| WlkLP/W2 = | **0.01100** | | HP Leakage to LPT Exit/Mass Flow W2 |
| eta t-s = | 0.84549 | | Total-Static Efficiency of the Power Turbine |

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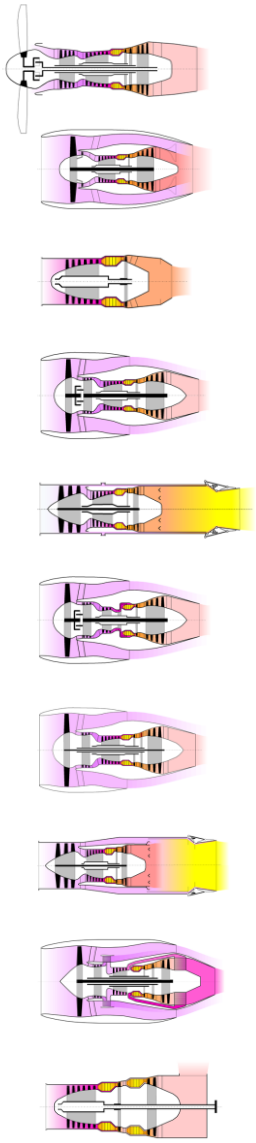
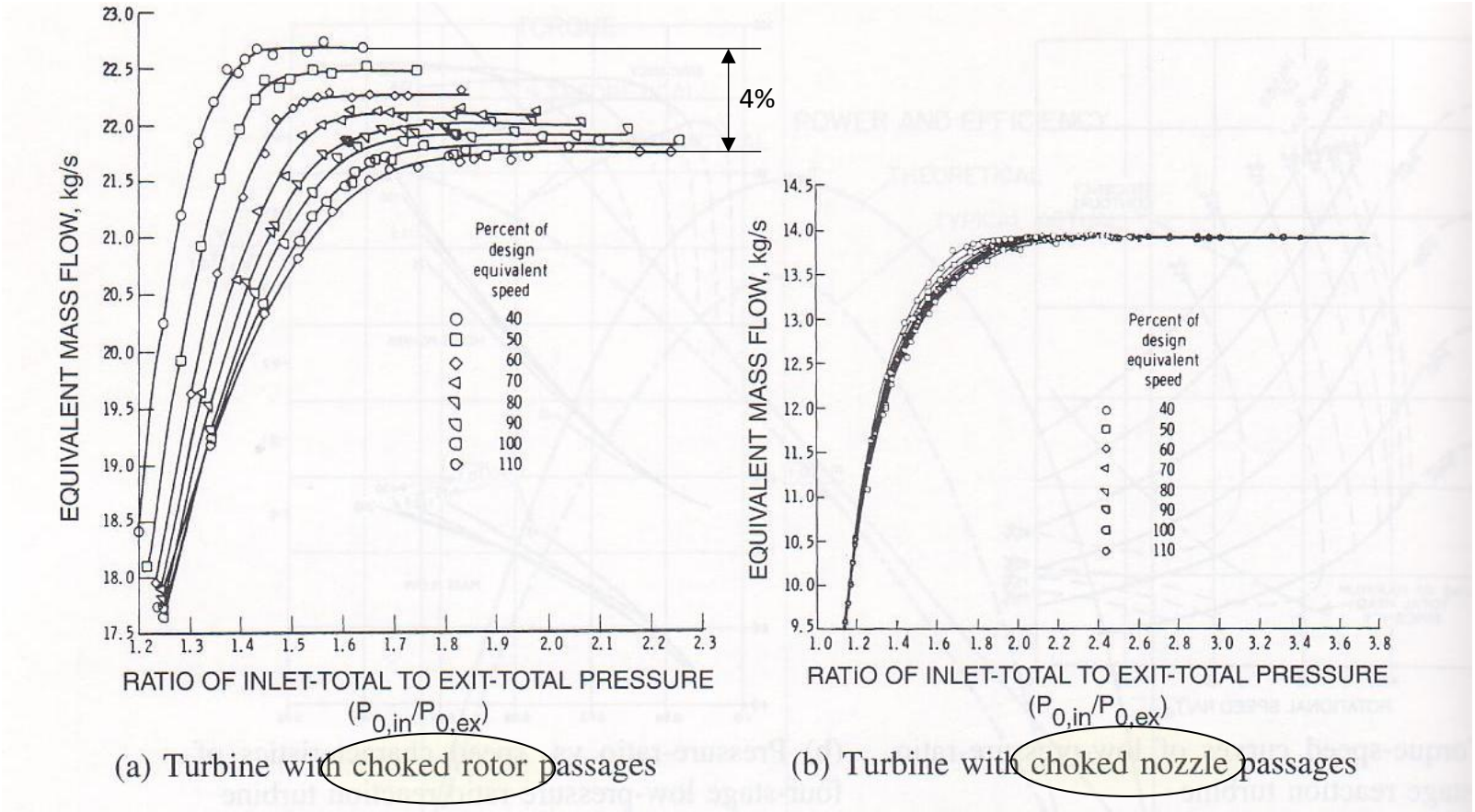
# Power Turbine Flow Characteristics



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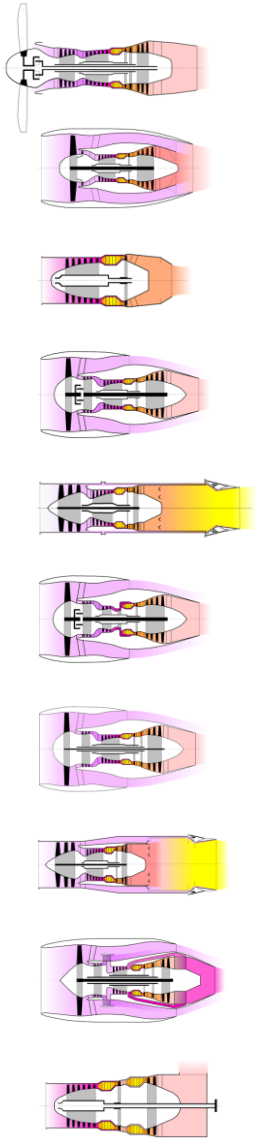
# Compressor Operating Lines



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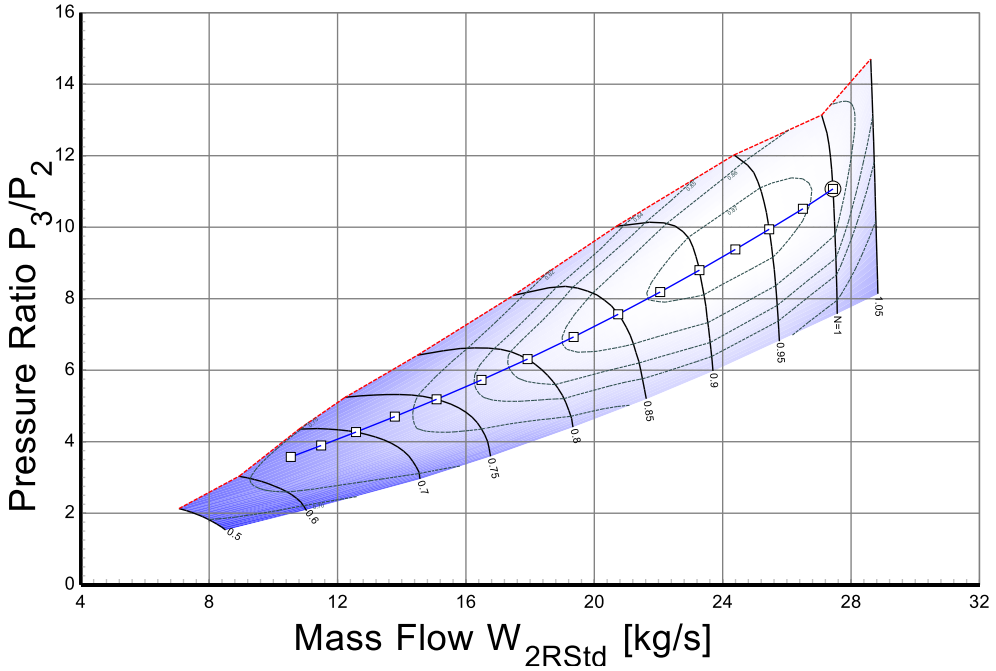
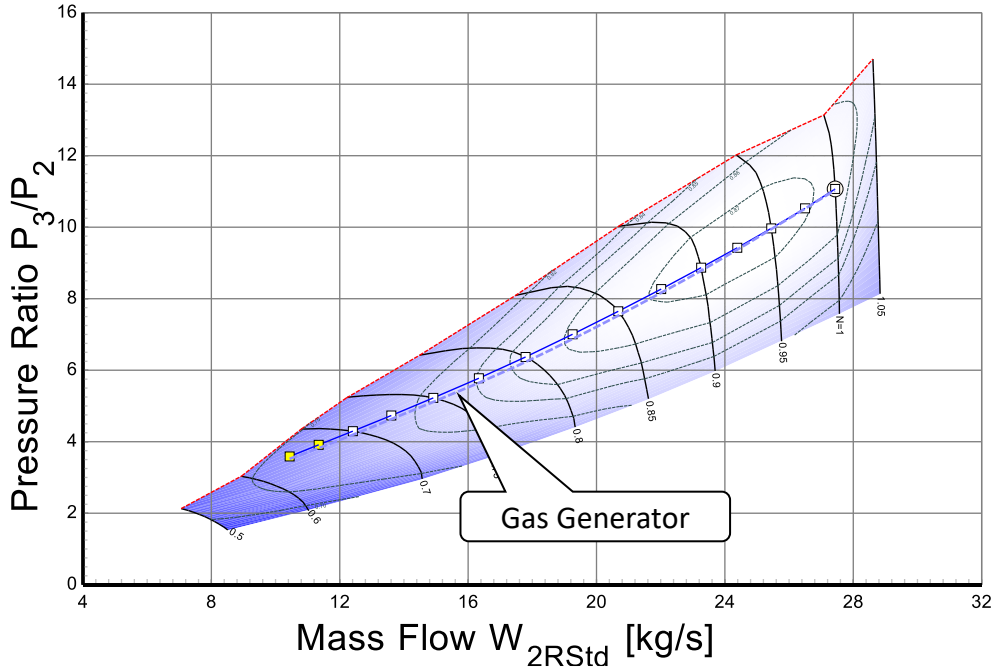
## Gas Generator




## Turboshaft



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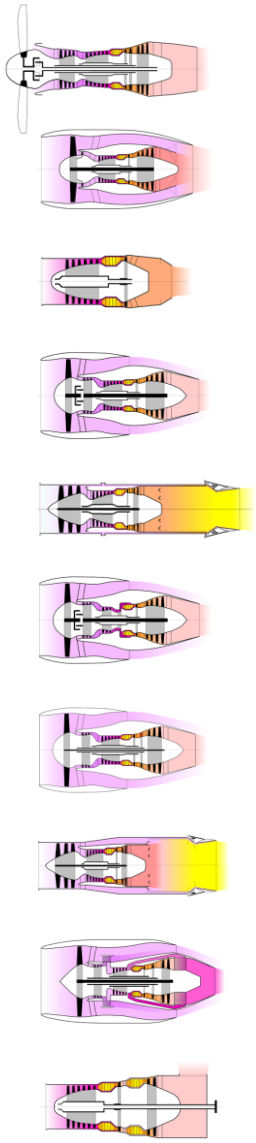
# HPT Operating Lines



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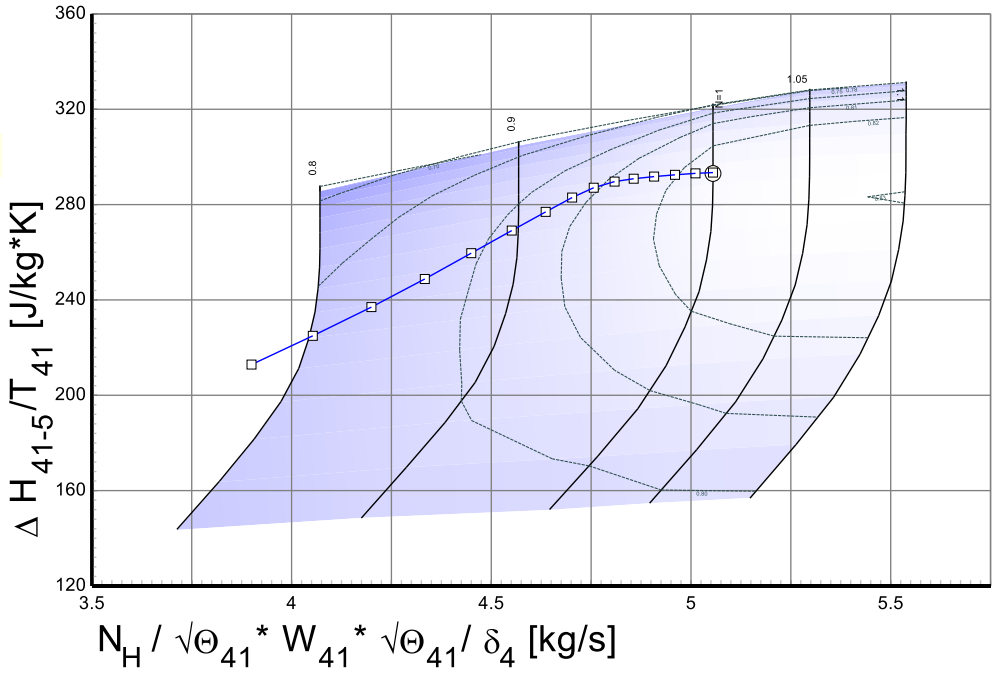
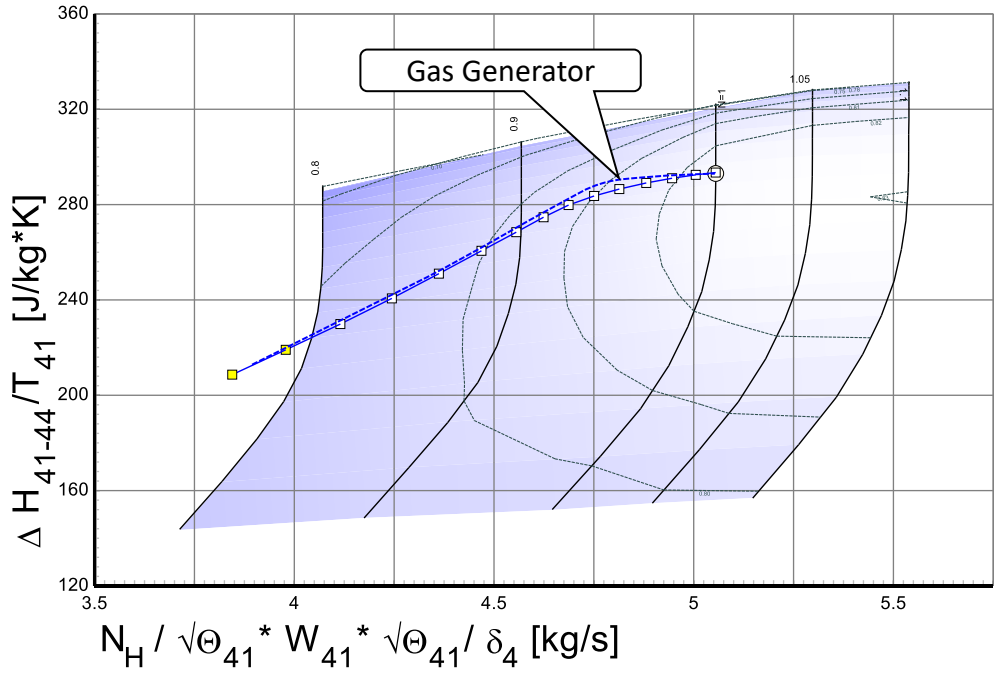
## Gas Generator




## Turboshaft

constant PT speed



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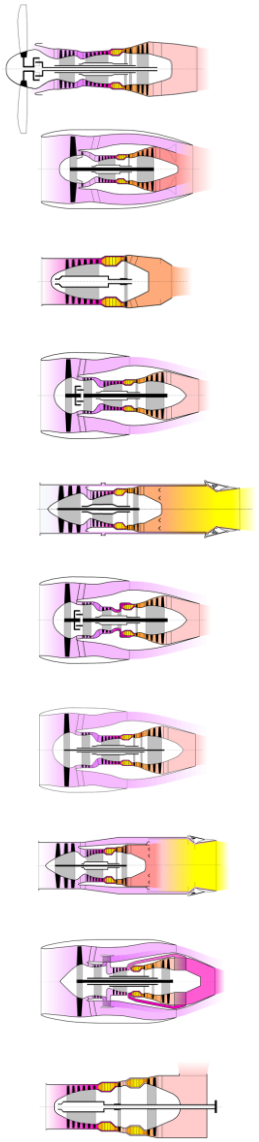
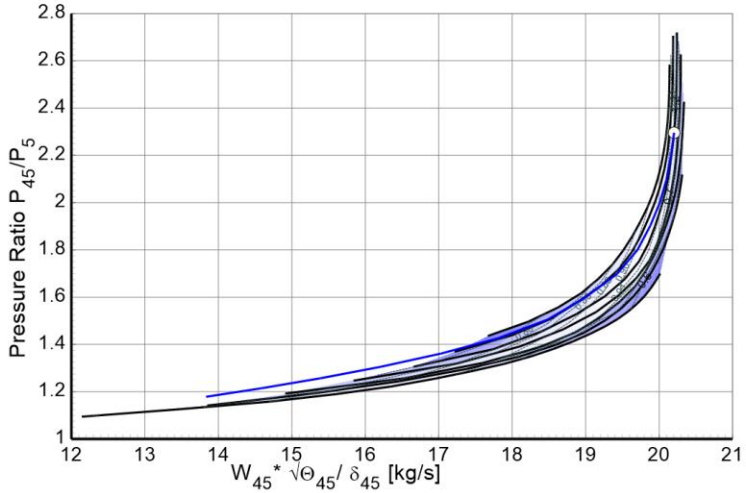
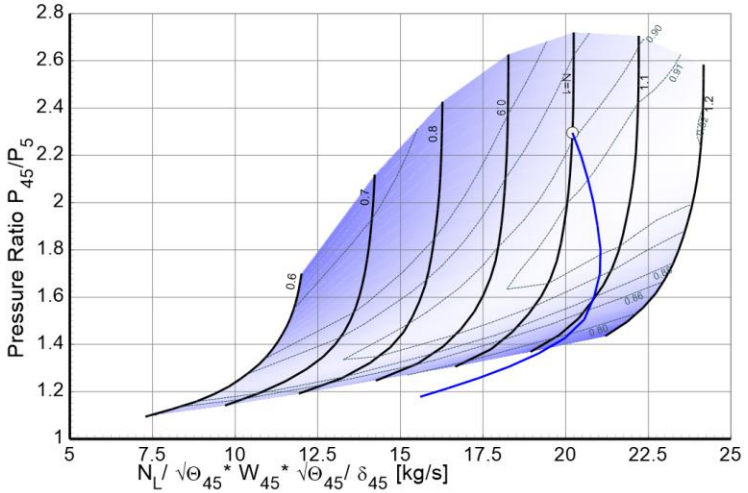
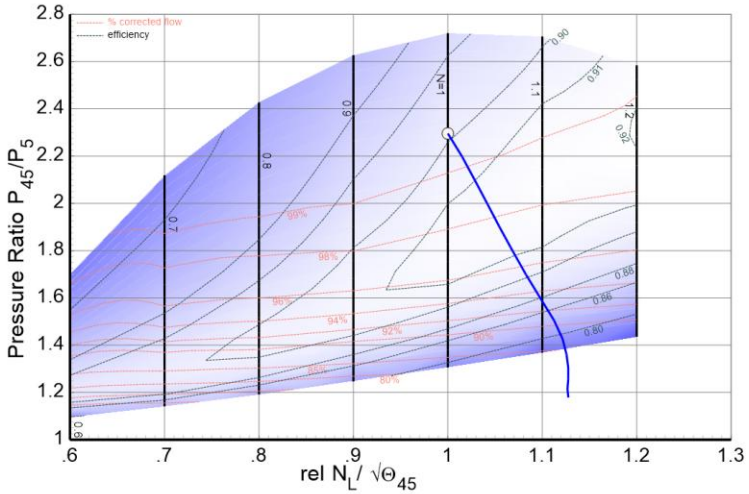
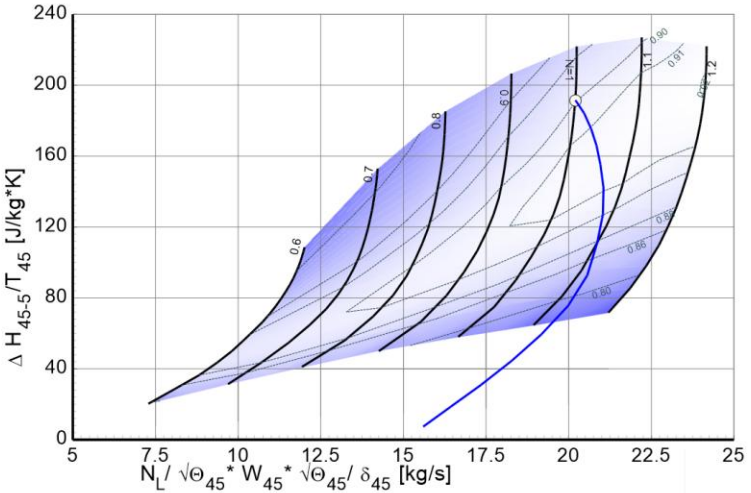
# Low Pressure Turbine Operating Line





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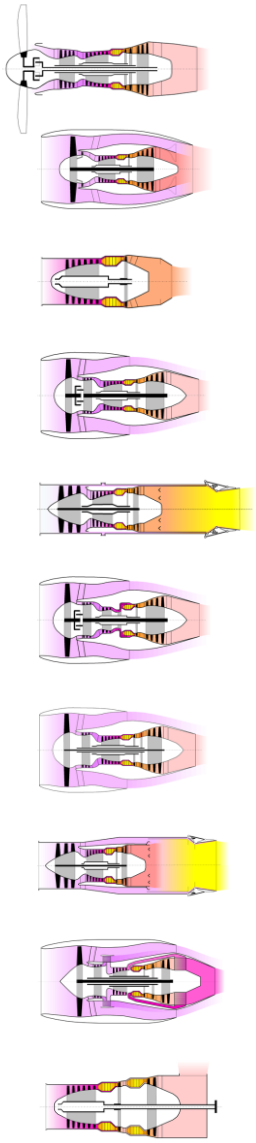

# Low Pressure Turbine Operating Line

- $N_{LPT}$=const yields increasing $N_{LPT}/\sqrt{T_{45}}$ with decreasing load
- Exhaust swirl angle changes up to 100 degrees within the operating range
  - This is a challenge for the design of the exit guide vanes
- The kinetic energy at the exhaust of a turboshaft engine is a loss to the process
- From a system point of view, it is favorable to consider the combined performance of the LPT and the exhaust diffuser
- Use of total-static efficiency is recommended
  - instead of the total pressure ratio $P_{45}/P_5$ the total-static pressure ratio $P_{45}/P_{amb}$ defines the ideal work

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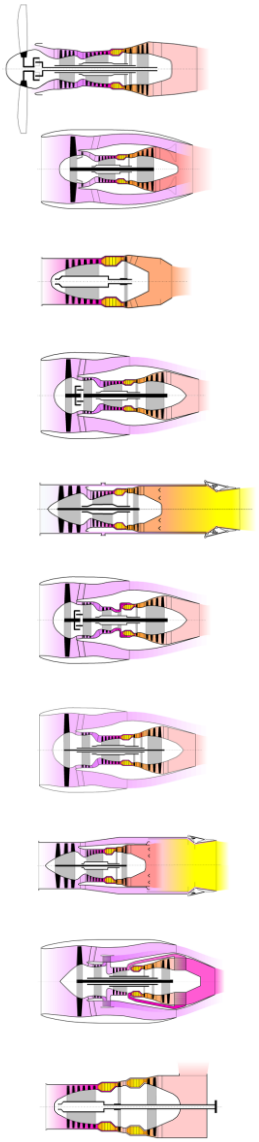
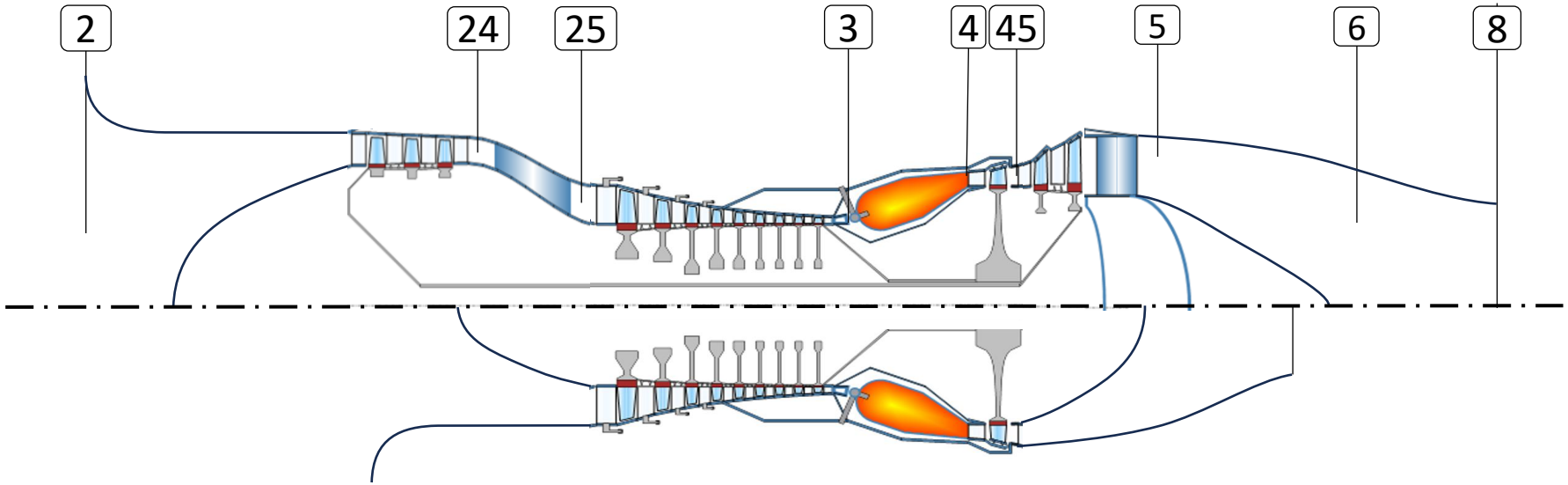
# From Gas Generator to 2-Spool Turbojet





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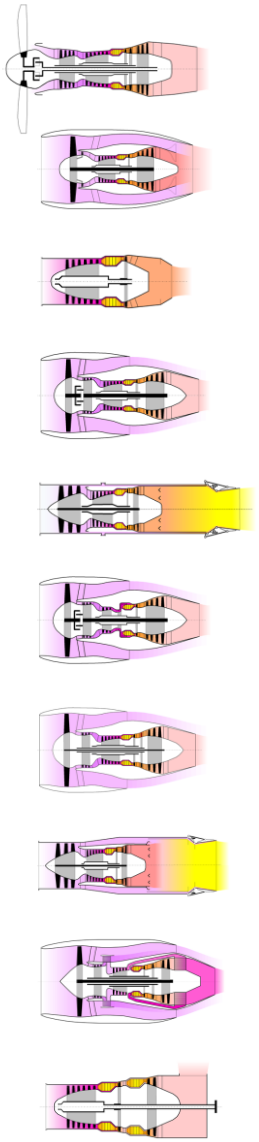
# 2-Spool Turbojet Reference Cycle

## CFM56-3 Gas Generator plus Booster and Low Pressure Turbine



| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 1 | 52.847 | 288.15 | 101.325 | |
| 2 | 52.847 | 288.15 | 101.325 | 52.847 |
| 24 | 52.847 | 369.90 | 221.133 | |
| 25 | 52.847 | **369.90** | **221.133** | **27.436** |
| 3 | 52.847 | 770.80 | 2447.945 | 3.578 |
| 31 | 45.396 | 770.80 | 2447.945 | |
| 4 | 46.492 | **1577.96** | 2325.549 | 4.740 |
| 41 | 50.191 | 1523.28 | 2325.549 | **5.028** |
| 43 | 50.191 | 1163.15 | 541.687 | |
| 44 | 53.362 | 1141.30 | 541.687 | |
| 45 | 53.362 | 1141.30 | 541.687 | **19.865** |
| 49 | 53.362 | 1073.33 | 406.816 | |
| 5 | 53.362 | 1073.33 | 406.816 | 25.651 |
| 6 | 53.943 | 1070.25 | 398.680 | |
| 8 | 53.943 | 1070.25 | 398.680 | 26.422 |
| Bleed | 0.000 | 770.80 | 2447.945 | |

| Efficiencies: | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| LP Compressor | 0.8779 | 0.8905 | 1.000 | 2.182 |
| HP Compressor | **0.8677** | 0.9026 | 1.621 | **11.070** |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | **0.8250** | 0.7985 | 3.281 | **4.293** |
| LP Turbine | 0.8999 | 0.8968 | 1.064 | 1.332 |

HP Spool mech Eff 0.9900 Speed 100.00 %
LP Spool mech Eff 1.0000 Speed 100.00 %

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | | |
|---|---|---|---|
| FN | = 45.39 | kN | Net Thrust |
| TSFC | = 24.1412 | g/(kN*s) | Thrust Specific Fuel Consumption |
| FN/W2 | = 858.87 | m/s | Specific Thrust |
| WF Burner | = 1.09575 | kg/s | Main Burner Fuel Flow |
| P2/P1 | = 1.0000 | | Inlet Pressure Ratio |
| P25/P24 | = 1.0000 | | Compressor Interduct Pressure Ratio |
| P3/P2 | = 24.1593 | | Overall Pressure Ratio |
| P45/P44 | = 1.0000 | | Interturbine Duct Pressure Ratio |
| P6/P5 | = 0.9800 | | Turbine Exit Duct Pressure Ratio |
| W_NGV/W25 | = **0.07000** | | HPT Nozzle Guide Vane Cooling Air/Mass Flow W25 |
| WHcl/W25 | = **0.06000** | | HPT Rotor Cooling Air/Mass Flow W25 |
| WLcl/W25 | = 0.00000 | | LPT Rotor Cooling Air/Mass Flow W25 |
| XM6 | = 0.20000 | | Jet Pipe Inlet |
| A8 | = 0.11755 | m² | Geometric Nozzle Throat Area |
| WBld/W2 | = 0.00000 | | Bleed Air Flow/Mass Flow W2 |
| Ang8 | = 25.00 | deg | Nozzle Petal Angle |
| CD8 | = 0.95000 | | Nozzle Discharge Coefficient |
| P8/Pamb | = 3.93466 | | Nozzle Pressure Ratio |
| WlkLP/W25 | = **0.01100** | | HP Leakage to LPT Exit/Mass Flow W25 |
| Loading | = 100.00 | % | Burner Loading in % of the Cycle Design Point Value |
| e444 th | = 0.80074 | | Thermodynamic HP-Turbine Efficiency |
| WlkO/W25 | = 0.00000 | | HP Leakage to Overboard |
| P5/P2 | = 4.0150 | EPR | Engine Pressure Ratio |
| PWX | = 0.0 | kW | Power Offtake |
| Core Eff | = 0.4132 | | Core Efficiency |
| Prop Eff | = 0.0000 | | Propulsion Efficiency |

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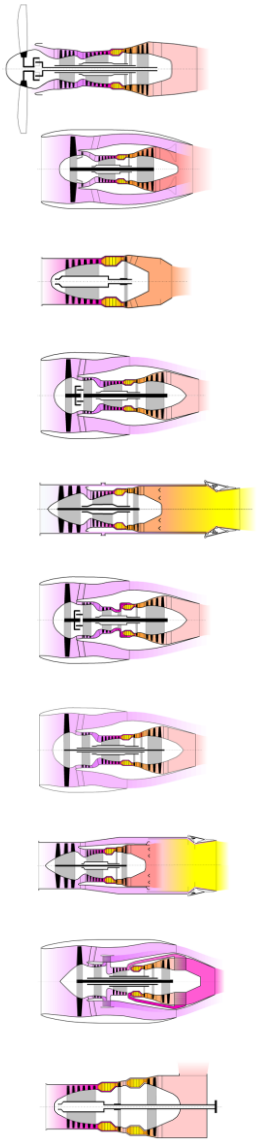
# Booster and HPC Operating Lines



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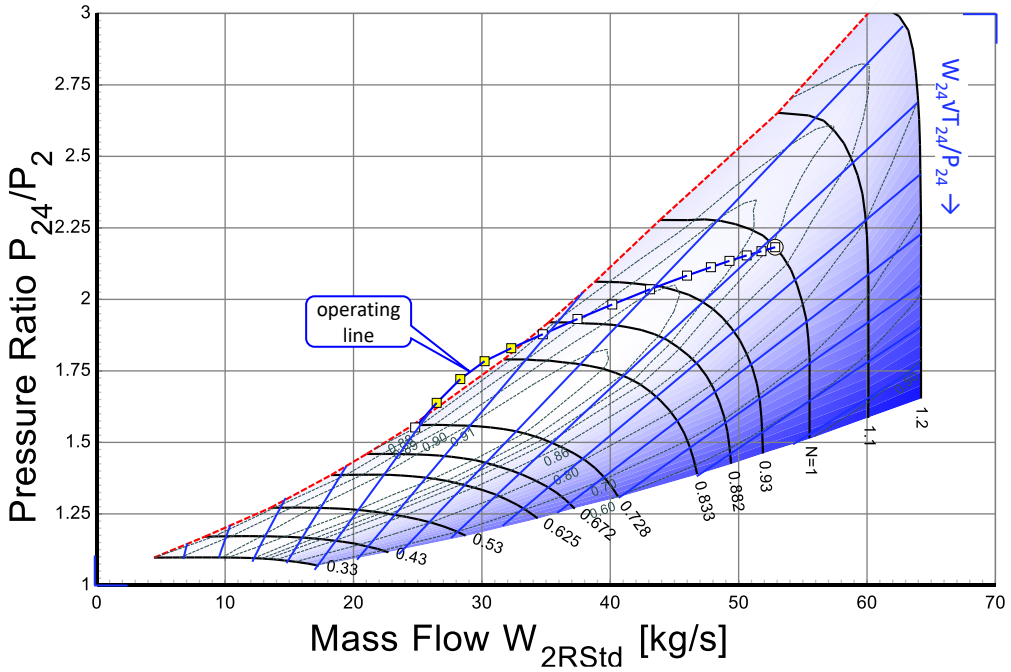


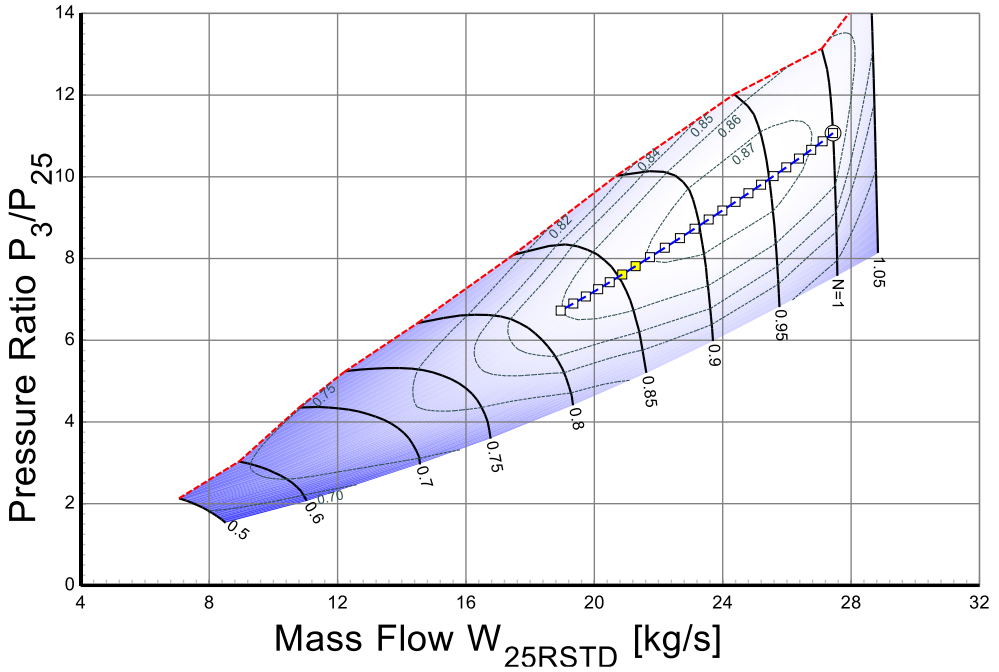

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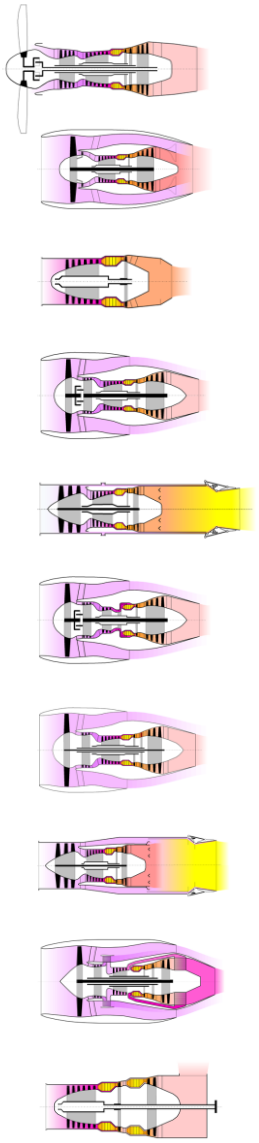
# From Gas Generator to a 2-Spool Turbofan

## CFM 56-3 on the Boeing 737-400



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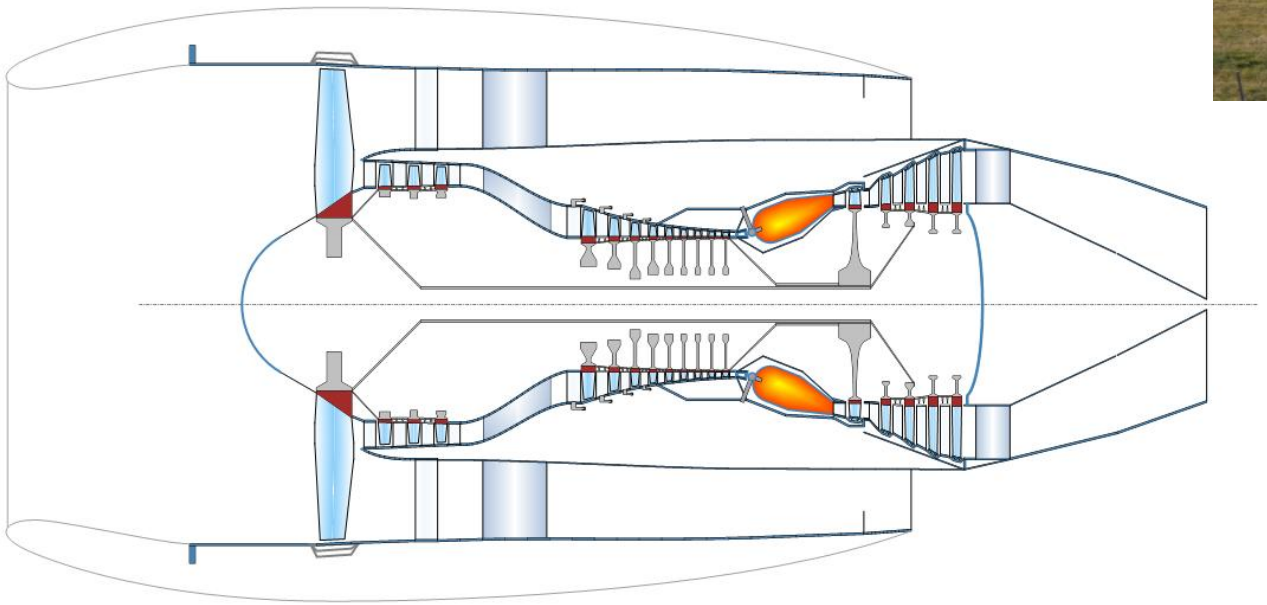
Unmixed Flow Turbofan



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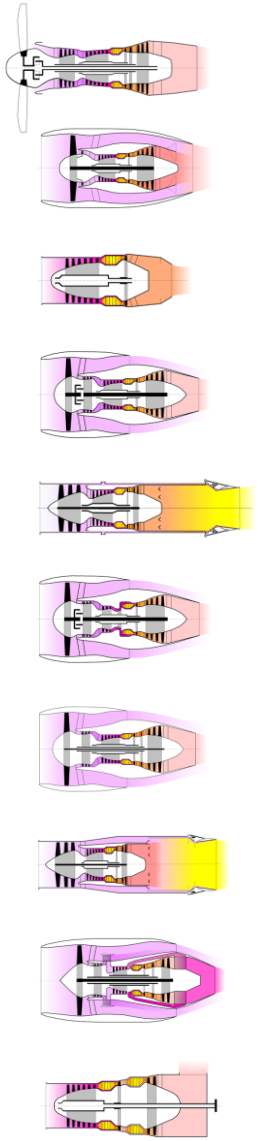
# CFM56-3 Reference Cycle



| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 2 | 313.702 | 288.15 | 101.325 | 313.702 |
| 13 | 260.854 | 338.16 | 167.694 | 170.746 |
| 21 | 52.847 | 288.24 | 101.426 | 52.803 |
| 22 | 52.847 | 288.24 | 101.426 | 52.803 |
| 24 | 52.847 | 369.90 | 221.093 | 27.441 |
| 25 | 52.847 | 369.90 | 221.093 | **27.441** |
| 3 | 52.847 | 770.80 | 2447.410 | 3.578 |
| 31 | 45.396 | 770.80 | 2447.410 | |
| 4 | 46.481 | 1577.55 | 2325.040 | 4.740 |
| 41 | 50.180 | 1522.88 | 2325.040 | **5.027** |
| 43 | 50.180 | 1162.51 | 541.051 | |
| 44 | 53.351 | 1140.69 | 541.051 | |
| 45 | 53.351 | 1140.69 | 541.051 | **19.879** |
| 49 | 53.351 | 862.24 | 147.971 | |
| 5 | 53.351 | 862.24 | 147.971 | 63.195 |
| 8 | 53.933 | 861.29 | 146.491 | 64.494 |
| 18 | 260.854 | 338.16 | 164.118 | 174.466 |
| Bleed | 0.000 | 770.80 | 2447.410 | |

| Efficiency | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Outer LPC | 0.8900 | 0.8975 | 1.000 | 1.655 |
| Inner LPC | 0.9000 | 0.8994 | 1.000 | 1.001 |
| IP Compressor | 0.8777 | 0.8903 | 1.001 | 2.180 |
| HP Compressor | **0.8677** | 0.9025 | 1.621 | **11.070** |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | 0.8250 | 0.7984 | 3.281 | 4.297 |
| LP Turbine | 0.9000 | 0.8843 | 1.063 | 3.656 |

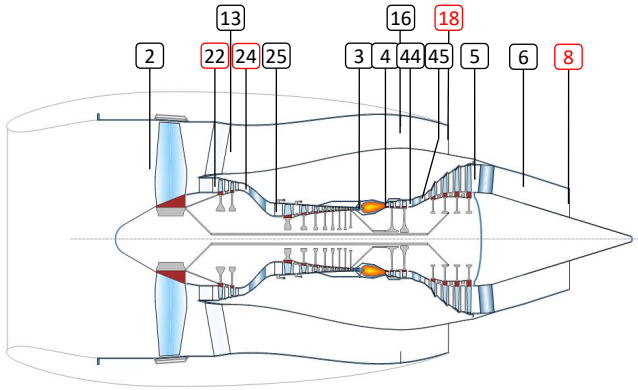
HP Spool mech Eff 0.9900 Speed 100.00 %
LP Sp0Ol mech Eff 1.0000 Speed 100.00 %
P22/P21=1.0000 P25/P24=1.0000 P45/P44=1.0000

Absolute HP PWX Input
Corrected HP PWX Input PwxHRstd 0.0
Corrected LP PWX Input PwxLRstd 0.0

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 43.124 | Generic |

| | | | |
|---|---|---|---|
| FN | = 99.37 | kN | Net Thrust |
| TSFC | = 10.9226 | g/(kN*s) | Thrust Specific Fuel Consumption |
| WF | = 1.08537 | kg/s | Fuel Flow |
| FN/W2 | = 316.8 | m/s | Specific Thrust |
| P5/P2 | = 1.4604 | EPR | Engine Pressure Ratio |
| Core Eff | = 0.4131 | | Core Efficiency |
| Prop Eff | = 0.0000 | | Propulsion Efficiency |
| BPR | = 4.9360 | | Bypass Ratio |
| P2/P1 | = 1.0000 | | Inlet Pressure Ratio |
| P3/P2 | = 24.15 | | Overall Pressure Ratio |
| P5/P2 | = 1.4604 | | Engine Pressure Ratio |
| P16/P13 | = 0.9787 | | Bypass Duct Pressure Ratio |
| P16/P6 | = 1.12033 | | Bypass Exit Pressure/Core Exit Pressure |
| P16/P2 | = 1.61972 | | Bypass Exit Pressure/Engine Inlet Pressure |
| P6/P5 | = 0.99000 | | Turbine Exit Duct Pressure Ratio |
| A8 | = 0.29364 | m² | Geometric Nozzle Throat Area |
| A18 | = 0.74236 | m² | Geometric Bypass Nozzle Throat Area |
| XM8 | = 0.75859 | | Nozzle Throat Mach No. |
| XM18 | = 0.85955 | | Bypass Nozzle Throat Mach No. |
| WBLD/W25 | = 0.00000 | | Bleed Air Flow/Mass Flow W25 |
| CD8 | = 0.97884 | | Nozzle Discharge Coefficient |
| CD18 | = 0.99183 | | Bypass Nozzle Discharge Coefficient |
| V18/V8,id | = 0.70907 | | Ideal Jet Velocity Ratio |
| Wreci/W25 | = 0.00000 | | Recirculating Air/Air Mass Flow W25 |
| WBLD/W22 | = 0.00000 | | Bleed Air Flow/Mass Flow W22 |
| WlkLP/W25 | = **0.01100** | | HP Leakage to LPT Exit/Mass Flow W25 |
| Loading | = 100.00 | % | Burner Loading in % of the Cycle Design Point Value |
| WCHN/W25 | = **0.07000** | | HPT Nozzle Guide Vane Cooling Air / W25 |
| WCHR/W25 | = **0.06000** | | HPT Rotor Cooling Air / W25 |
| WCLN/W25 | = 0.00000 | | LPT Nozzle Guide Vane Cooling Air / W25 |
| WCLR/W25 | = 0.00000 | | LPT Rotor Cooling Air / W25 |

| | | | |
|---|---|---|---|
| PWX | = 0.00 | kW | Power Offtake |
| PWXH | = 0.0 | kW | Second Power Offtake from HP Spool |
| PWXL | = 0.0 | kW | Power Offtake Low Pressure Spool |



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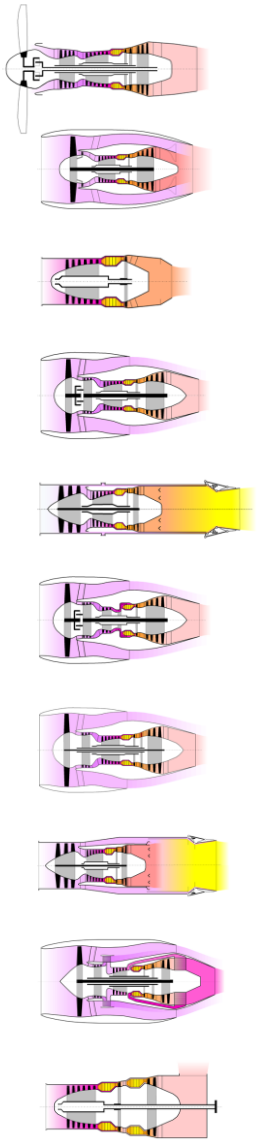
# Fan Operating Line



The fan operating line of a high bypass ratio turbofan is dominated by the flow characteristics of the bypass nozzle

- only a small part of the air enters the core engine

The corrected flow through the bypass nozzle depends on the pressure ratio $P_{18}/P_{amb}$ which is all the lower the higher the bypass ratio is.

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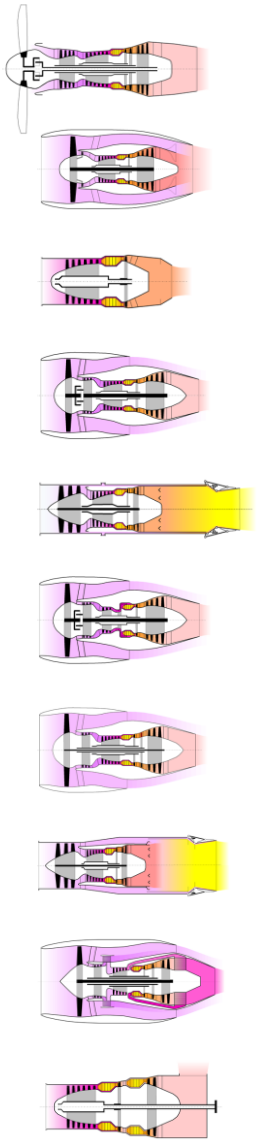
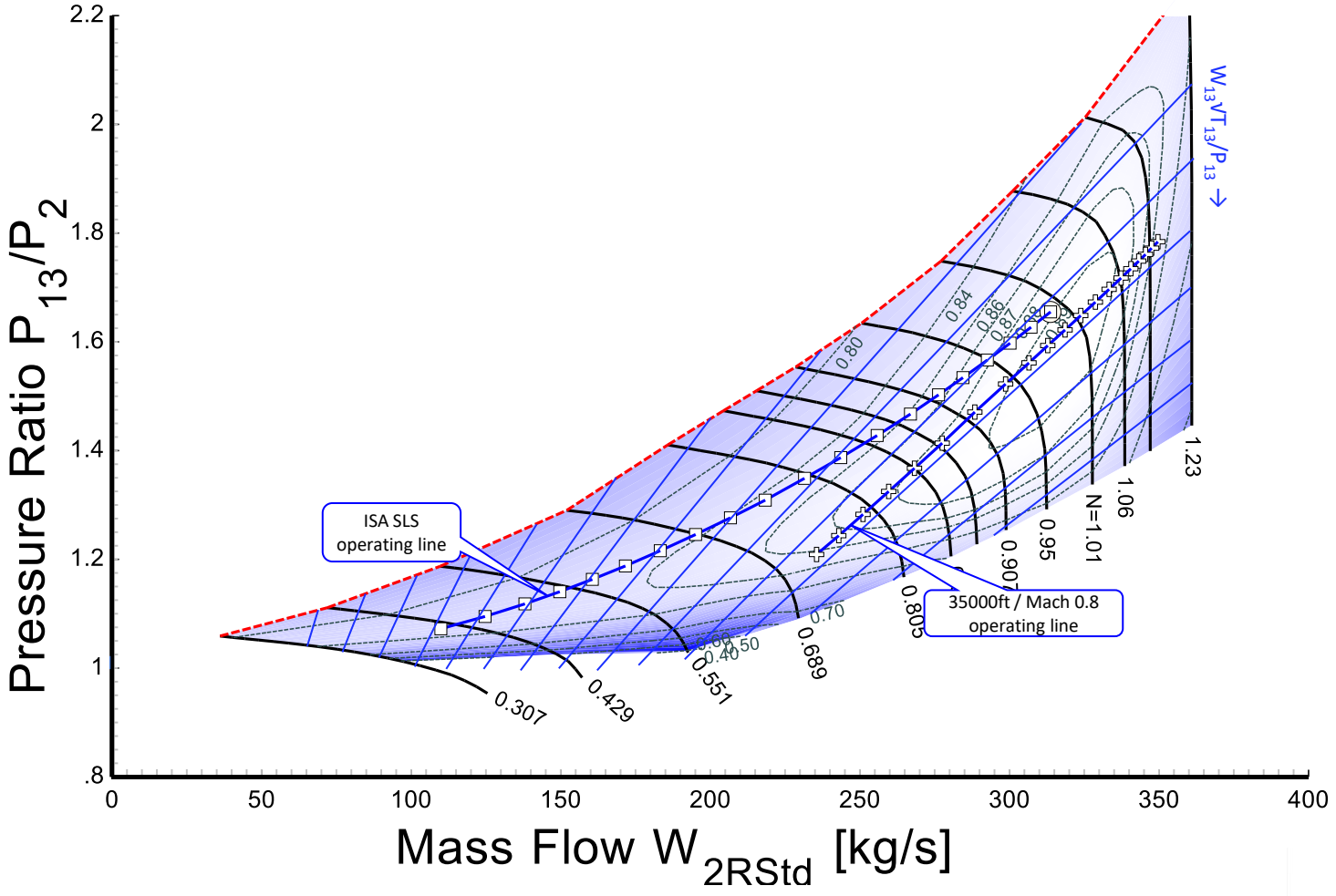
# CFM56-3 Fan Operating Lines
## ISA SLS and 35000ft Mach 0.8





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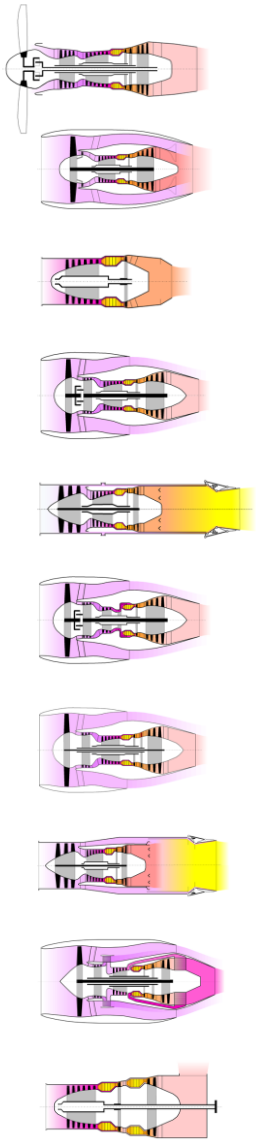
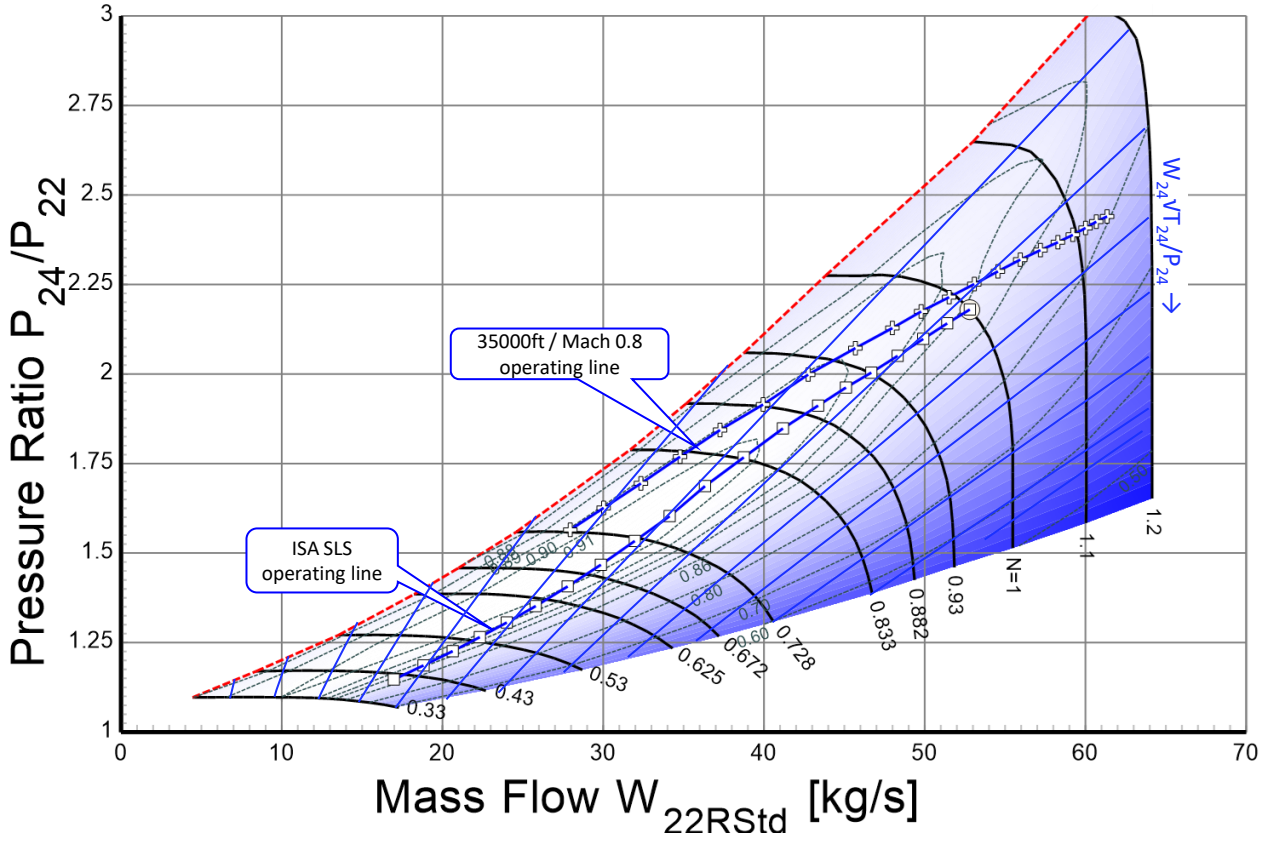
# CFM56-3 Booster Operating Lines
## ISA SLS and 35000ft Mach 0.8





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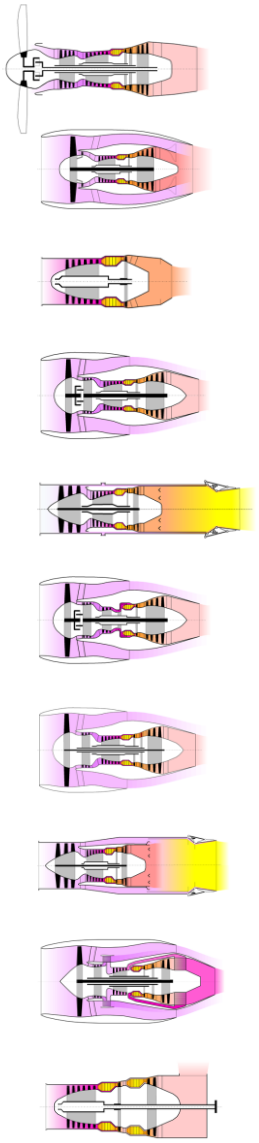
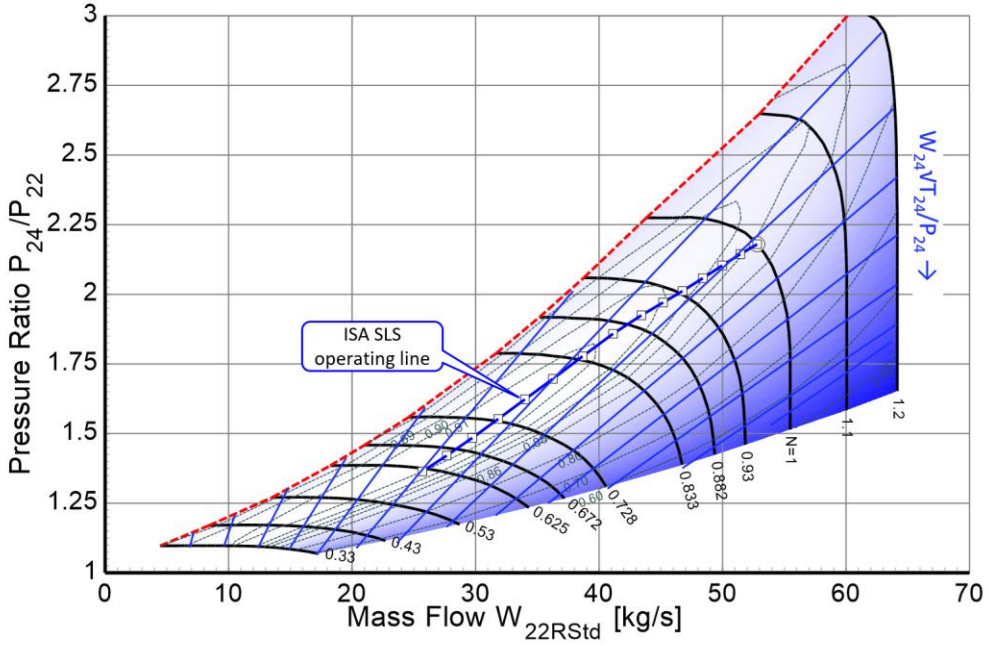
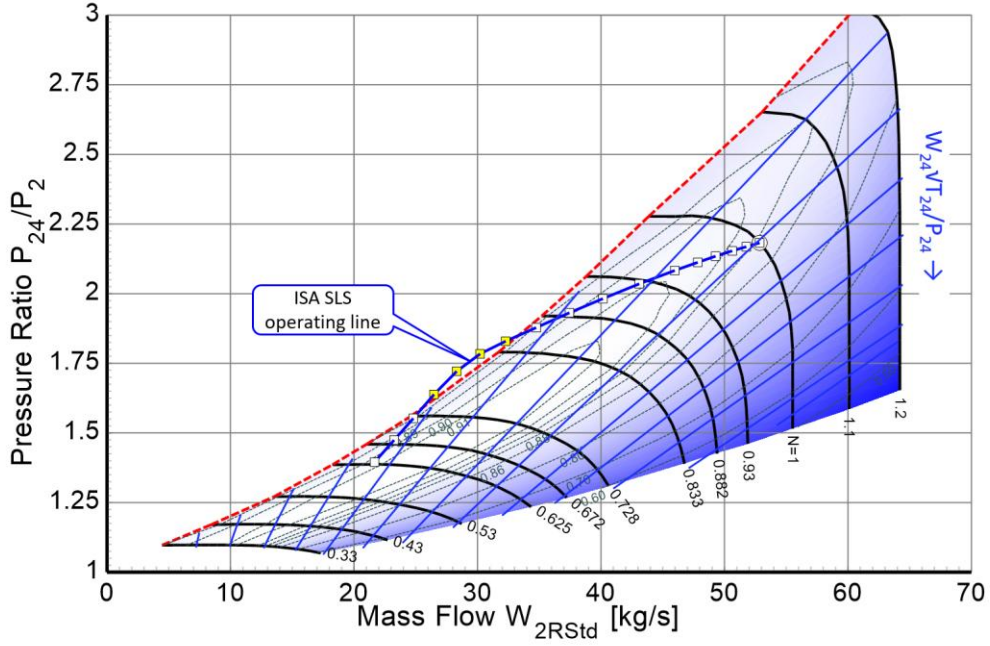
# Booster Operating Lines



Turbofan




2 Spool Turbojet



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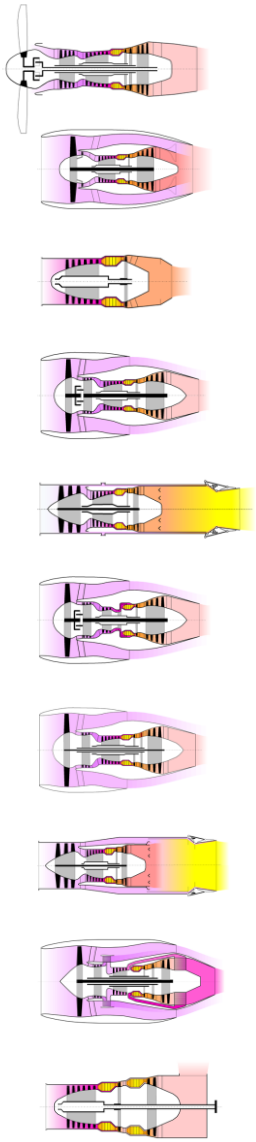
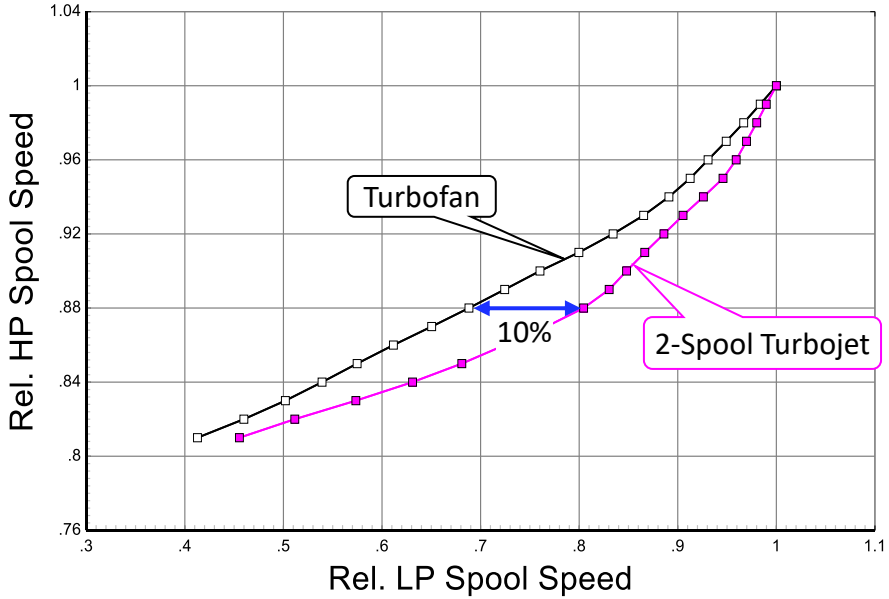
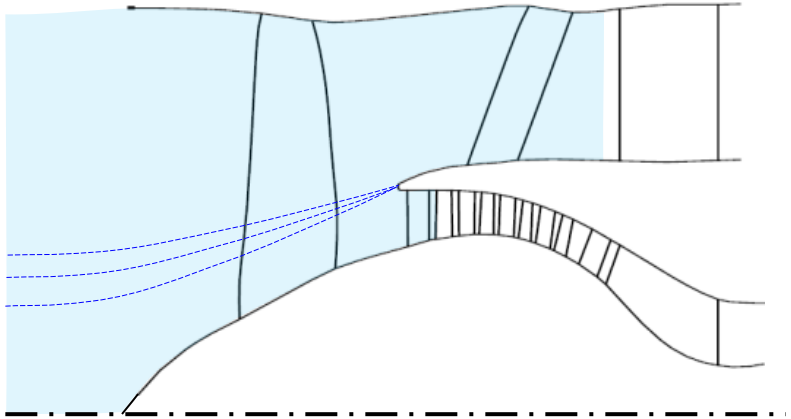


# Why are the Booster Operating Lines Different?



- Fan and booster are on the same spool
- In case of the Turbofan, the Fan dictates the booster spool speed
- In case of the 2-Spool Turbojet, the LP speed is higher

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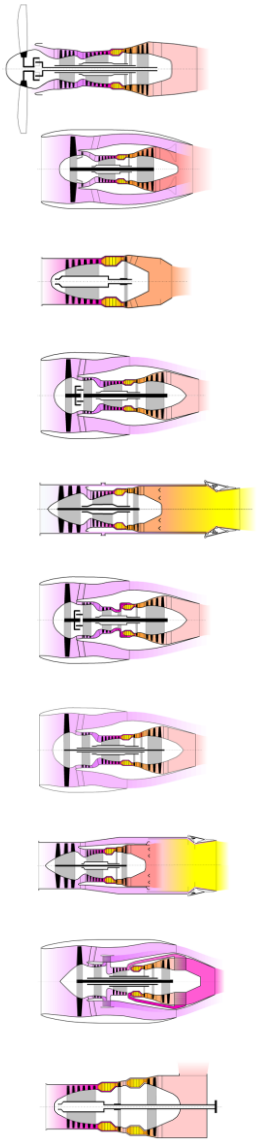
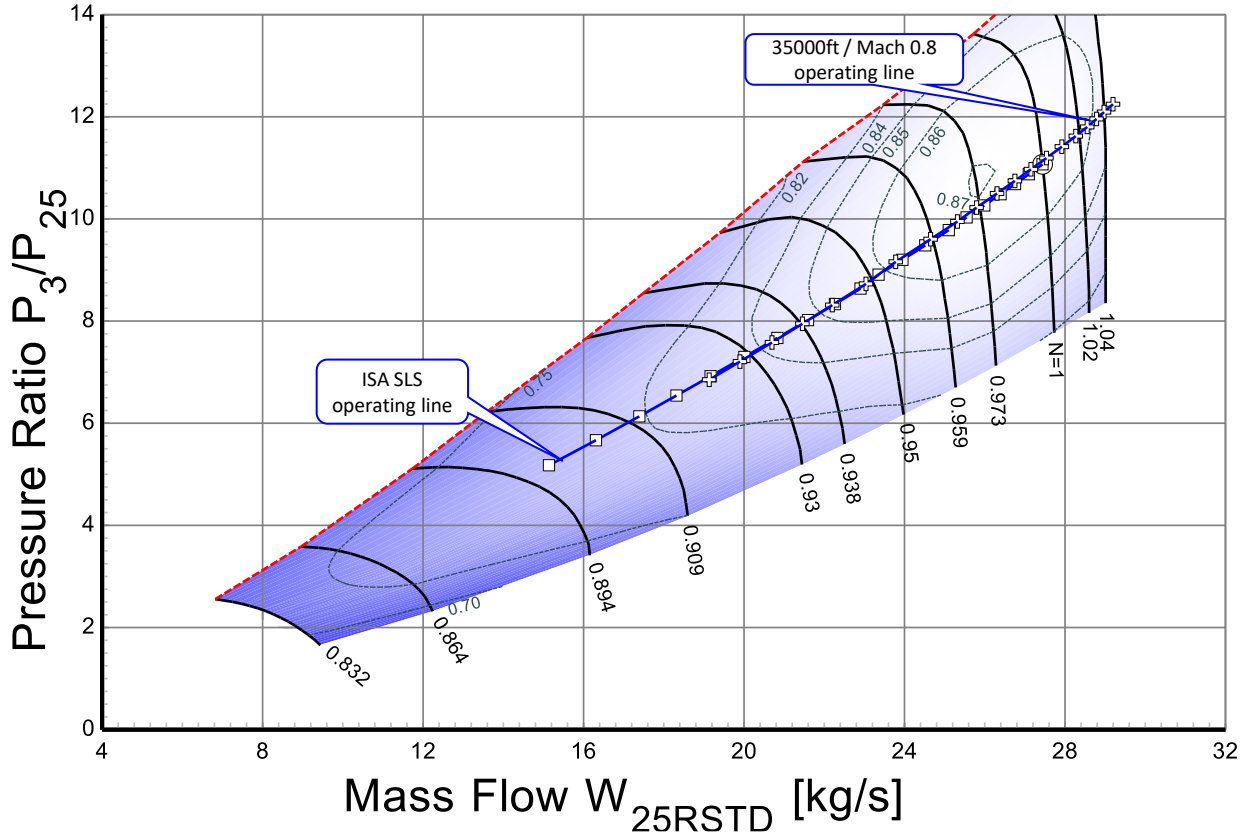
# CFM56-3 HPC Operating Lines
## ISA SLS and 35000ft Mach 0.8





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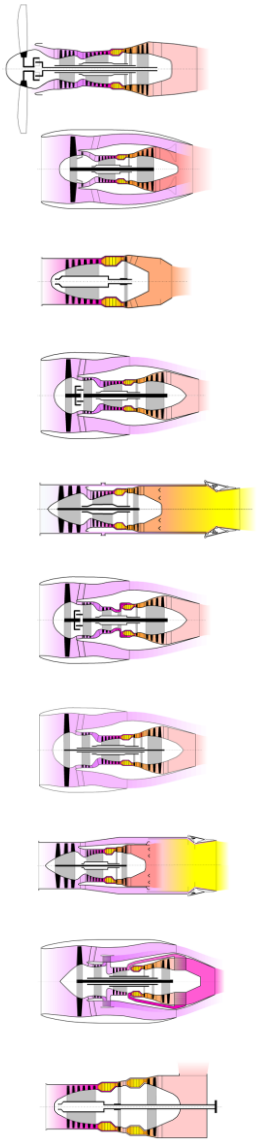
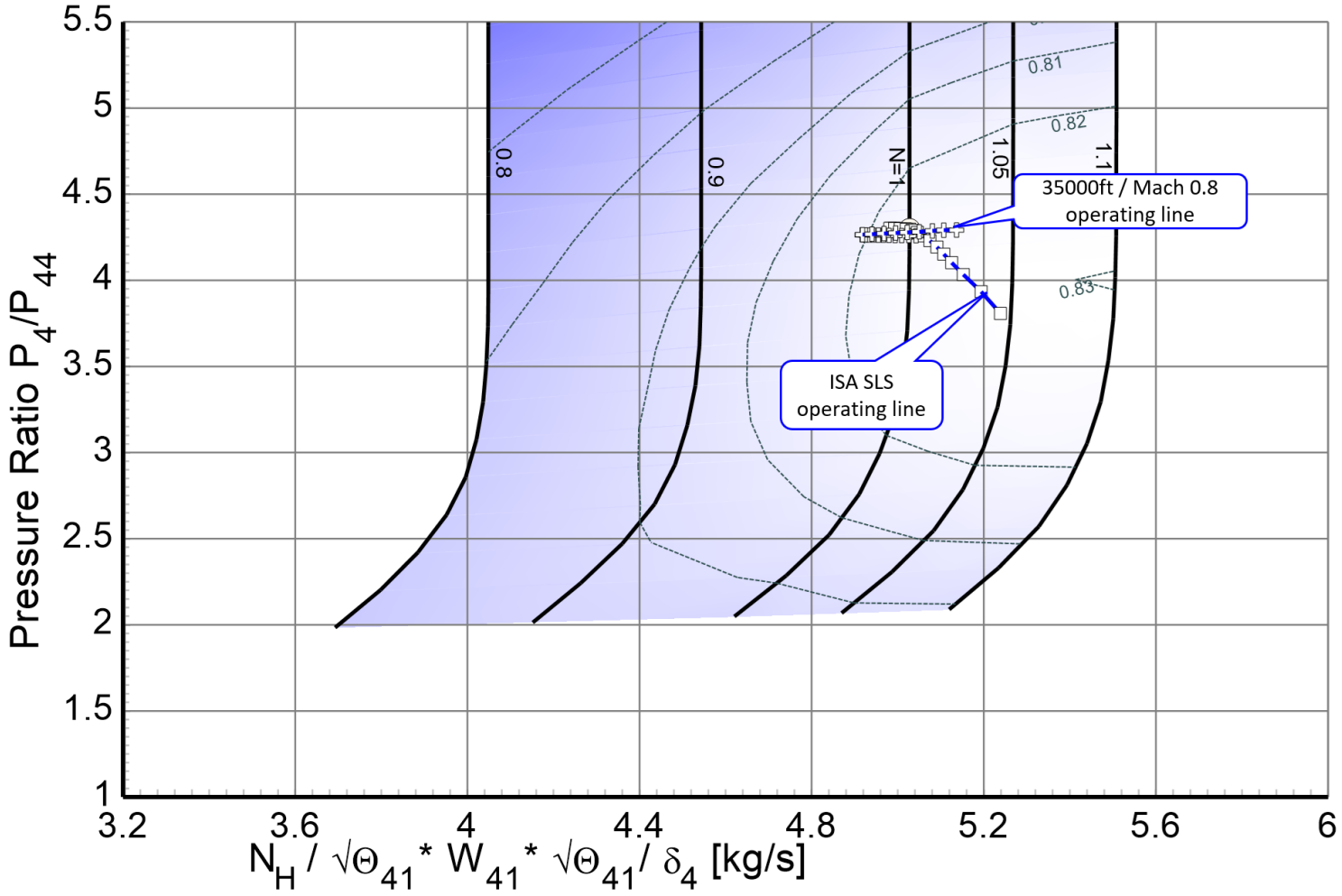
# CFM56-3 HPT Operating Lines
## ISA SLS and 35000ft Mach 0.8





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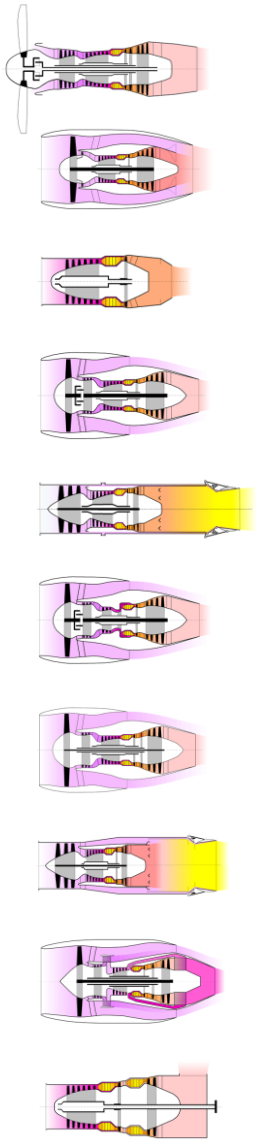
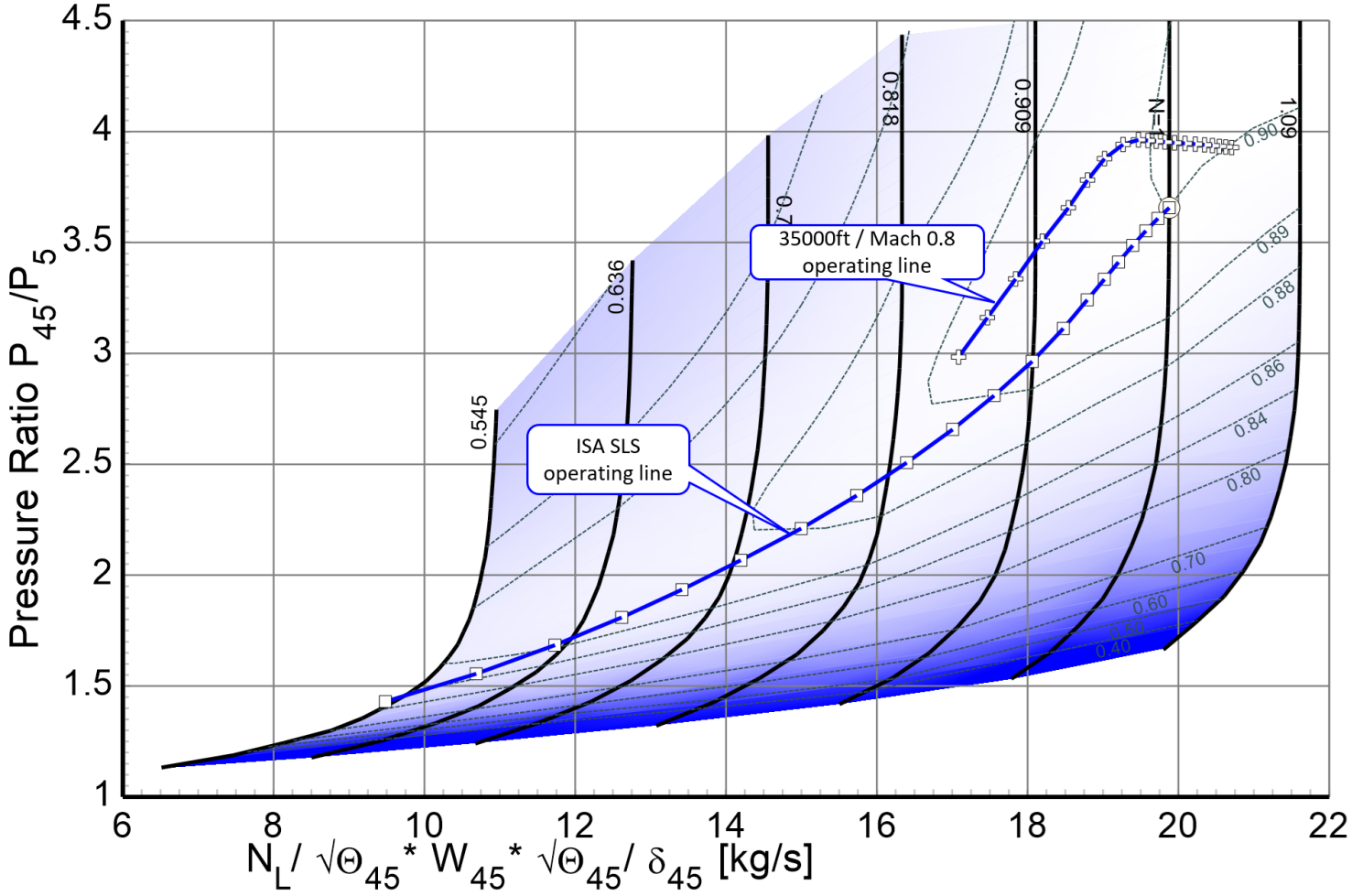
# CFM56-3 LPT Operating Lines
## ISA SLS and 35000ft Mach 0.8





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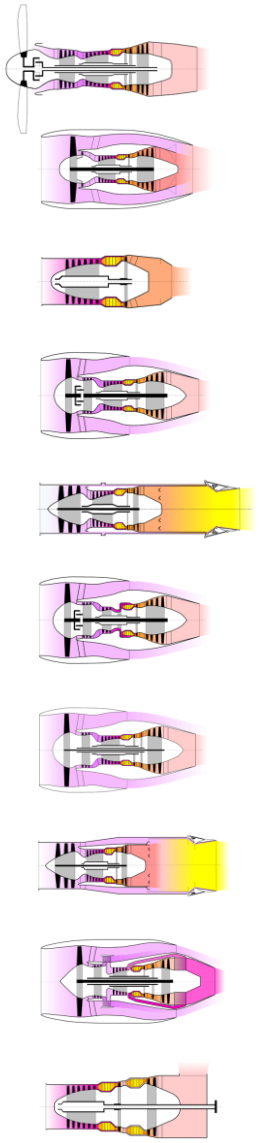
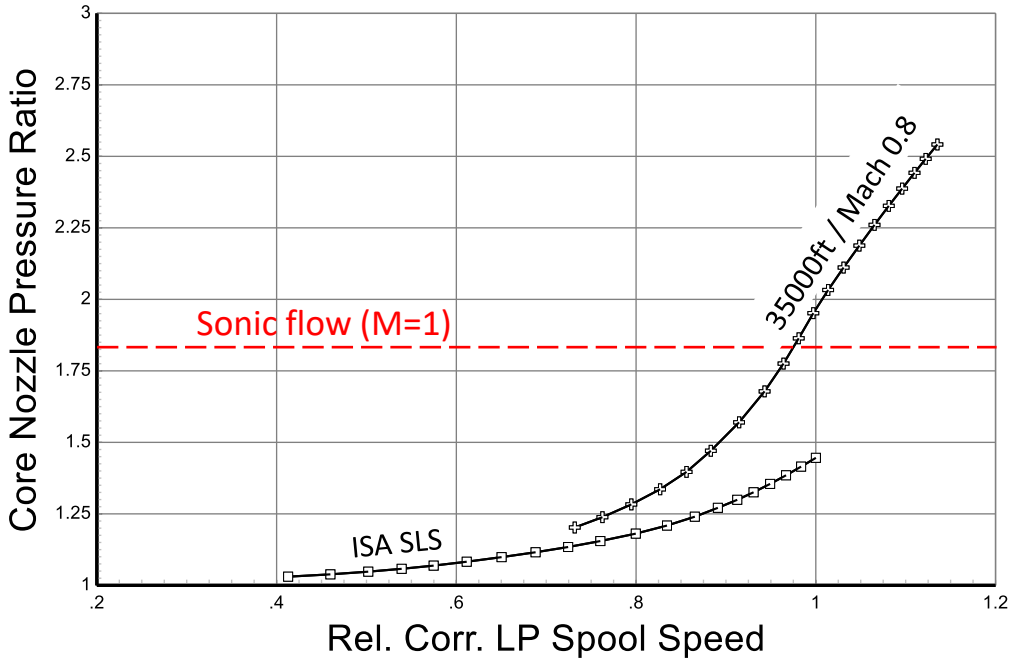
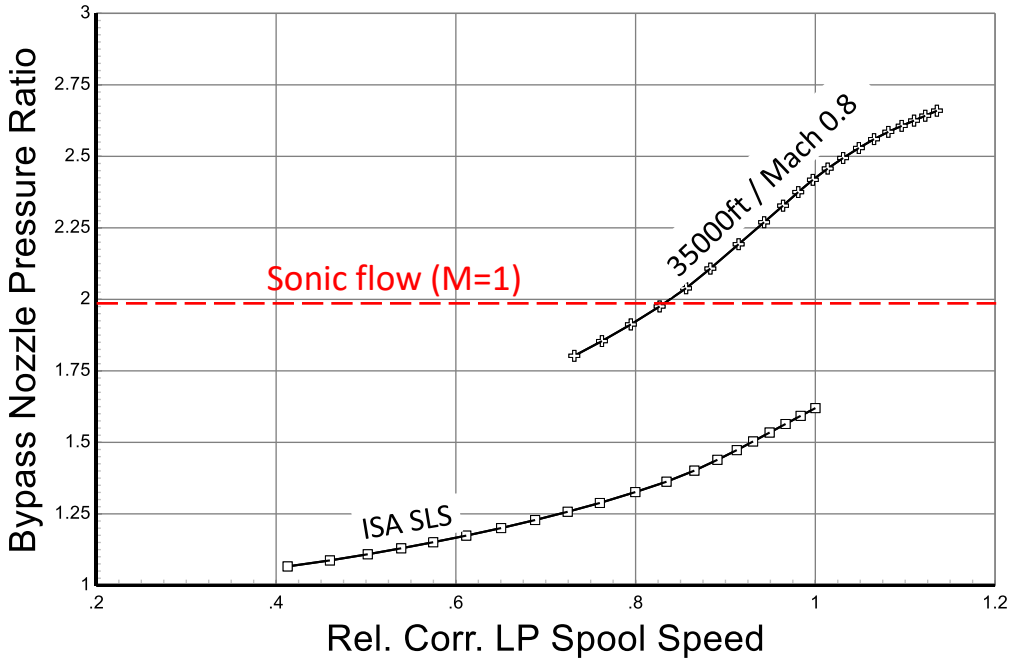
# CFM56-3 Nozzle Pressure Ratios
## ISA SLS and 35000ft Mach 0.8





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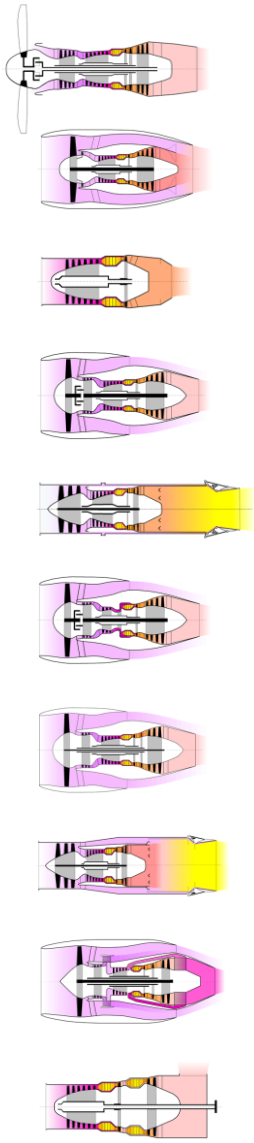
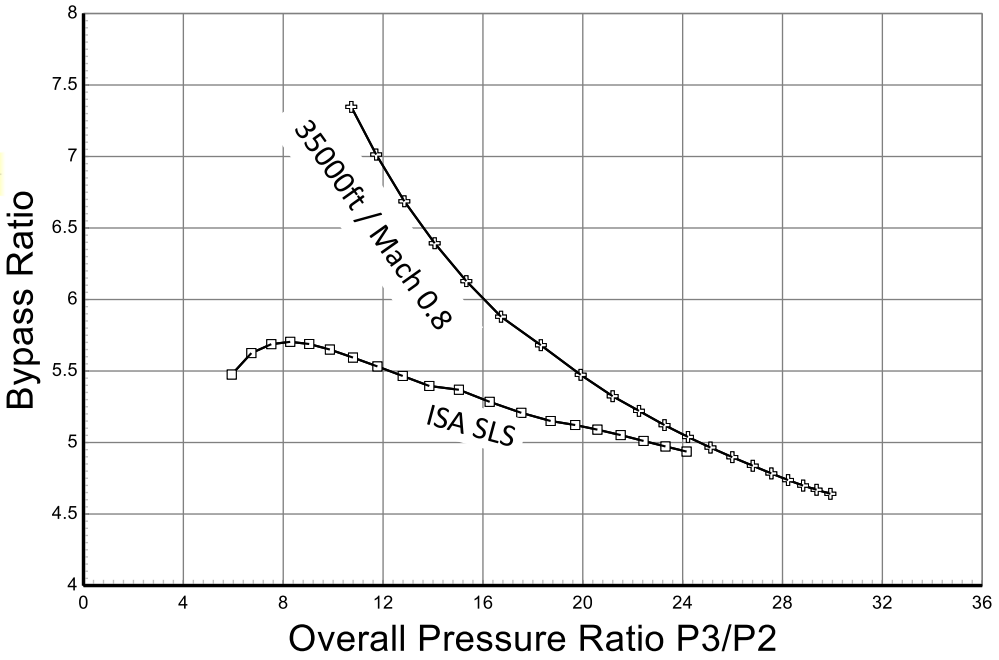
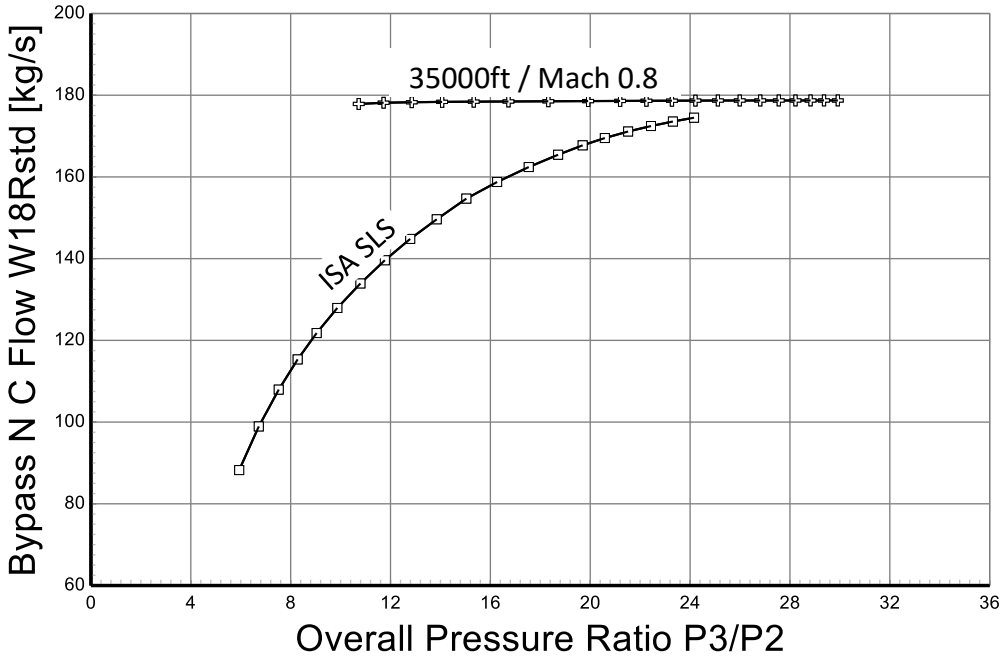
# Bypass Ratio
## Dominated by the Fan Exit Corrected Flow





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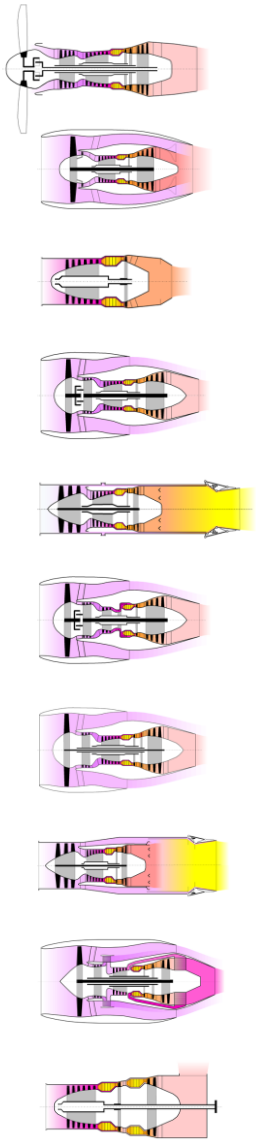
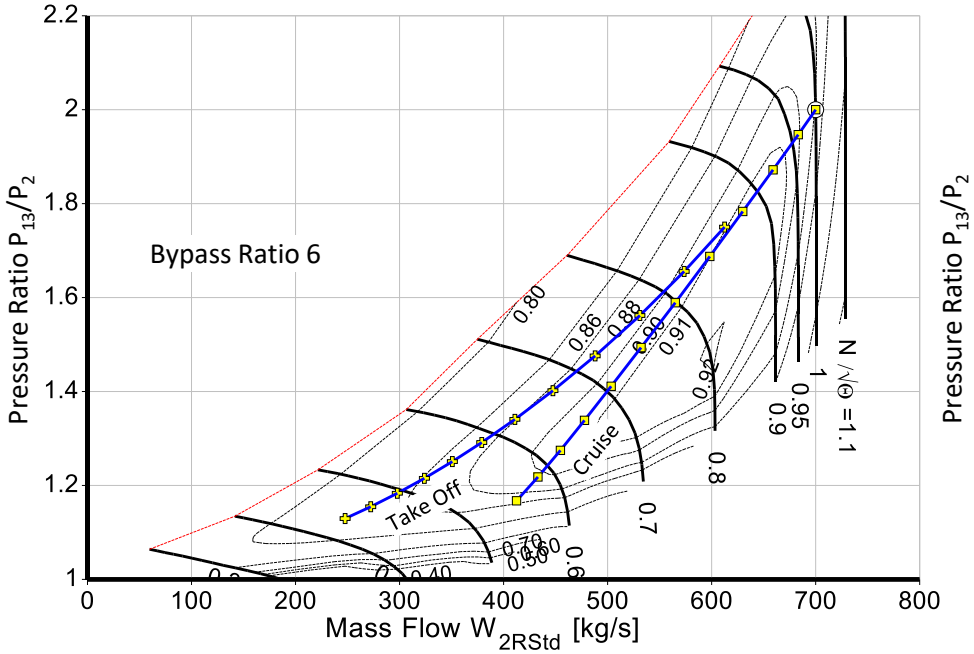
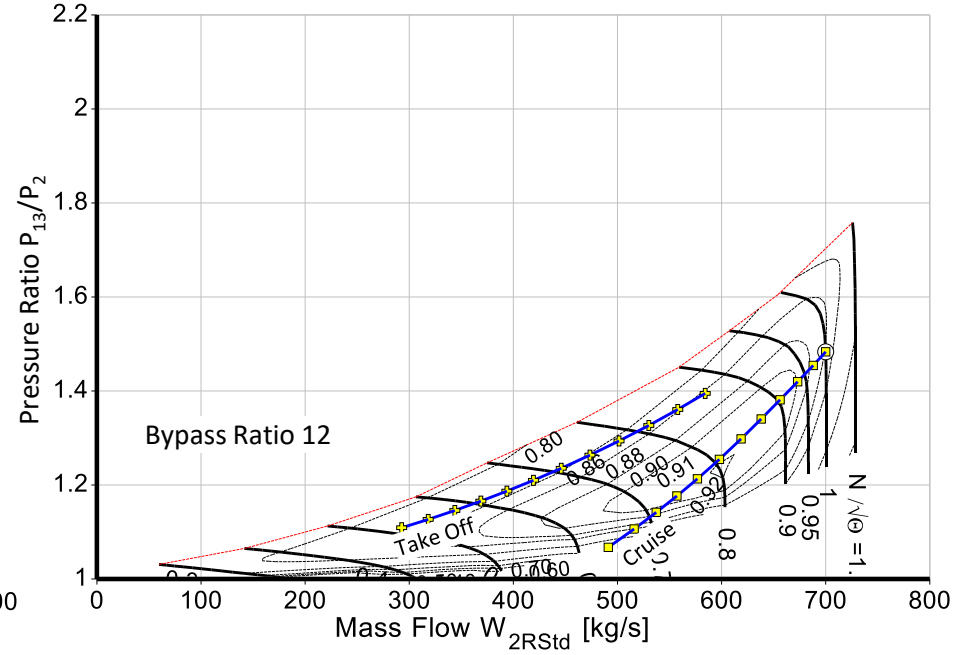
# Fan Operating Lines
## Effect of Design Bypass Ratio





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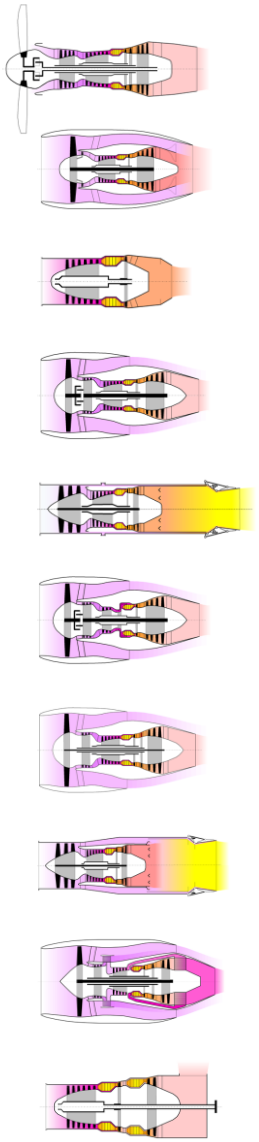

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# Outline

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components

Cooperation of the Components

Gas Generator +

## Variable Geometry

- Compressor
  - Gas Generator
  - Single Spool Engine (Power Generation)
- Turbine
  - Turboshaft with Heat Exchanger
- Nozzle
  - Low Bypass Ratio Turbofan

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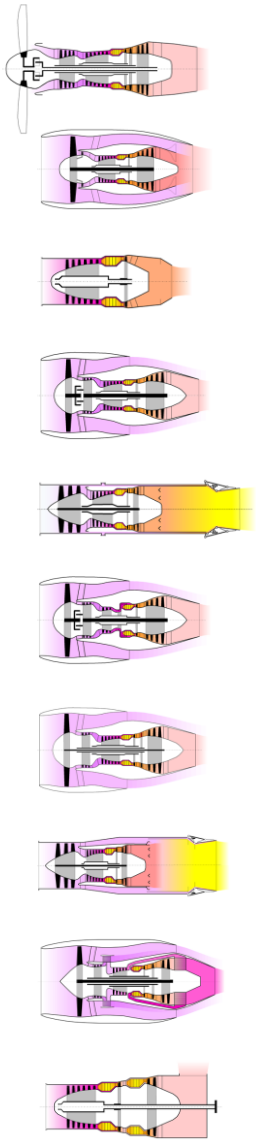
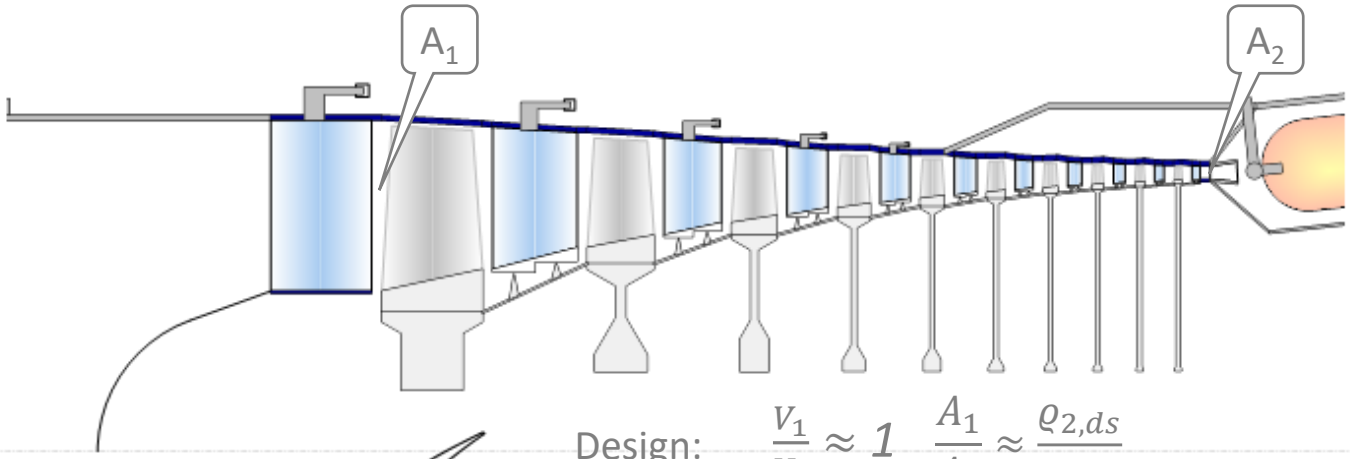
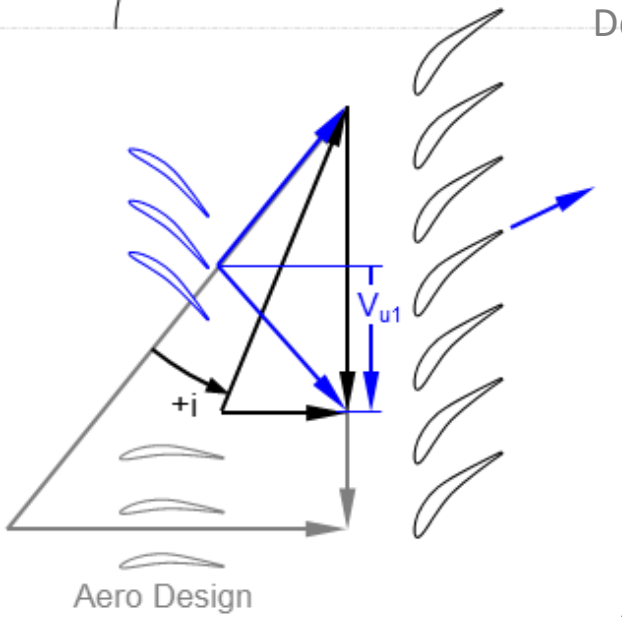
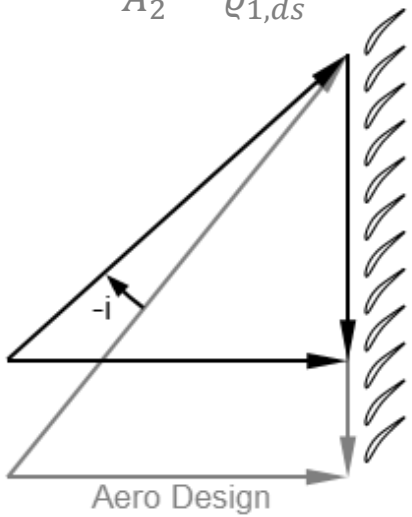
# The Compressor Off-Design Problem






Design: $\frac{V_1}{V_2} \approx 1 \quad \frac{A_1}{A_2} \approx \frac{\varrho_{2,ds}}{\varrho_{1,ds}}$




Off Design: $\frac{V_1}{V_2} \approx \frac{\varrho_2}{\varrho_1}\frac{A_2}{A_1}$

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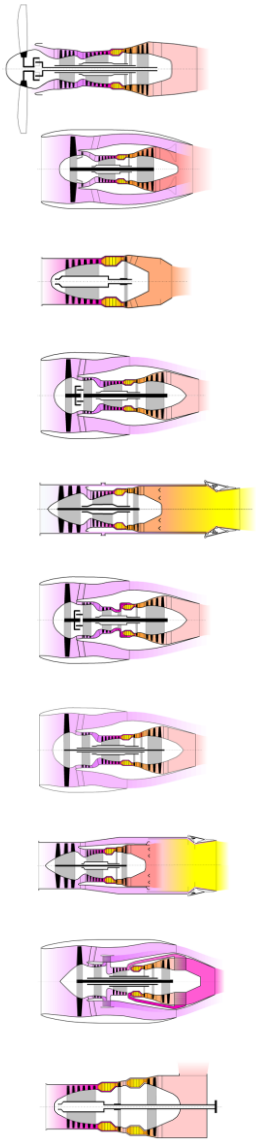
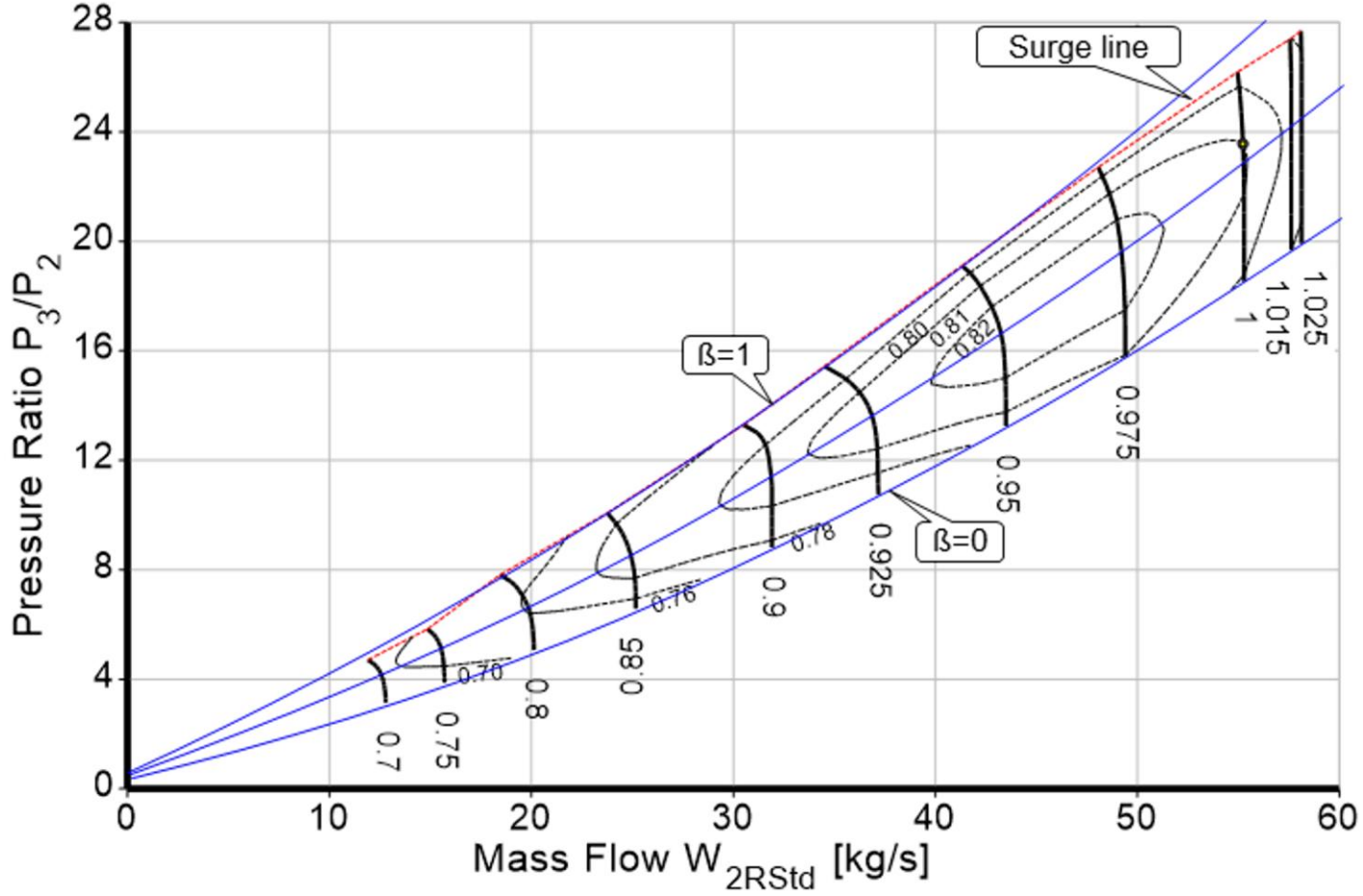
17m - 17p

# 10 Stage Compressor






Ref. Energy Efficient Engine: High Pressure Compressor Component Performance Report, NASA CR-168245, 1975

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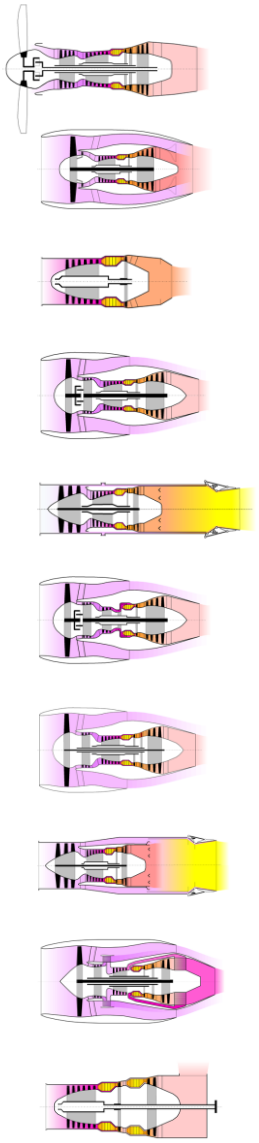
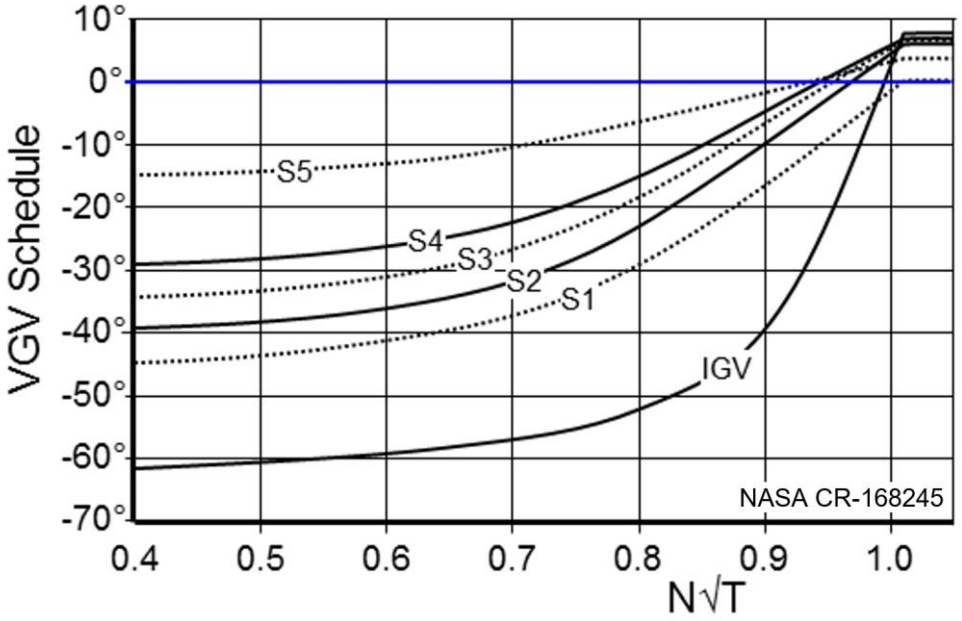
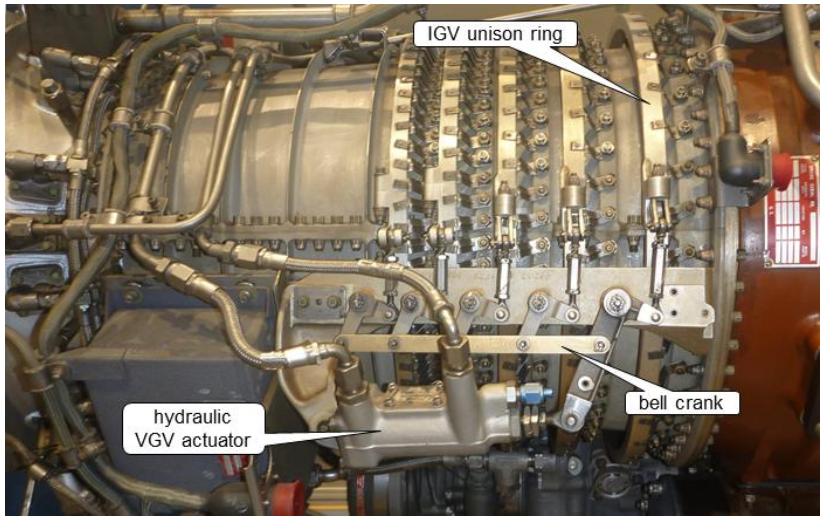
# Variable Guide Vane Schedule






Hardware Example in the MTU Museum

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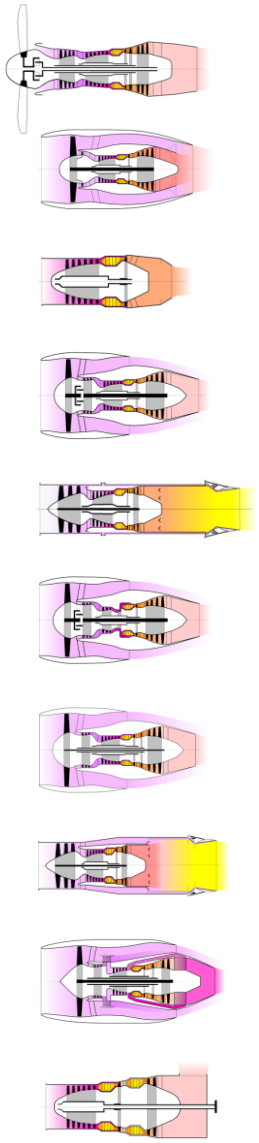
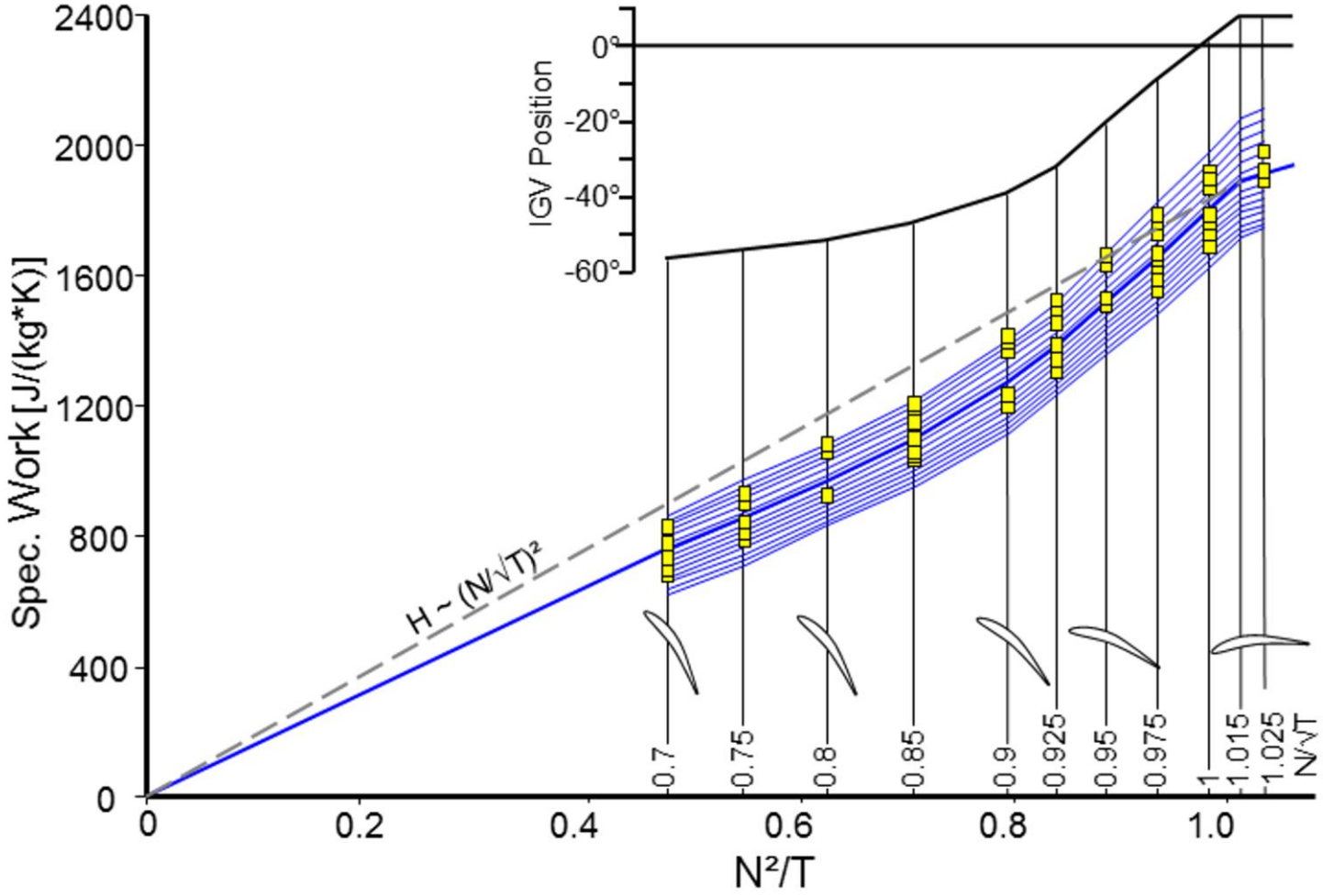
15m - 15p

# VGV Effect on Map





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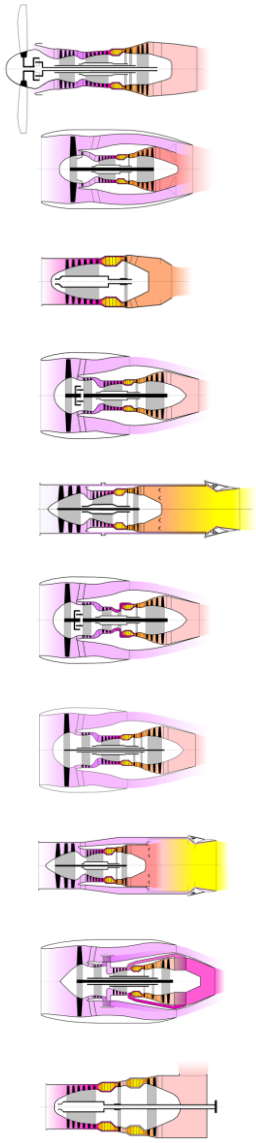
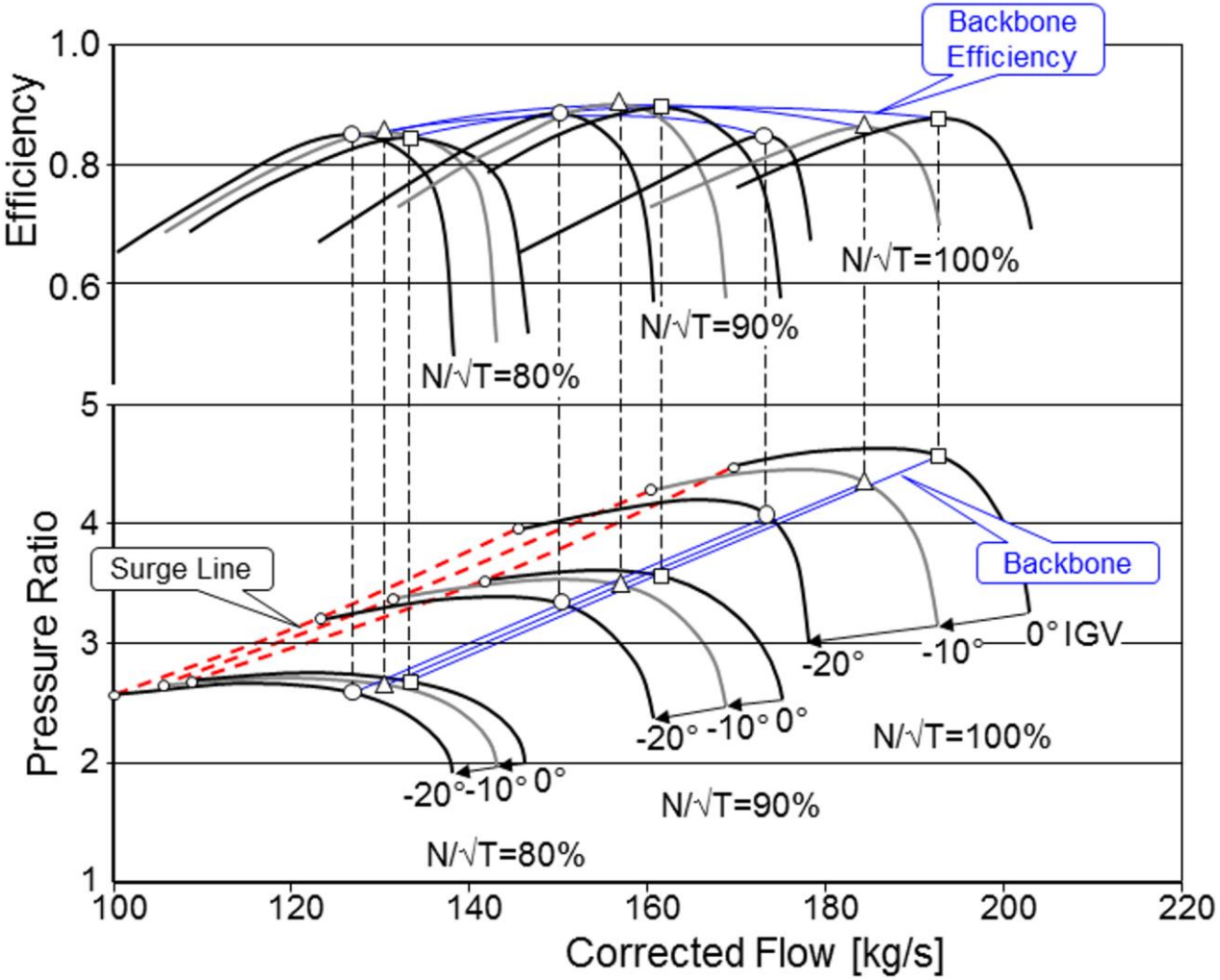
# VGV Effects on a Compressor Map






Ref. ASME GT-2002-30443

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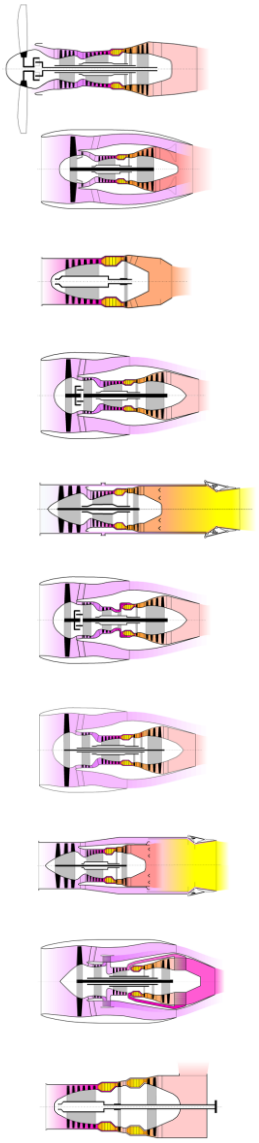
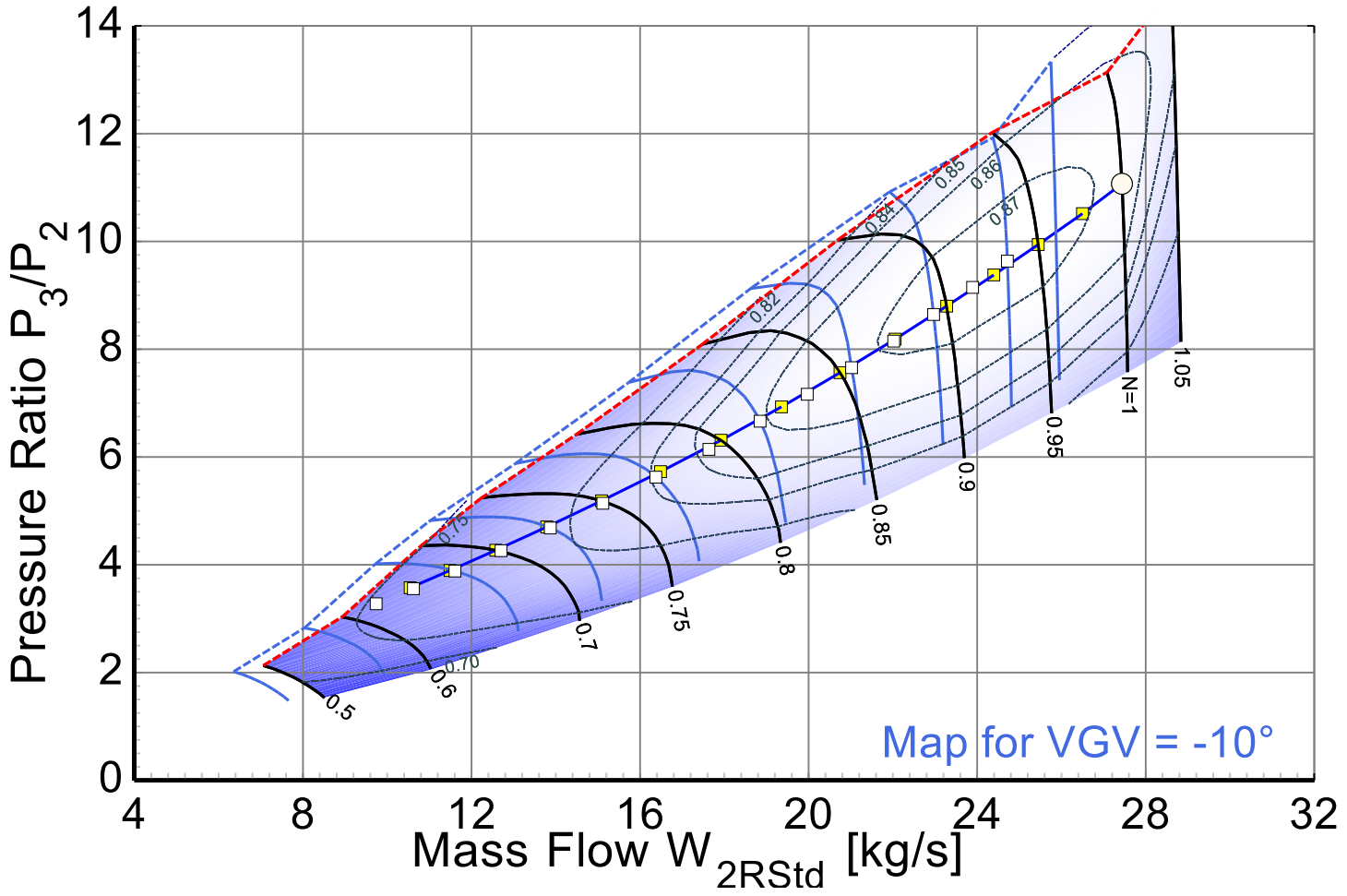
# Effect of VGV's on the Compressor Operating Line





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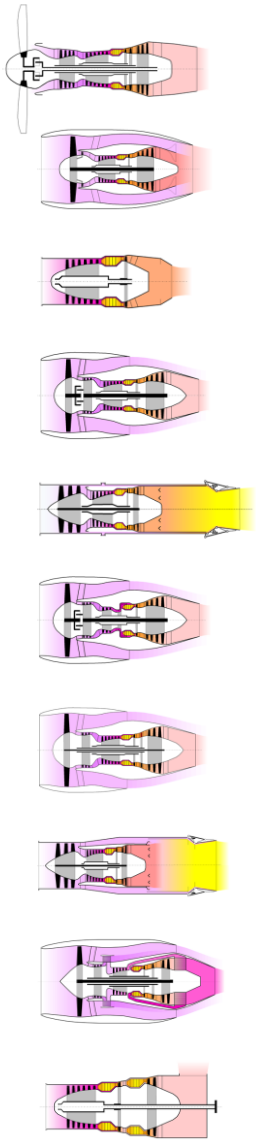

# Variable Guide Vanes

- VGV position affects surge line but not the operating line
- Changes speed for a given mass flow
- Changes mass flow for a given speed
- At maximum power, the VGVs are fully open. Only closing is possible.
- Closing the VGV’s increases the speed for a given mass flow
- If the spool speed is given, then changing the VGV position changes thrust (jet engine) or power (turboshaft)

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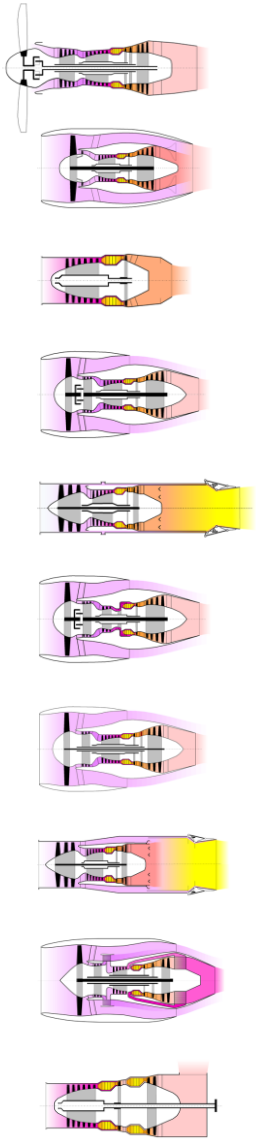

# Single Spool Turboshaft

Gas Turbine Design and Performance

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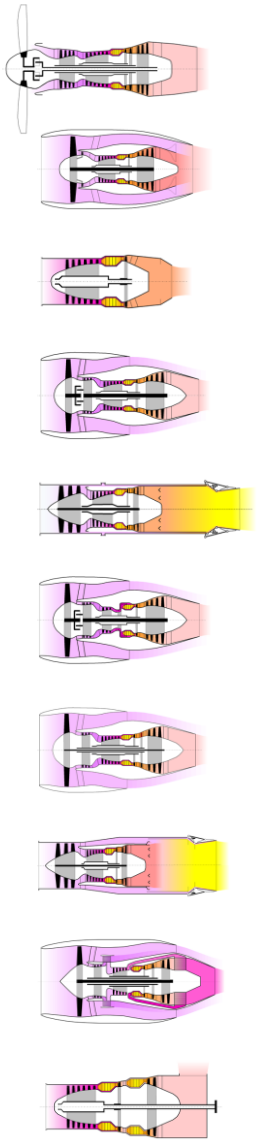
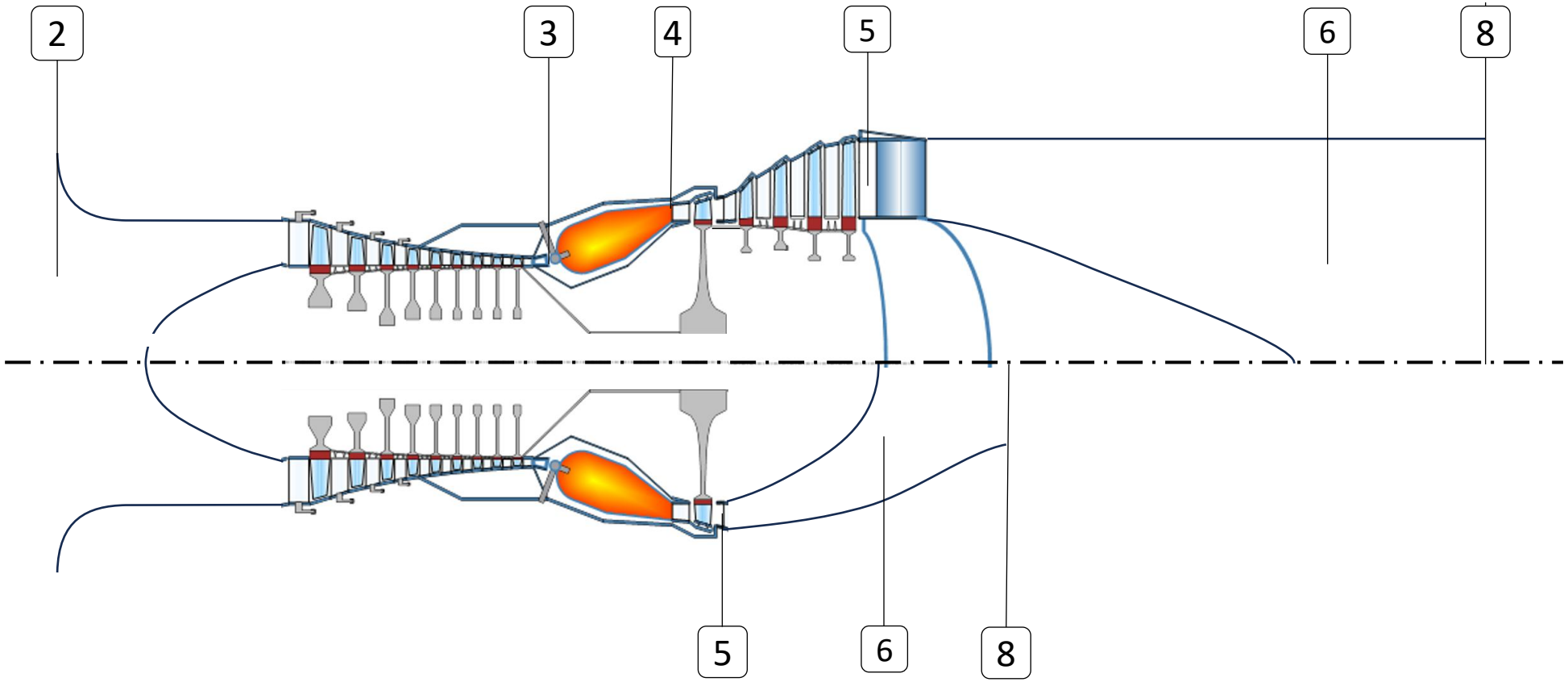
# From Gas Generator to Single Spool Turboshaft





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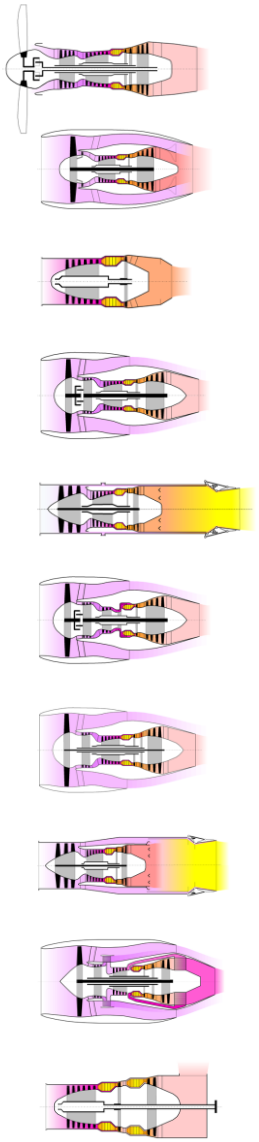
# CFM56-3 Core as Single Spool Turboshaft

## Power Generation: Simple Cycle



| W Station | T kg/s | P K | WRstd kPa | kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 1 | 27.436 | 288.15 | 101.325 | |
| 2 | 27.436 | 288.15 | 101.325 | **27.436** |
| 3 | 27.436 | 609.27 | 1121.668 | 3.604 |
| 31 | 23.568 | 609.27 | 1121.668 | |
| 4 | 23.989 | 1250.00 | 1065.584 | 4.751 |
| 405 | 25.910 | 1206.10 | 1065.584 | **5.040** |
| 41 | 27.226 | 1179.21 | 1065.584 | 5.237 |
| 49 | 27.226 | 711.42 | 106.495 | |
| 5 | 27.556 | 710.25 | 106.495 | 41.162 |
| 6 | 27.556 | 710.25 | 104.365 | |
| 8 | 27.556 | 710.25 | 104.365 | 42.002 |
| Coolg | 0.000 | 609.26 | 1121.665 | |
| Bleed | 0.302 | 609.26 | 1121.665 | |

| Efficiencies: | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Compressor | **0.8677** | 0.9033 | 1.000 | **11.070** |
| Burner | 0.9995 | | | 0.950 |
| Turbine | 0.9085 | 0.8800 | 2.016 | 10.006 |
| Generator | 1.0000 | | | |

| Spool mech Eff | 0.9999 | Nom Spd | 12727 rpm |
|---|---|---|---|

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | | |
|---|---|---|---|
| **PWSD** | = **5699.5** | **kW** | **Shaft Power Delivered** |
| FN_res | = 0.00 | | FN_res |
| PSFC | = 0.2662 | kg/(kW*h) | Power Specific Fuel Consumption |
| Heat Rate | = 11386.0 | kJ/(kW*h) | Fuel Flow * Fuel Heating Value / Shaft Power Delivered |
| Therm Eff | = 0.3162 | | Thermal Efficiency |
| WF | = 0.42148 | kg/s | Fuel Flow |
| NGV Exit 5 HPT | | | |
| s NOx | = 0.24987 | | NOx Severity Parameter |
| incidence | = 0.00 | deg | incidence |
| XM8 | = 0.2094 | | Nozzle Throat Mach No. |
| A8 | = 0.5020 | m² | Geometric Nozzle Throat Area |
| P8/Ps8 | = 1.03000 | | Exhaust Pressure Ratio |
| Wcl_L/W2 | = 0.00000 | | Low Pressure Cooling Air / W2 |
| WBld/W2 | = **0.01100** | | Bleed Air Flow/Mass Flow W2 |
| P2/P1 | = 1.00000 | | Inlet Pressure Ratio |
| WCLN/W2 | = 0.11800 | | LPT Nozzle Guide Vane Cooling Air / W2 |
| WCLR/W2 | = 0.01200 | | LPT Rotor Cooling Air / W2 |
| Loading | = 100.00 | % | Burner Loading in % of the Cycle Design Point Value |
| e45 th | = 0.90501 | | Thermodynamic Turbine Efficiency |
| PW_gen | = 5699.5 | kW | Electric Power |
| P6/P5 | = 0.9800 | | Turbine Exit Duct Pressure Ratio |

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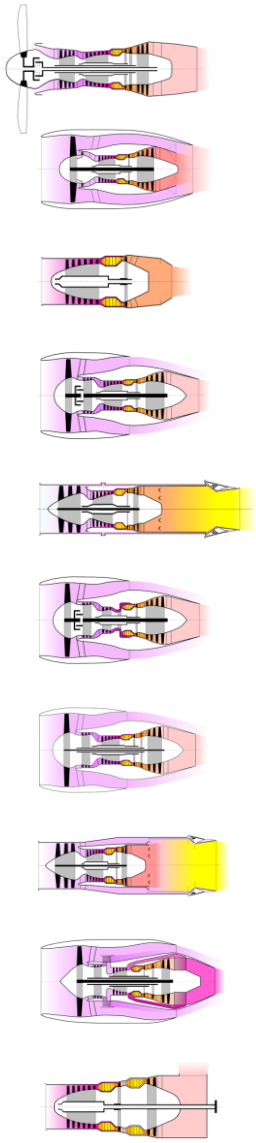

# Single Spool Gas Turbine
## Operating Characteristics

- Single spool gas turbines as used in power gerneration are operated at constant spool speed because they drive an electric generator.
- The mass flow at a given spool speed can be adjusted with the variable guide vanes of the compressor
- The turbine pressure ratio is (nearly) equal to the compressor pressure ratio
- The $T_4/T_2$ lines in the compressor map are as usual

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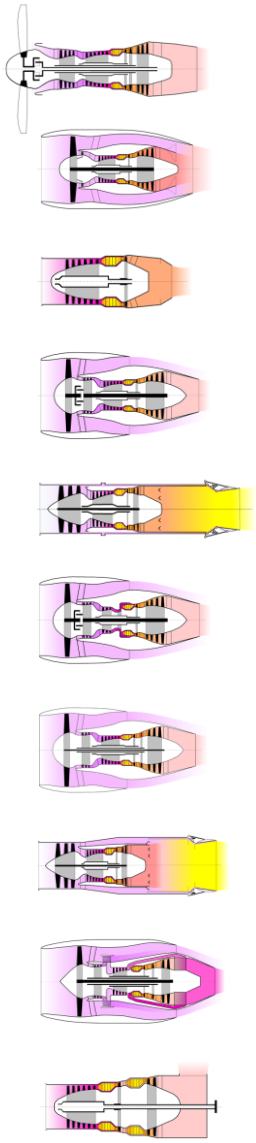
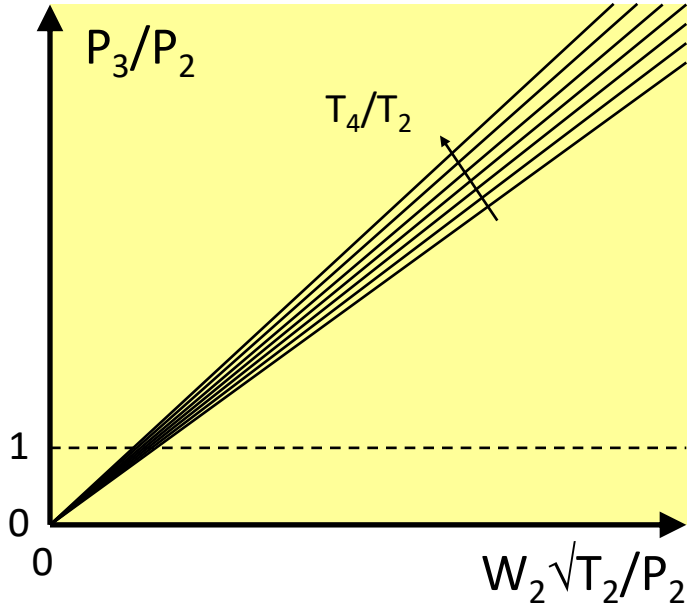
# Mass Flow Continuity 1
## Compressor and Turbine



$$\frac{W_2 * \sqrt{T_2}}{P_2} = \frac{W_4 * \sqrt{T_4}}{A_4 * P_4} * A_4 * \frac{P_4}{P_3} * \frac{W_2}{W_4} * \frac{P_3}{P_2} * \sqrt{\frac{T_2}{T_4}}$$

$$\frac{P_3}{P_2} = const_A * \frac{W_2 * \sqrt{T_2}}{P_2} * \sqrt{\frac{T_4}{T_2}}$$

The $T_4/T_2$ lines are straight lines that go through the origin in the compressor map!



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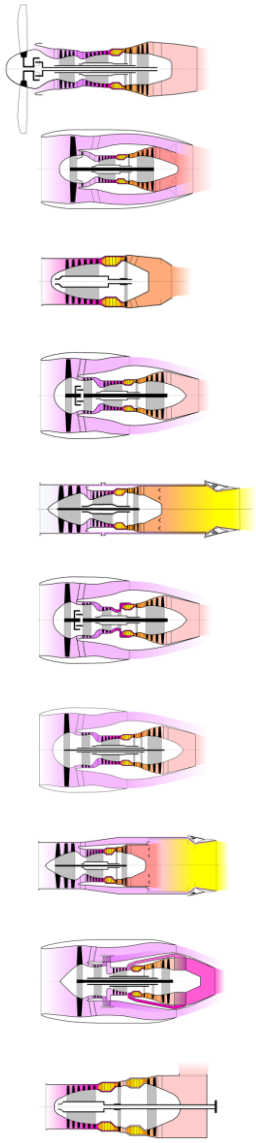
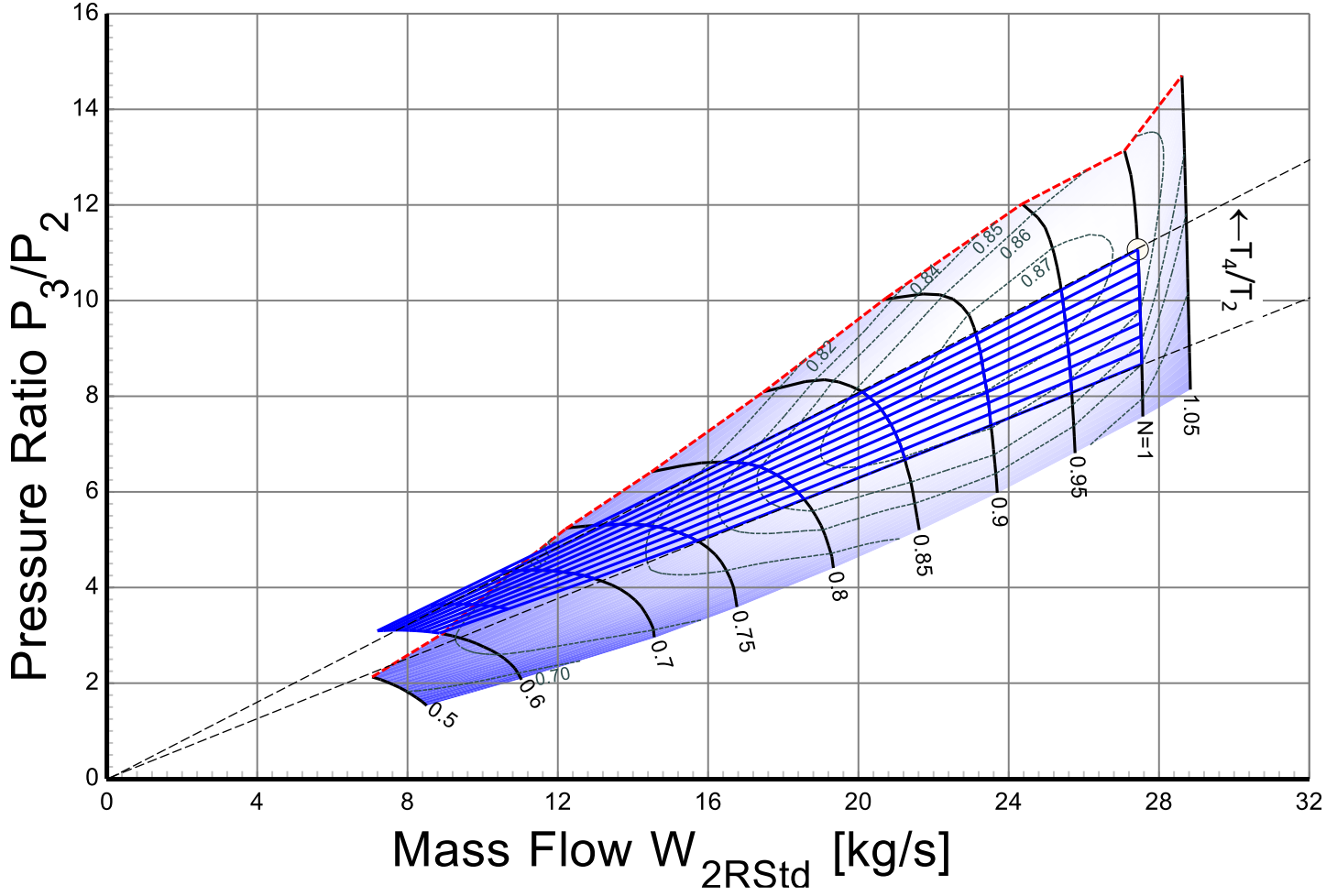
# $T_4/T_2$ Lines
## Full Cycle Calculation





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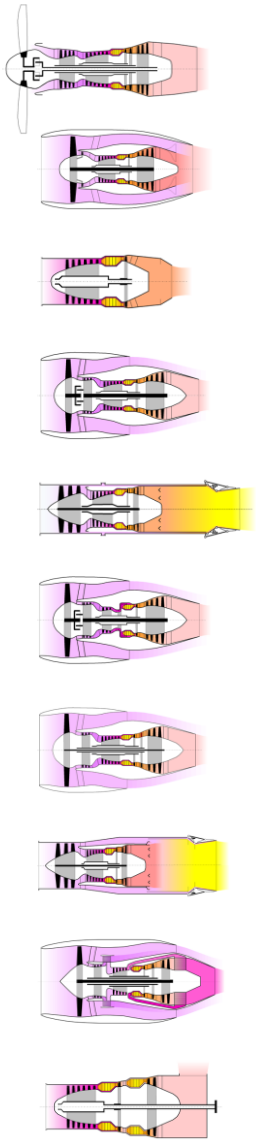
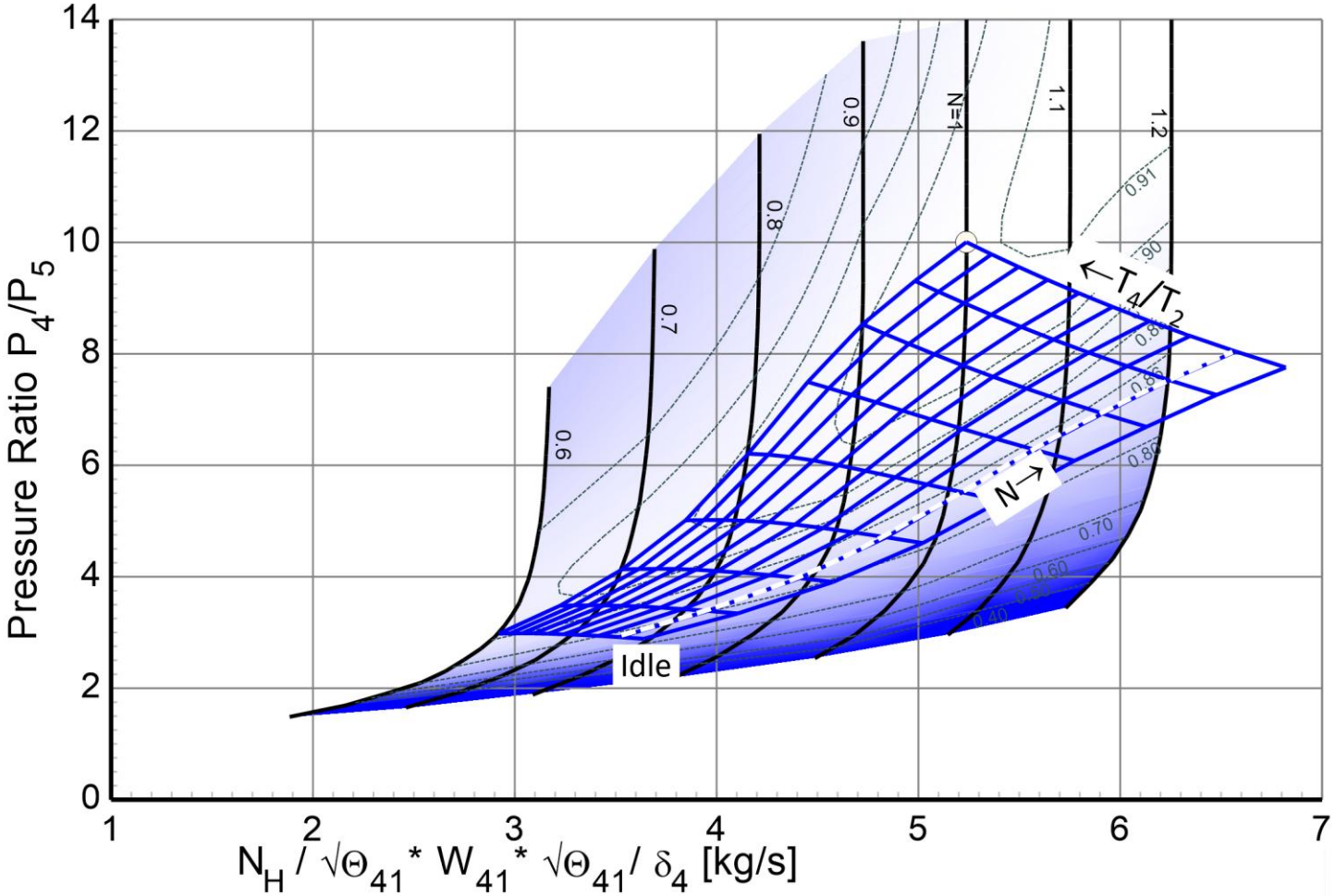
# Variable Speed
## Startup





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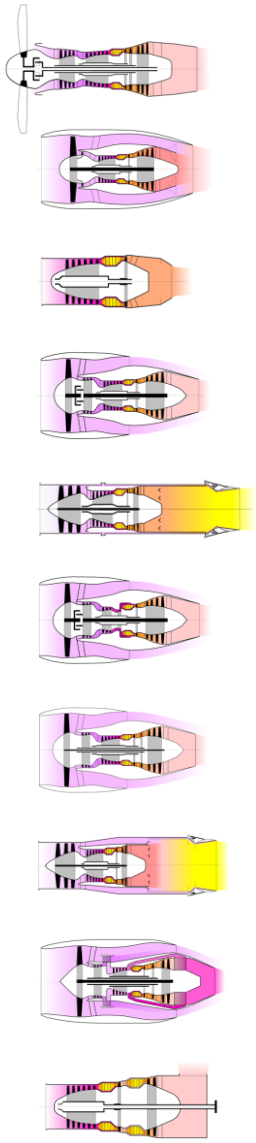
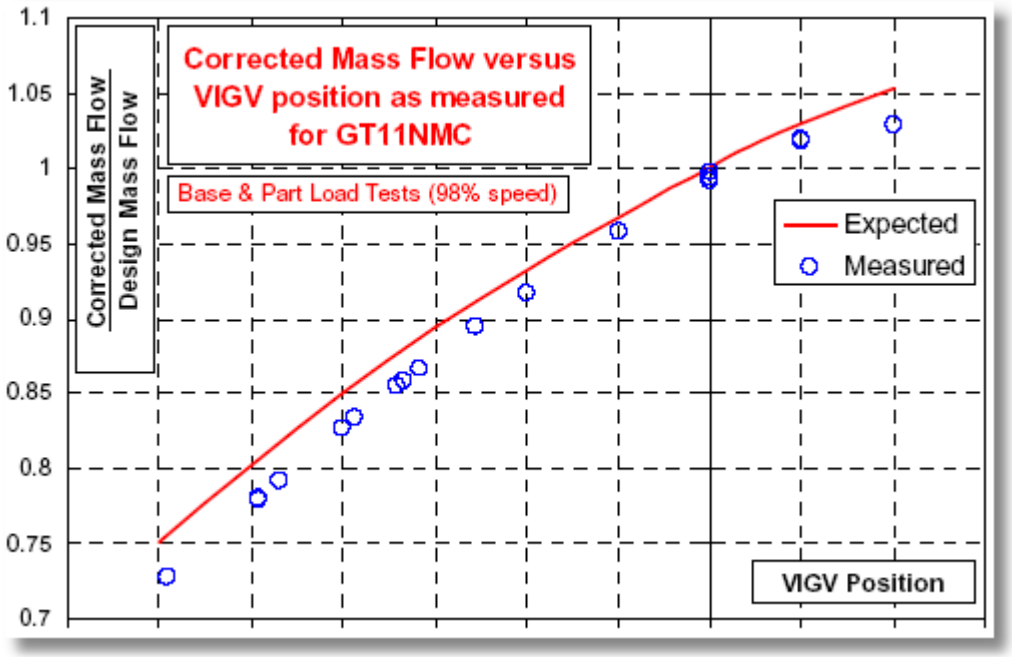
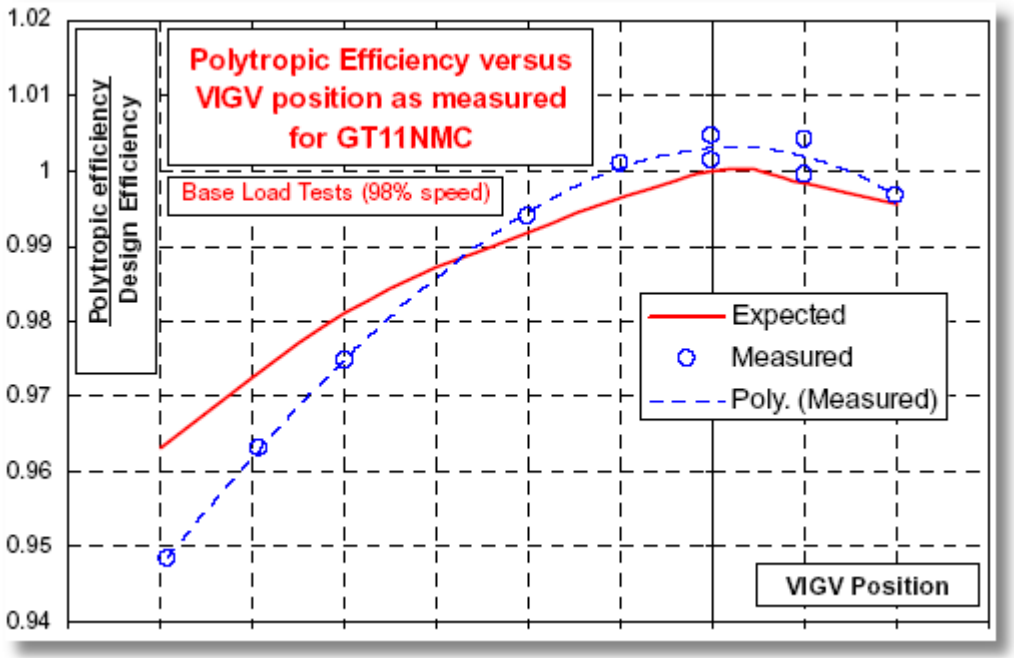
# Variable Compressor Guide Vanes






Ref.: S.M.Savic, M.A.Micheli
Redesign of a multistage axial compressor for a heavy duty industrial Gas turbine (GT11NMC)
ASME GT2005-68315

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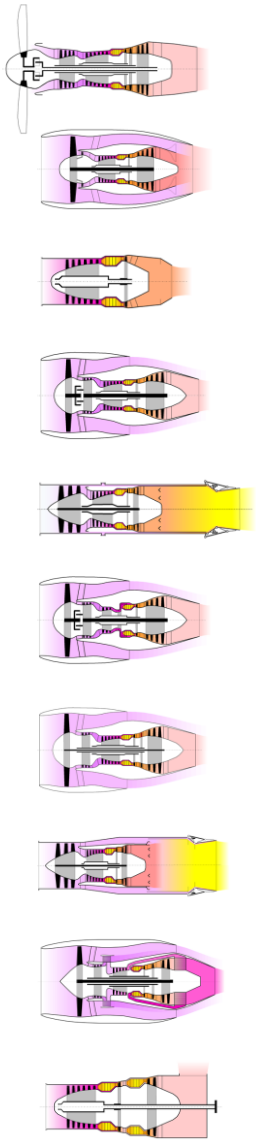
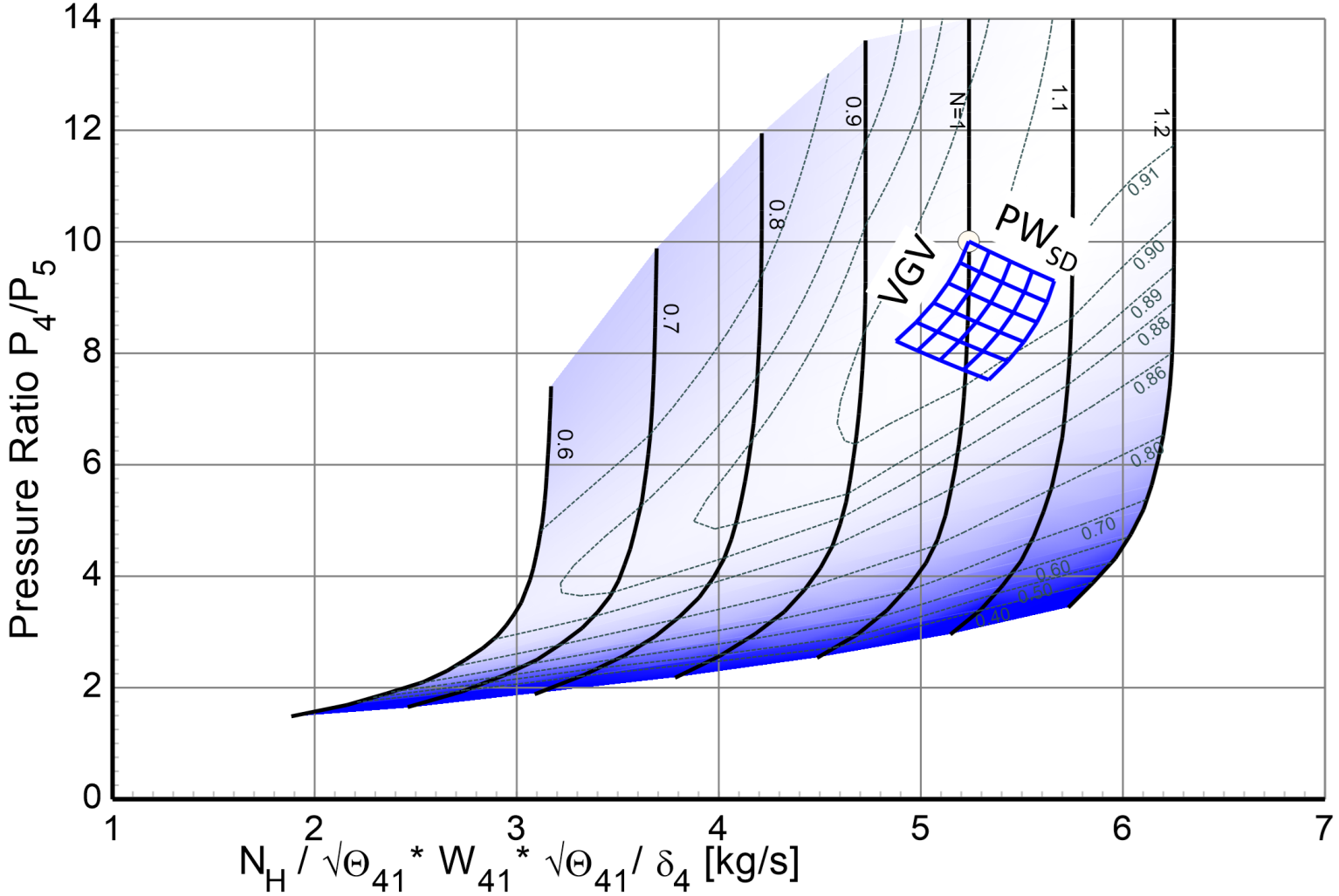
# Operation at Constant Speed



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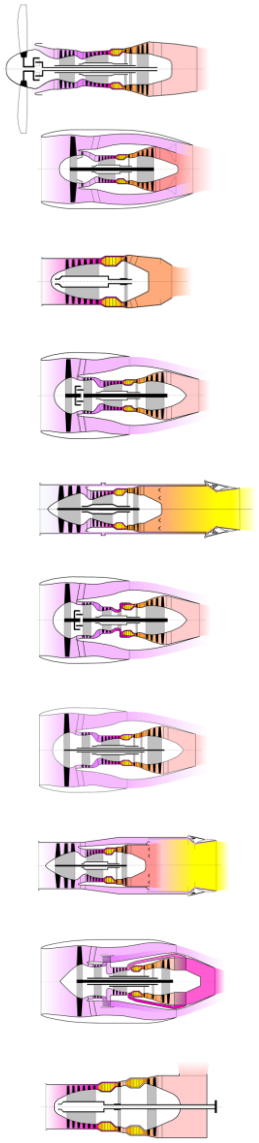
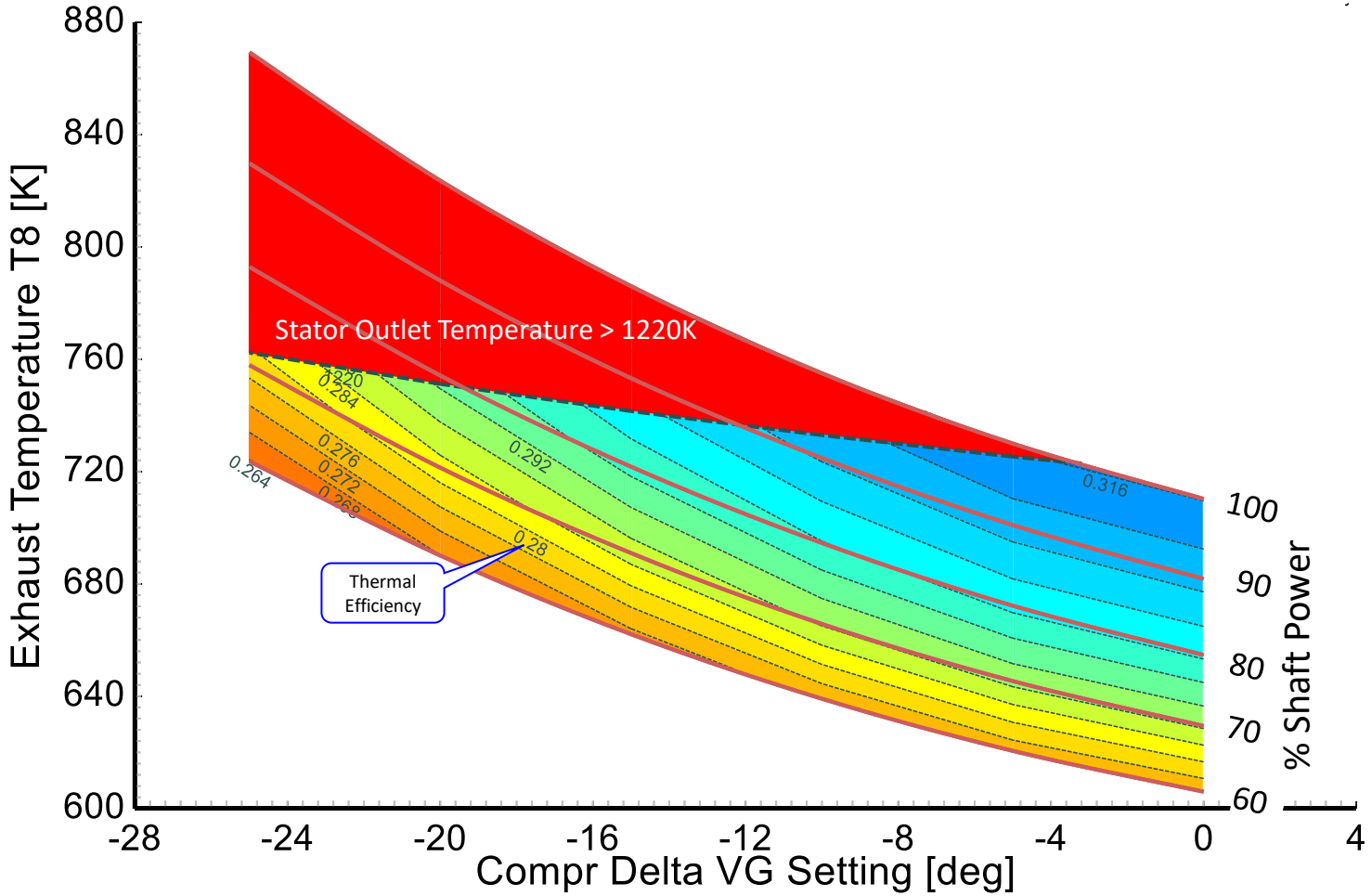
# Operation at Constant Speed
## High $T_8$ is Desirable for Cogeneration





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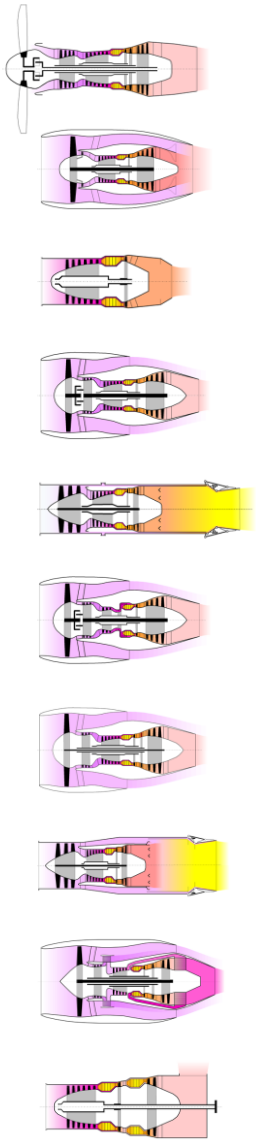

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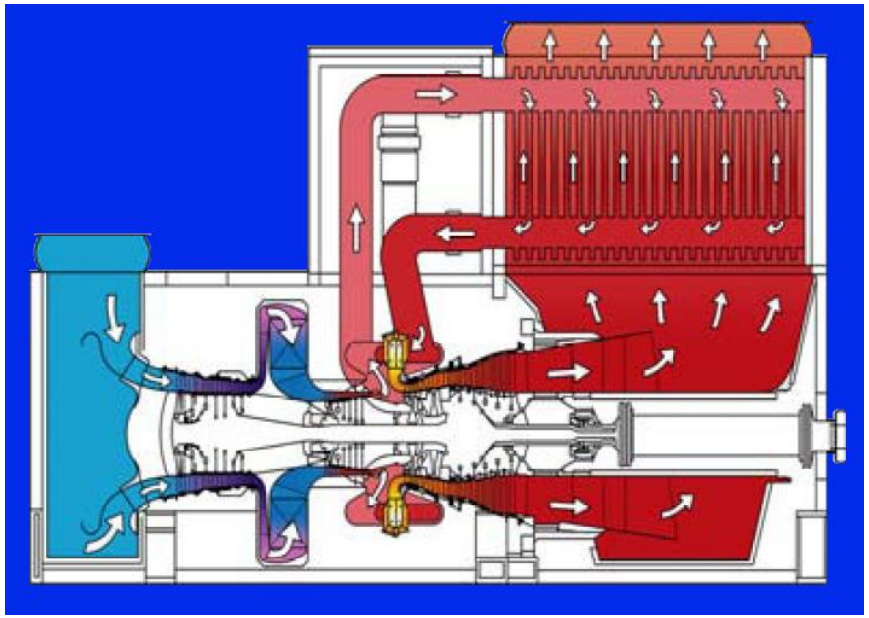
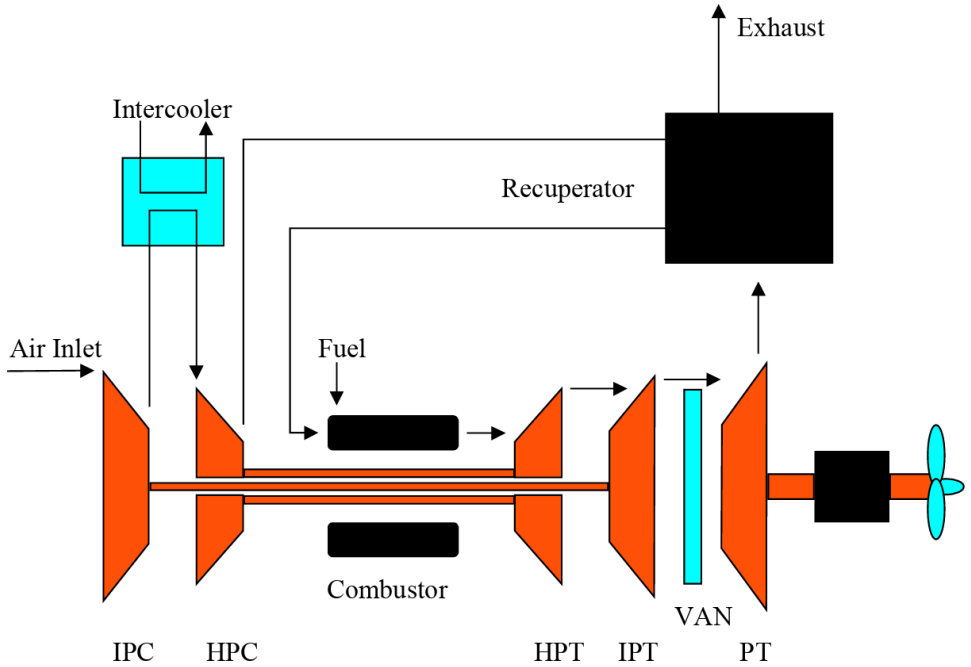
# Turboshaft with Heat Exchanger

Gas Turbine Design and Performance

# Rolls Royce WR-21






Ref.:
Colin R English
The WR-21 Intercooled Recuperated Gas Turbine Engine Integration Into Future Warships
IGTC2003Tokyo OS-203

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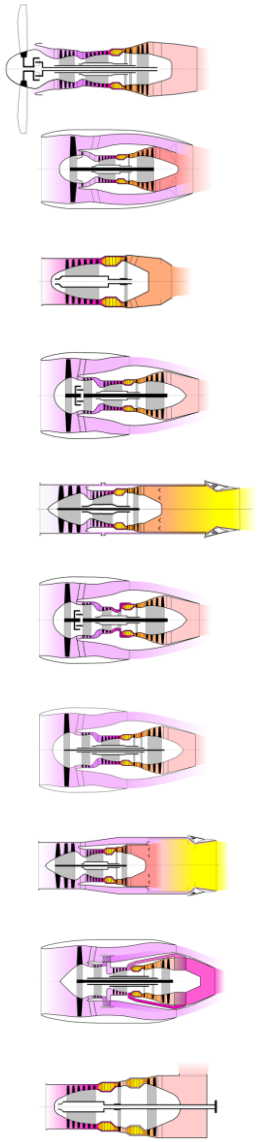
# CFM56-3 Gas Generator plus Power Turbine
## With Heat Exchanger



| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 1 | 27.436 | 288.15 | 101.325 | |
| 2 | 27.436 | 288.15 | 101.325 | 27.436 |
| 3 | 27.436 | 609.27 | 1121.668 | 3.604 |
| 31 | 25.488 | 609.27 | 1121.668 | 3.348 |
| 35 | 23.568 | 717.47 | 1099.234 | |
| 4 | 23.906 | 1228.40 | 1044.273 | 4.789 |
| 41 | 25.826 | 1192.69 | 1044.273 | 5.098 |
| 43 | 25.826 | 891.83 | 235.500 | |
| 44 | 27.473 | 875.56 | 235.500 | |
| 45 | 27.473 | 875.56 | 235.500 | 20.604 |
| 49 | 27.473 | 745.86 | 115.755 | |
| 5 | 27.774 | 744.42 | 115.755 | 39.077 |
| 6 | 27.774 | 744.42 | 113.440 | |
| 7 | 27.774 | 647.42 | 104.365 | |
| 8 | 27.774 | 647.42 | 104.365 | 40.420 |
| Bleed | 0.000 | 609.26 | 1121.665 | |

| Efficiencies: | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Compressor | 0.8677 | 0.9033 | 1.000 | **11.070** |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | **0.8250** | 0.7961 | 1.950 | **4.434** |
| LP Turbine | 0.8900 | 0.8806 | 0.627 | 2.034 |
| Heat Exch | 0.8000 | | | |
| Generator | 1.0000 | | | |

HP Spool mech Eff 0.9900 Nom Spd 38000 rpm
PT Spool mech Eff 0.9780 Nom Spd 20000 rpm

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | | | |
|---|---|---|---|---|
| PWSD | = | **3903.8** | kW | Shaft Power Delivered |
| PSFC | = | 0.31211 | kg/(kW*h) | Power Specific Fuel Consumption |
| Heat Rate | = | 13348.4 | kJ/(kW*h) | Fuel Flow * Fuel Heating Value / Shaft Power Delivered |
| V0 | = | 0.00 | m/s | Flight Velocity |
| FN res | = | 2.91 | kN | Residual Net Thrust |
| P35/P3 | = | 0.98000 | | Heat Exchanger Pressure Ratio |
| WF | = | 0.33844 | kg/s | Fuel Flow |
| Therm Eff | = | **0.26969** | | Thermal Efficiency |
| P2/P1 | = | 1.00000 | | Inlet Pressure Ratio |
| TRQ | = | 100.0 | % | Torque Delivered Relative to the Cycle Design Point Value |
| P45/P44 | = | 1.00000 | | Interturbine Duct Pressure Ratio |
| Incidence | = | 0.00000 | deg | Flow Incidence Angle @ Turbine Exit Guide Vanes |
| P6/P5 | = | 0.98000 | | Turbine Exit Duct Pressure Ratio |
| PWX | = | 0.0 | kW | Power Offtake |
| P7/P6 | = | 0.92000 | | Heat Exchanger Pressure Ratio |
| P8/Pamb | = | 1.03000 | | Nozzle Pressure Ratio |
| WBld/W2 | = | 0.00000 | | Bleed Air Flow/Mass Flow W2 |
| A8 | = | 0.48308 | m² | Geometric Nozzle Throat Area |
| WCHN/W2 | = | **0.07000** | | HPT Nozzle Guide Vane Cooling Air / W2 |
| WCHR/W2 | = | **0.06000** | | HPT Rotor Cooling Air / W2 |
| Loading | = | 100.00 | % | Burner Loading in % of the Cycle Design Point Value |
| WCLN/W2 | = | 0.00000 | | LPT Nozzle Guide Vane Cooling Air / W2 |
| WCLR/W2 | = | 0.00000 | | LPT Rotor Cooling Air / W2 |
| PW_gen | = | 3903.8 | kW | Electric Power |
| eta t-s | = | 0.76202 | | Total-Static Efficiency of the Power Turbine |

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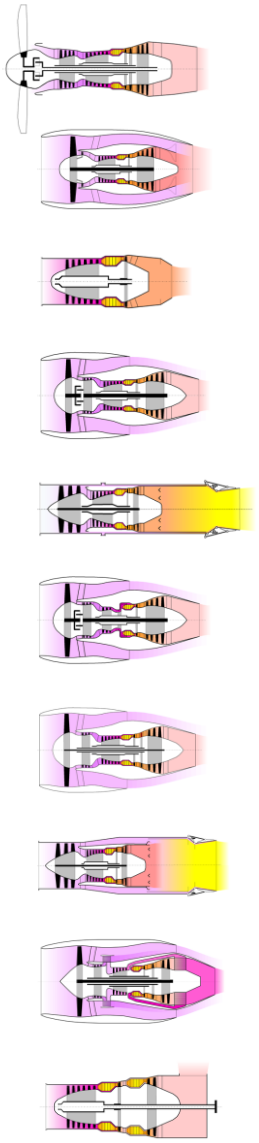
# Heat Exchange Potential



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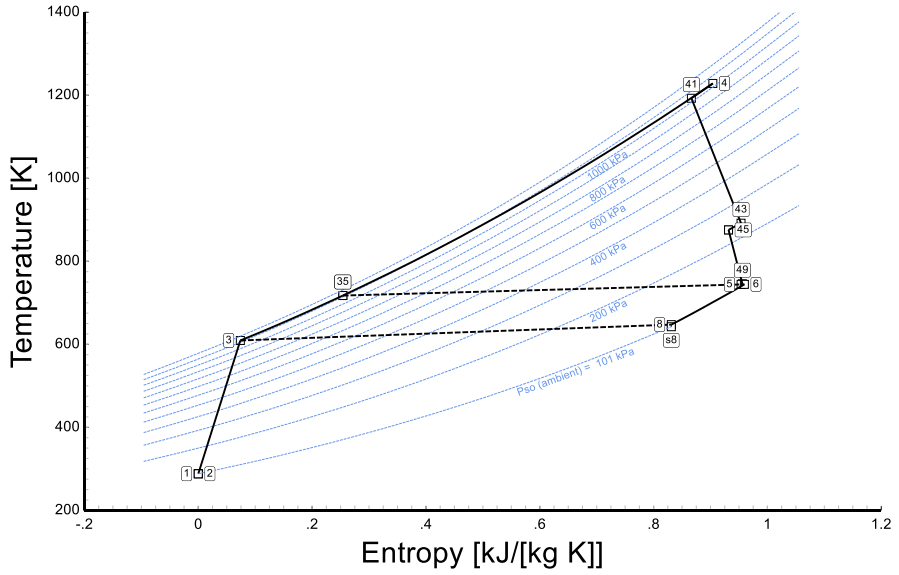
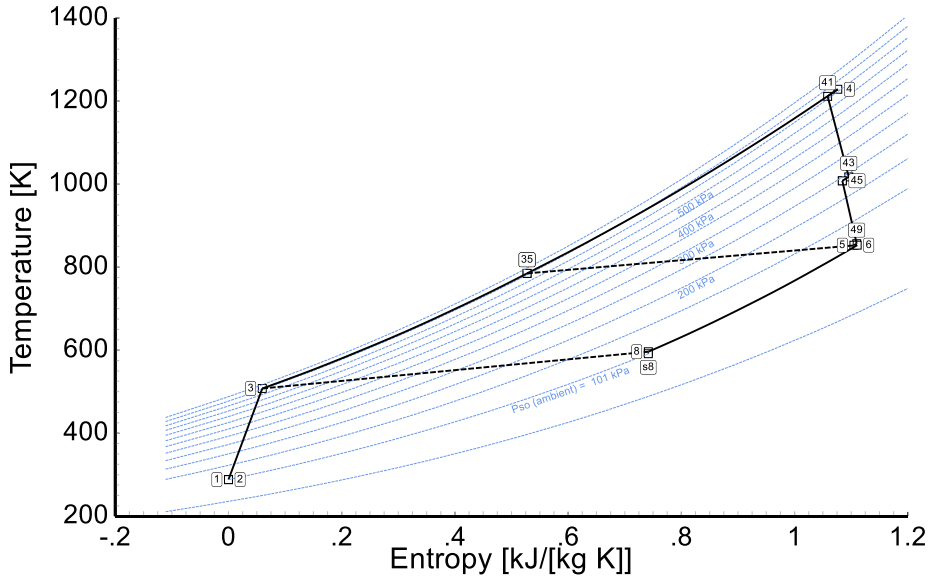
CFM56-3 Gas Generator plus Power Turbine
With Heat Exchanger




Alternate Gas Generator:

- Reduced $P_3/P_2$ → more heat exchange
- Lower $P_4/P_{45}$ → better HPT Efficiency
- Less turbine cooling air

→ better thermal efficiency



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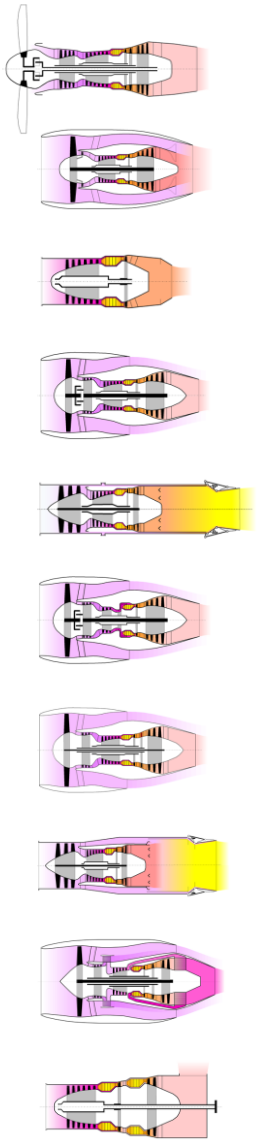
# Turboshaft with Heat Exchanger



| Station | W kg/s | T K | P kPa | WRstd kg/s |
|---|---|---|---|---|
| amb | | 288.15 | 101.325 | |
| 1 | 27.436 | 288.15 | 101.325 | |
| 2 | 27.436 | 288.15 | 101.325 | **27.436** |
| 3 | 27.436 | 507.68 | 607.950 | 6.070 |
| 31 | 26.585 | 507.68 | 607.950 | 5.881 |
| 35 | 25.488 | 784.93 | 595.791 | |
| 4 | 25.808 | 1228.40 | 566.001 | 9.539 |
| 41 | 26.905 | 1211.30 | 566.001 | 9.875 |
| 43 | 26.905 | 1017.38 | 242.142 | |
| 44 | 27.454 | 1007.92 | 242.142 | |
| 45 | 27.454 | 1007.92 | 242.142 | 21.486 |
| 49 | 27.454 | 856.47 | 115.755 | |
| 5 | 27.756 | 852.87 | 115.755 | 41.798 |
| 6 | 27.756 | 852.87 | 113.440 | |
| 7 | 27.756 | 596.15 | 104.365 | |
| 8 | 27.756 | 596.15 | 104.365 | 38.760 |
| Bleed | 0.000 | 507.68 | 607.948 | |

| Efficiencies: | isentr | polytr | RNI | P/P |
|---|---|---|---|---|
| Compressor | 0.8677 | 0.8959 | 1.000 | **6.000** |
| Burner | 0.9995 | | | 0.950 |
| HP Turbine | **0.8600** | 0.8470 | 1.038 | **2.337** |
| LP Turbine | 0.8900 | 0.8804 | 0.548 | 2.092 |
| Heat Exch | 0.8000 | | | |
| Generator | 1.0000 | | | |

HP Spool mech Eff 0.9900 Nom Spd 38000 rpm
PT Spool mech Eff 0.9780 Nom Spd 20000 rpm

| hum [%] | war0 | FHV | Fuel |
|---|---|---|---|
| 0.0 | 0.00000 | 42.769 | Generic |

| | | | | |
|---|---|---|---|---|
| PWSD | = | **4661.1** | kW | Shaft Power Delivered |
| PSFC | = | 0.24694 | kg/(kW*h) | Power Specific Fuel Consumption |
| Heat Rate | = | 10561.4 | kJ/(kW*h) | Fuel Flow * Fuel Heating Value / Shaft Power Delivered |
| V0 | = | 0.00 | m/s | Flight Velocity |
| FN res | = | 2.79 | kN | Residual Net Thrust |
| P35/P3 | = | 0.98000 | | Heat Exchanger Pressure Ratio |
| WF | = | 0.31973 | kg/s | Fuel Flow |
| Therm Eff | = | **0.34086** | | Thermal Efficiency |
| P2/P1 | = | 1.00000 | | Inlet Pressure Ratio |
| TRQ | = | 100.0 | % | Torque Delivered Relative to the Cycle Design Point Value |
| P45/P44 | = | 1.00000 | | Interturbine Duct Pressure Ratio |
| Incidence | = | 0.00000 | deg | Flow Incidence Angle @ Turbine Exit Guide Vanes |
| P6/P5 | = | 0.98000 | | Turbine Exit Duct Pressure Ratio |
| PWX | = | 0.0 | kW | Power Offtake |
| P7/P6 | = | 0.92000 | | Heat Exchanger Pressure Ratio |
| P8/Pamb | = | 1.03000 | | Nozzle Pressure Ratio |
| WBld/W2 | = | 0.00000 | | Bleed Air Flow/Mass Flow W2 |
| A8 | = | 0.46316 | m² | Geometric Nozzle Throat Area |
| WCHN/W2 | = | **0.04000** | | HPT Nozzle Guide Vane Cooling Air / W2 |
| WCHR/W2 | = | **0.02000** | | HPT Rotor Cooling Air / W2 |
| Loading | = | 100.00 | % | Burner Loading in % of the Cycle Design Point Value |
| WCLN/W2 | = | 0.00000 | | LPT Nozzle Guide Vane Cooling Air / W2 |
| WCLR/W2 | = | 0.00000 | | LPT Rotor Cooling Air / W2 |
| PW_gen | = | 4661.1 | kW | Electric Power |
| eta t-s | = | 0.76639 | | Total-Static Efficiency of the Power Turbine |

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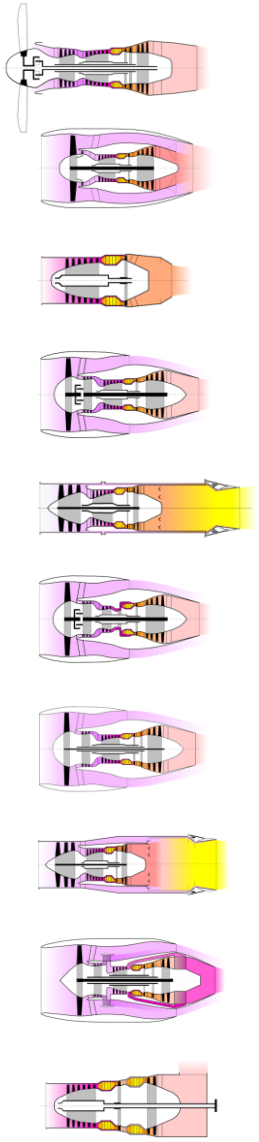
# Compressor Operating Lines



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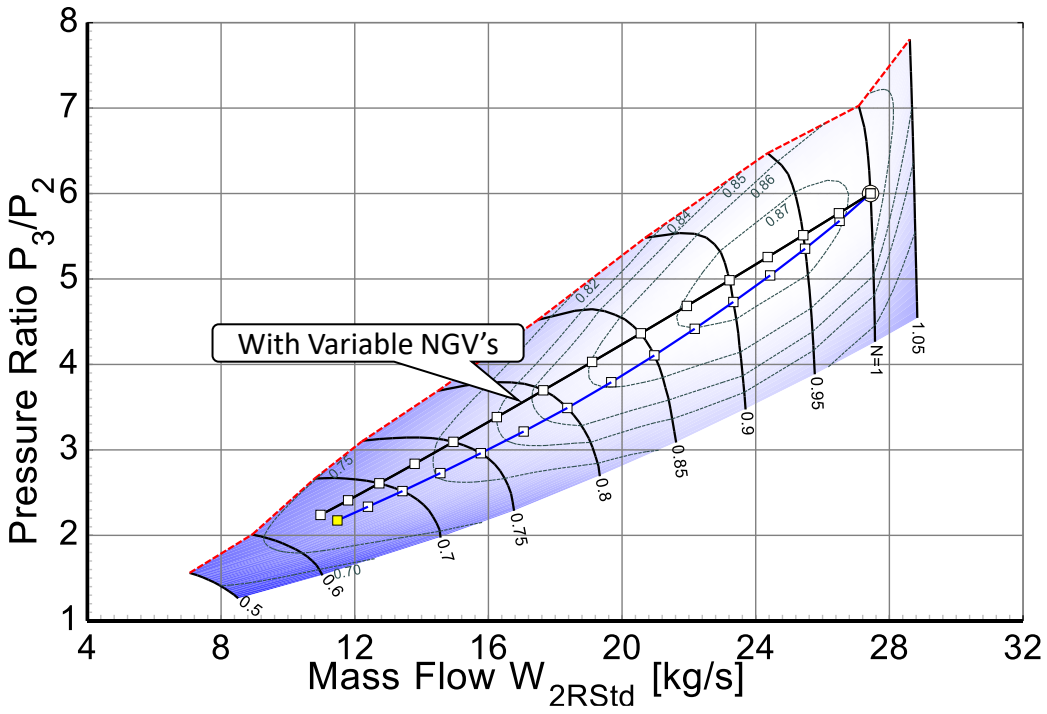


Rolls Royce WR-21 LP turbine

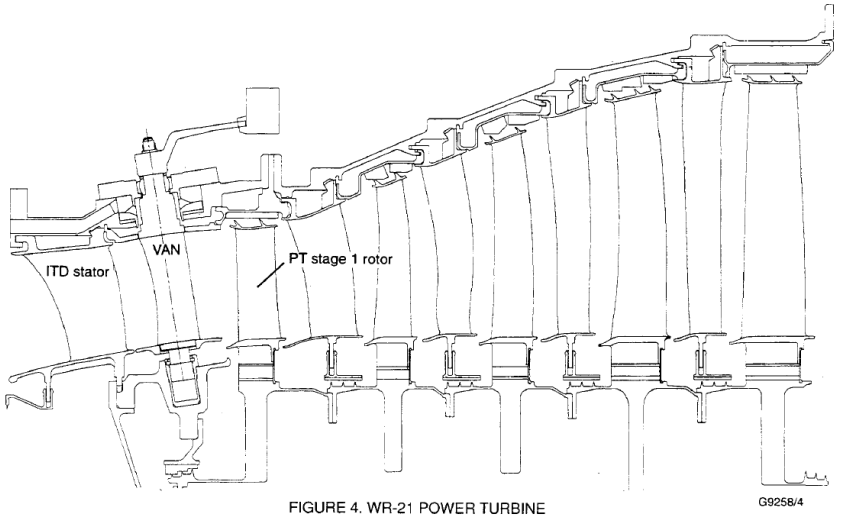


FIGURE 4. WR-21 POWER TURBINE

Ref. ASME 95-GT-54

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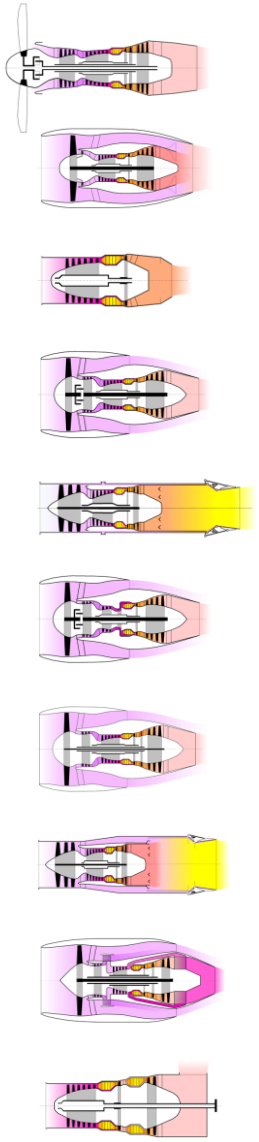
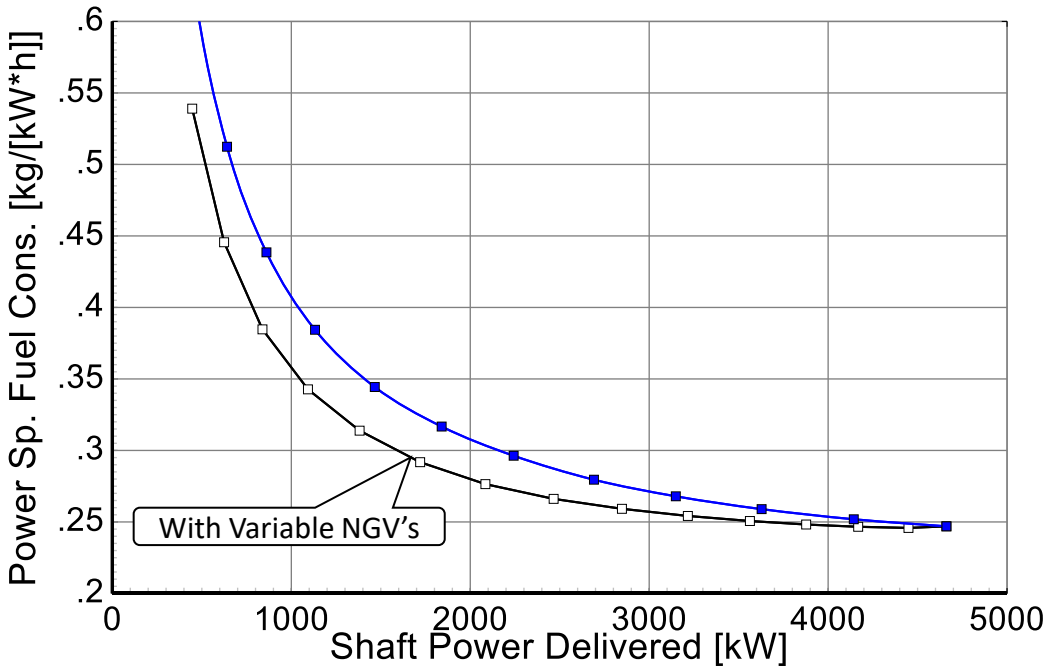
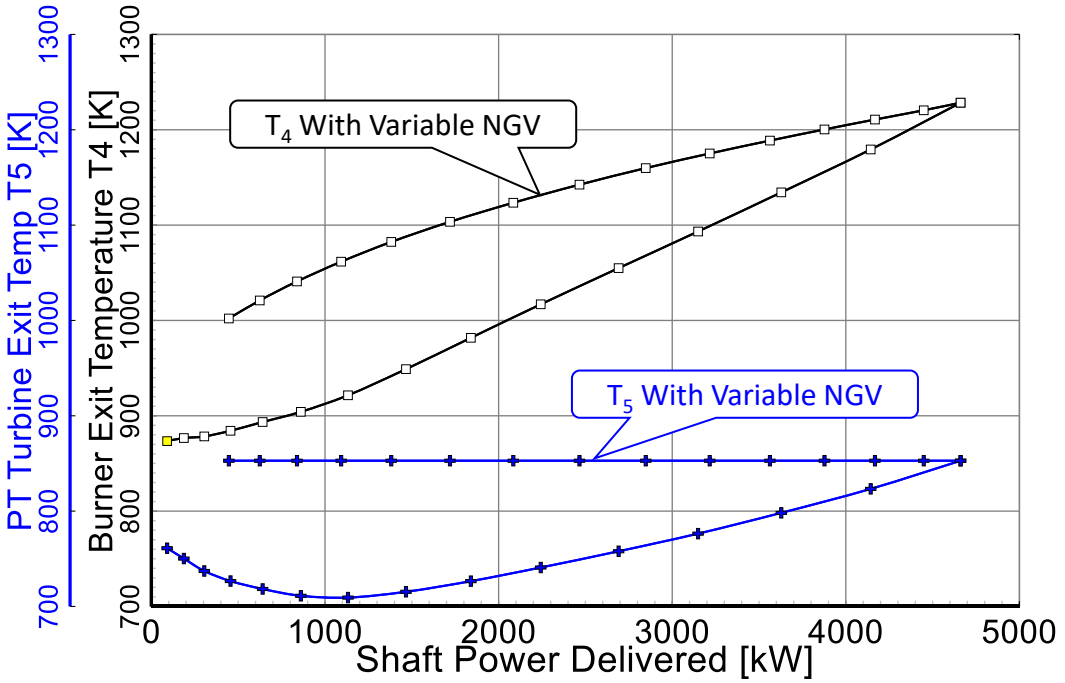
# Effect of Variable LPT NGV's
## Maximize Heat Exchange





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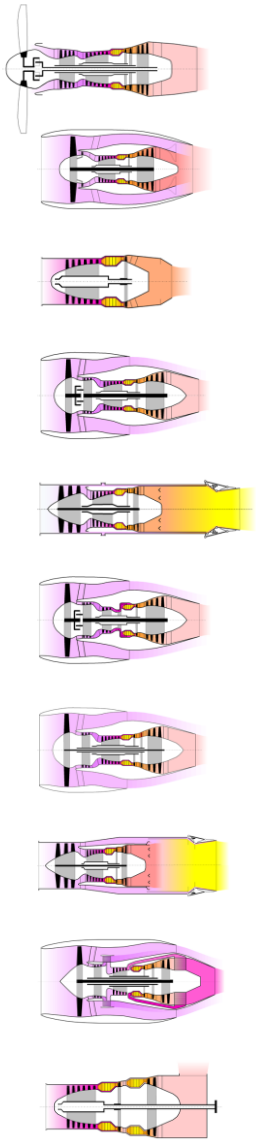

# Low Bypass Ratio Turbofan

Gas Turbine Design and Performance

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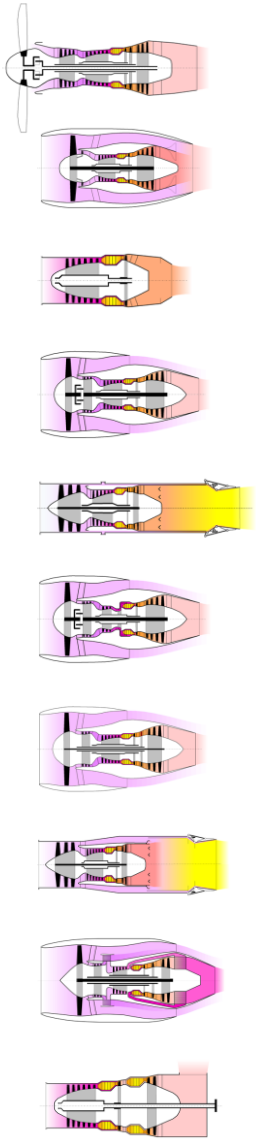

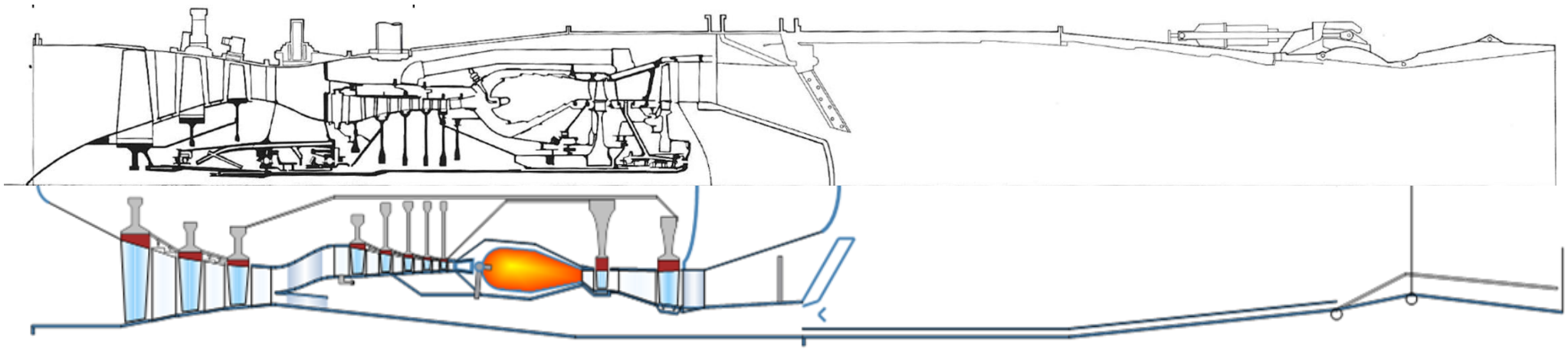

## EJ200 ENGINE SPECIFICATIONS

| | |
|---|---|
| Type | Twin Spool Turbofan with Afterburner |
| Application | Eurofighter Typhoon |
| Thrust | 90 kN (20,000 lbf) with reheat \| 60 kN (13,500 lbf) without reheat |
| Bypass ratio | 0.4 : 1 |
| Fan pressure ratio | 4.2 : 1 |
| Overall pressure ratio | 26 : 1 |
| Specific fuel consumption | 47–49 g/kNs with reheat \| 21–23 g/kNs without reheat |
| Airflow | 75–77 kg/s |
| Compressor stages | 3 LP, 5 HP |
| Turbine stages | 1 HP, 1 LP |
| Combustion system | Annular Airspray |
| Weight | ca. 1,000 kg |
| Length | ca. 4 m |

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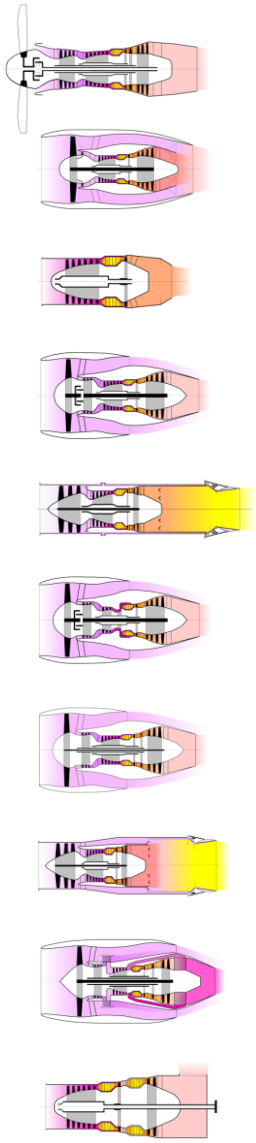
# Variable Nozzle Area
## Affects Only the Fan Operating Line



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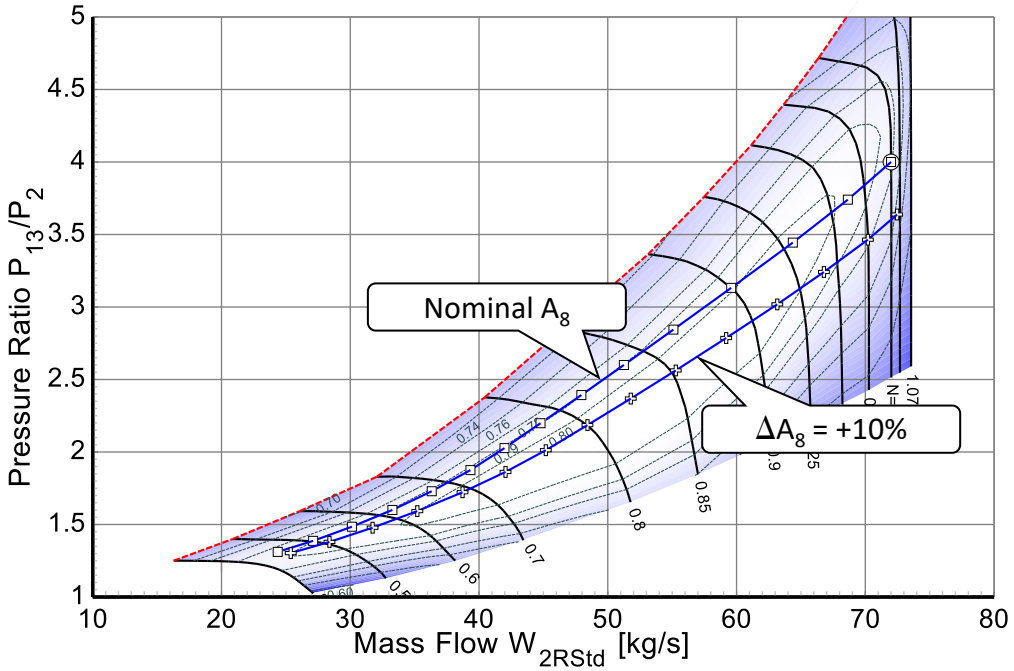
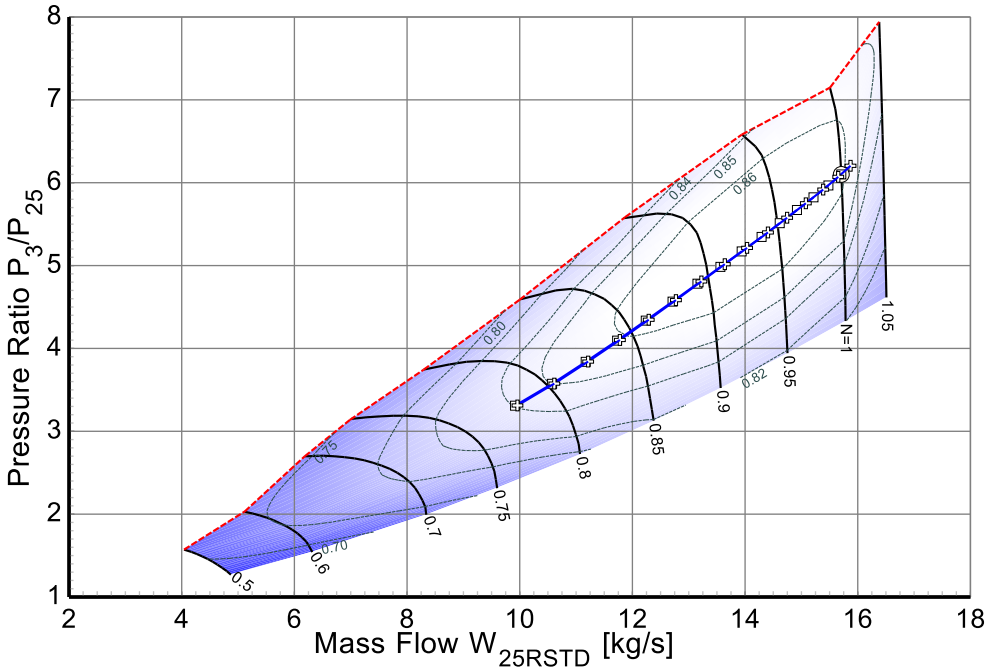
### Low Pressure Compressor (Fan)




### Gas Generator Compressor (HPC)



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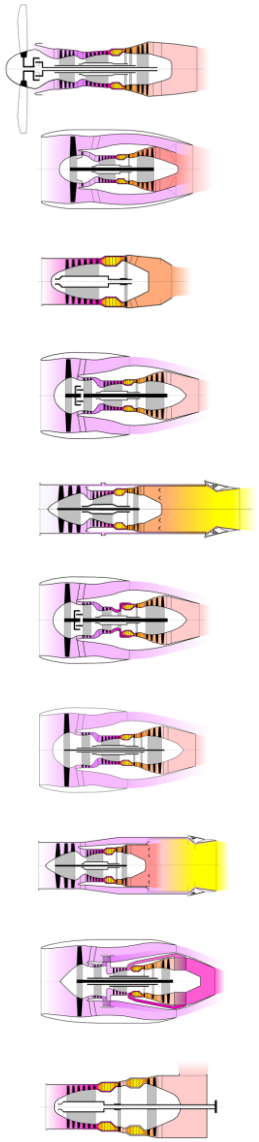

# Summary

The Gas Generator of a Turbofan

Basic Correlations, Nomenclature

Gas Generator Components
- Compressor
- Burner
- Turbine
- Nozzle

Cooperation of the Components
- Nominal Performance
- Modifiers

Gas Generator +
- Power Turbine = 2 Spool Turboshaft
- Booster and Low Pressure Turbine = 2 Spool Turbojet
- Fan, Booster and Low Pressure Turbine = 2 Spool Turbofan

Variable Geometry
- Compressor
  - Gas Generator
  - Single Spool Engine (Power Generation)
- Turbine
  - Turboshaft with Heat Exchanger
- Nozzle
  - Low Bypass Ratio Turbofan

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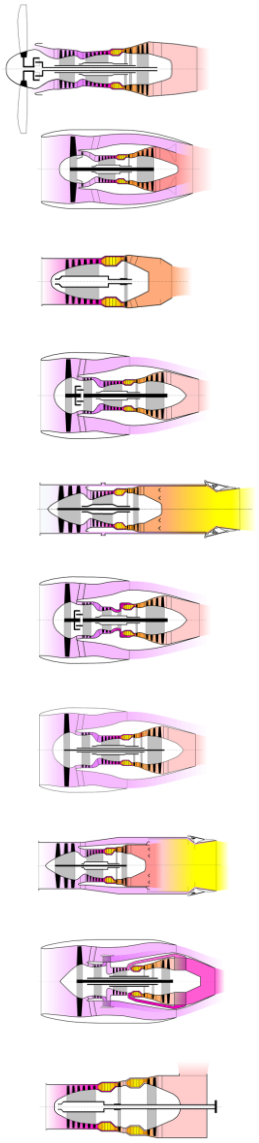

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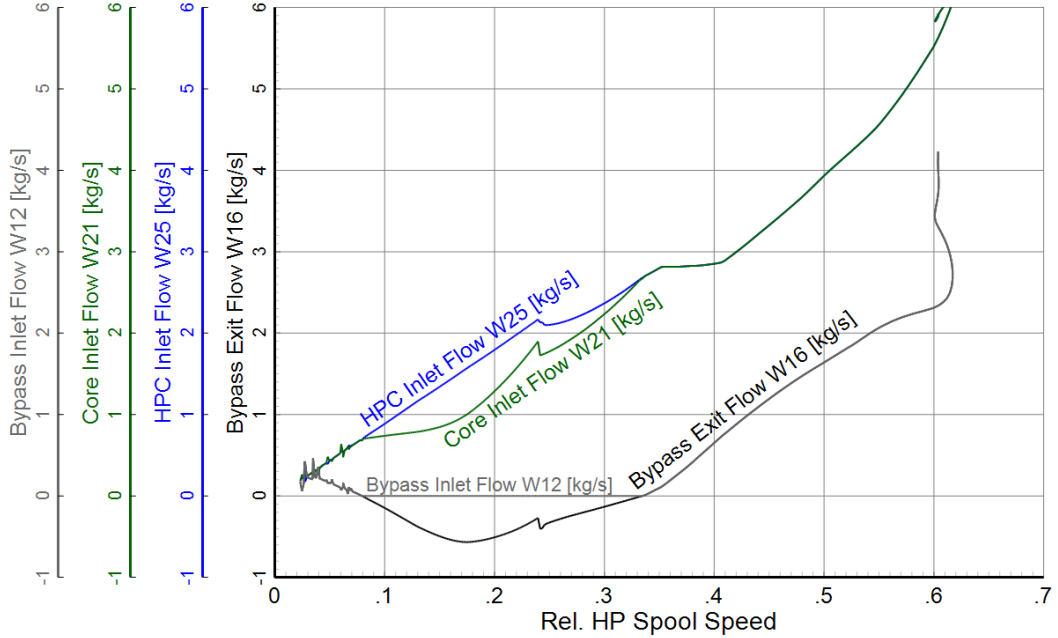
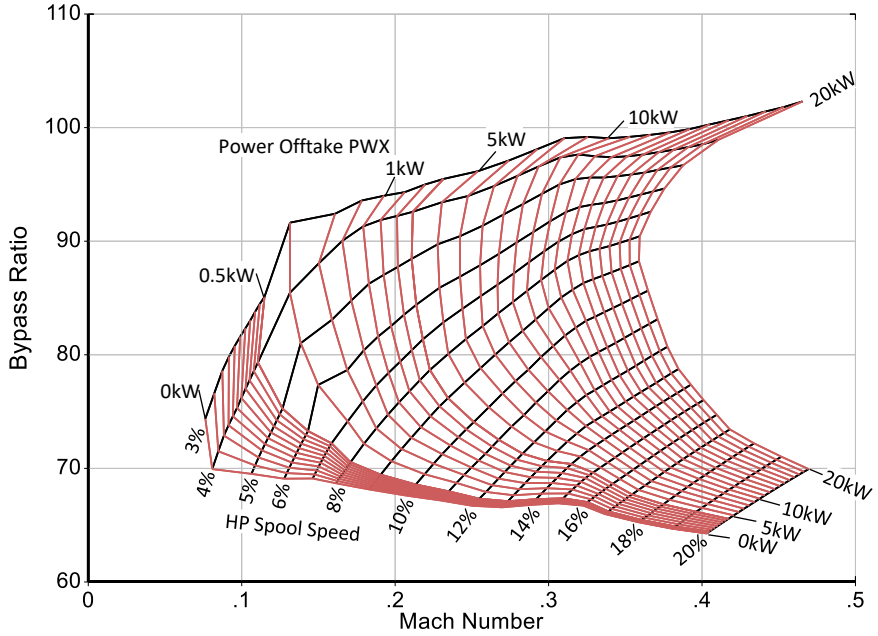
# Beyond the Basics …

## Extreme Off-Design Operation

### Starting




### Windmilling



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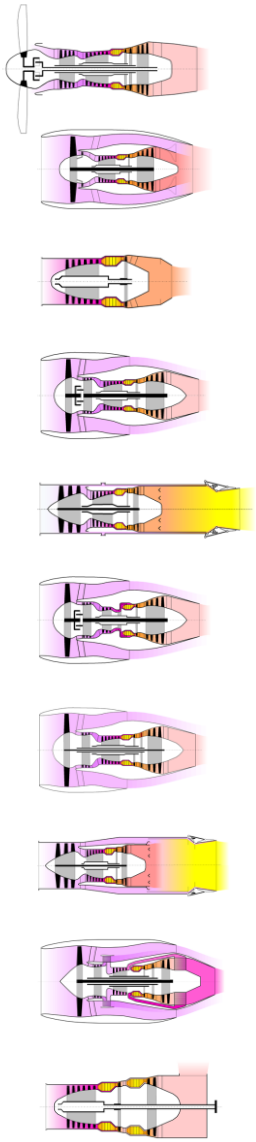
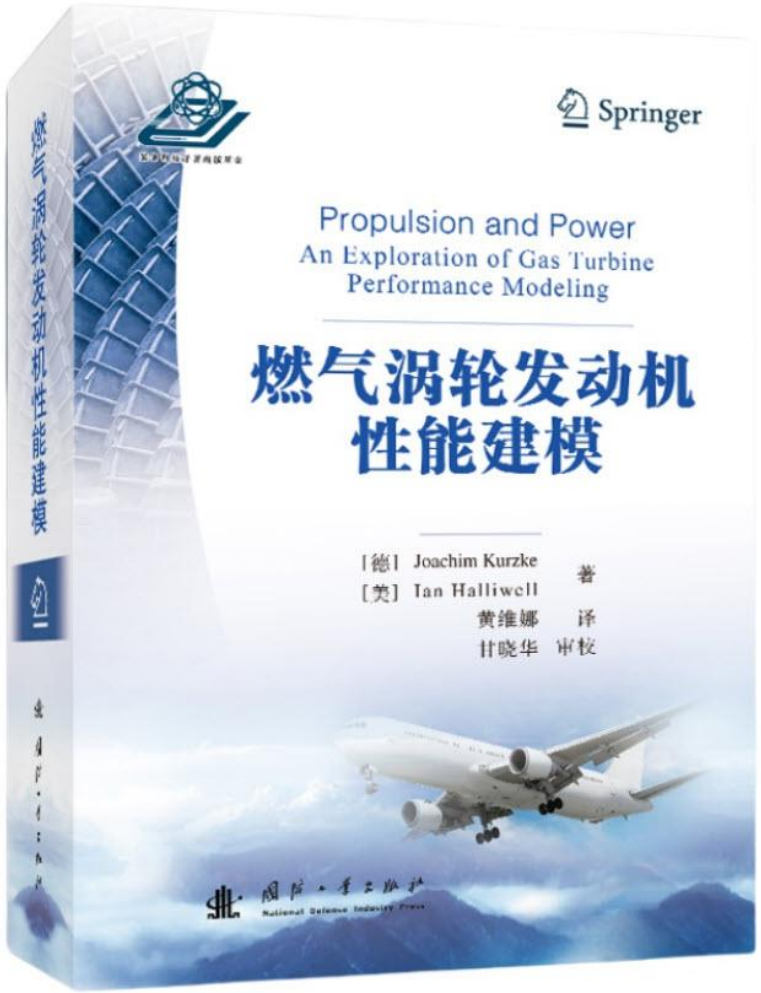
# References





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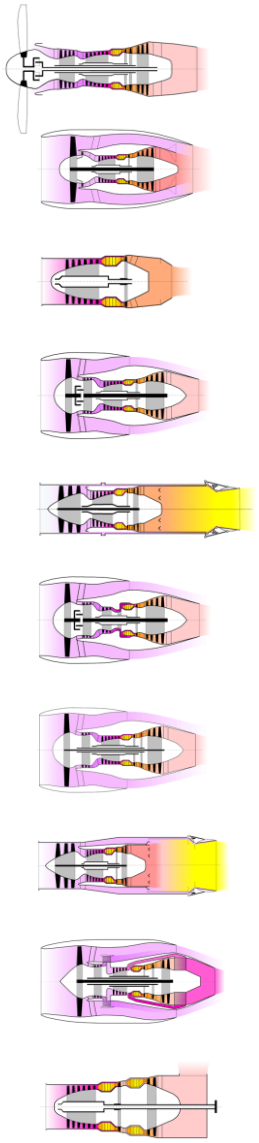

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# References

## Not only a valuable engineering textbook but also a good read:

SPRINGER NATURE

Springer

Joachim Kurzke, Ian Halliwell, Robert Hill

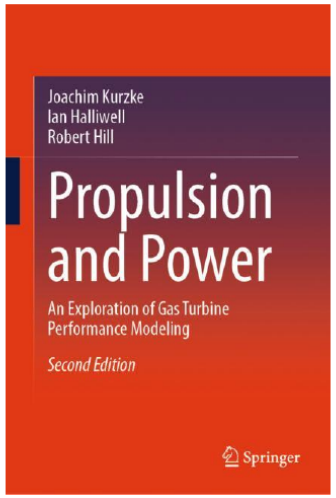
### Propulsion and Power

An Exploration of Gas Turbine Performance Modeling

Guide for solving real world problems with modern computer software

Good text for teaching gas turbine design and performance

Solutions of overall system simulation problems

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