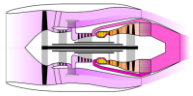
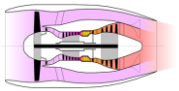
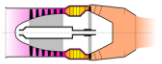
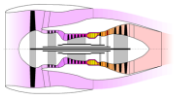
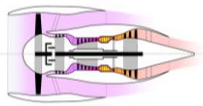
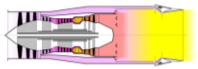
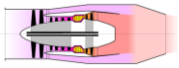
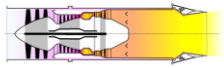
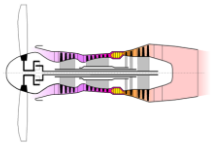

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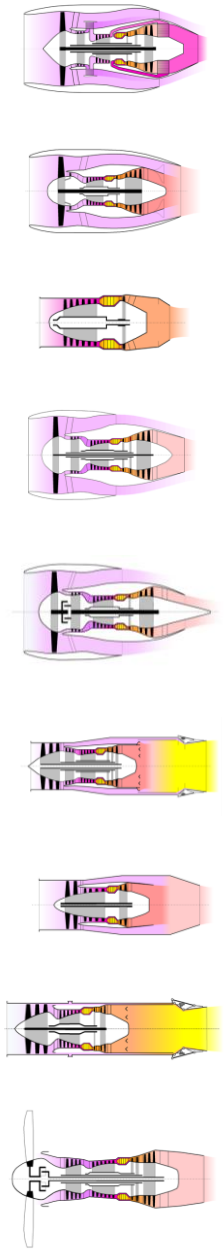
The Basics of Aircraft Engine
Thrust Management

A tutorial presented at the Turbo Expo 2026 in Milano, Italy

GT2026-TOB-01-01

Joachim Kurzke



Eurofighter Typhoon. Image Created by Ideogram.

Wing-mounted Engines

Thrust

- Thrust Setting Parameters
- Engine Pressure Ratio
- Spool Speed

Ratings

- Flat Rating
- Generating Schedules
- Derating
- Idle

Exhaust Gas Temperature

- Deterioration
- EGT Margin

The Cockpit

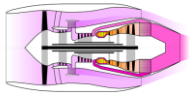
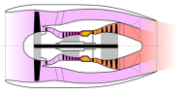
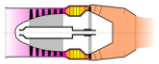
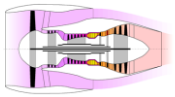
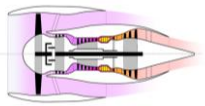
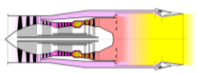
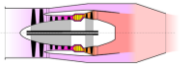
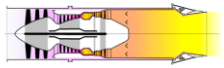
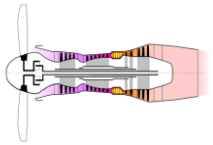
- A320
- A350

Transient

Embedded Engines

Ratings

- Limiters
- Deterioration
- Thrust Rating

Outline

Constant thrust, independent from engine-to-engine variations and deterioration

Wing-mounted Engines

Thrust

- Thrust Setting Parameters
- Engine Pressure Ratio
- Spool Speed

Ratings

- Flat Rating
- Generating Schedules
- Derating
- Idle

Exhaust Gas Temperature

- Deterioration
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- A320
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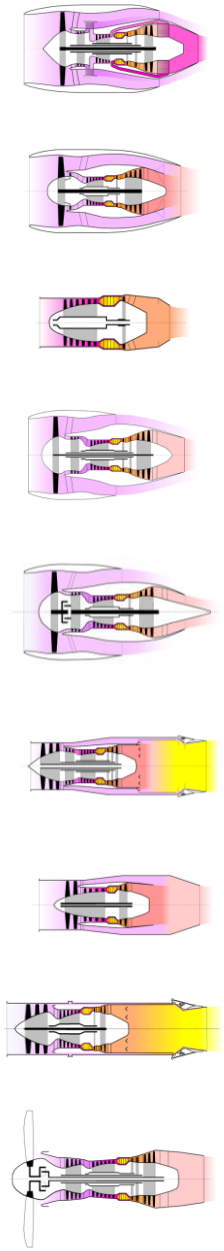
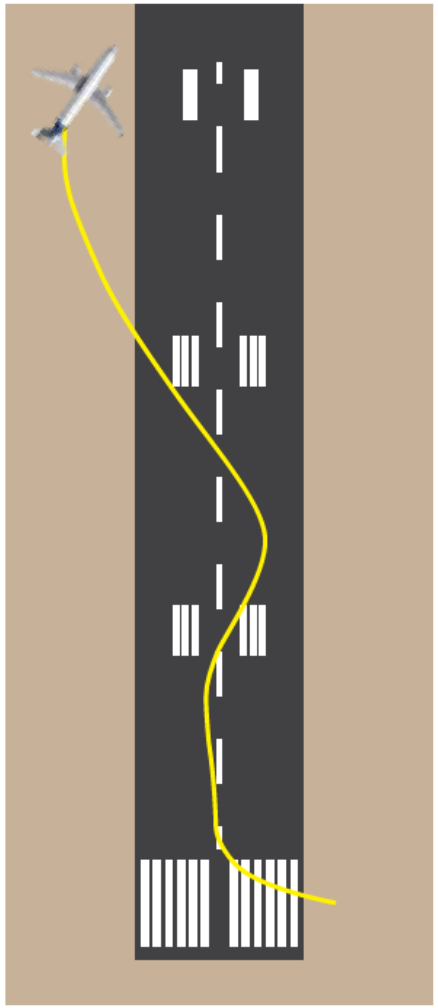


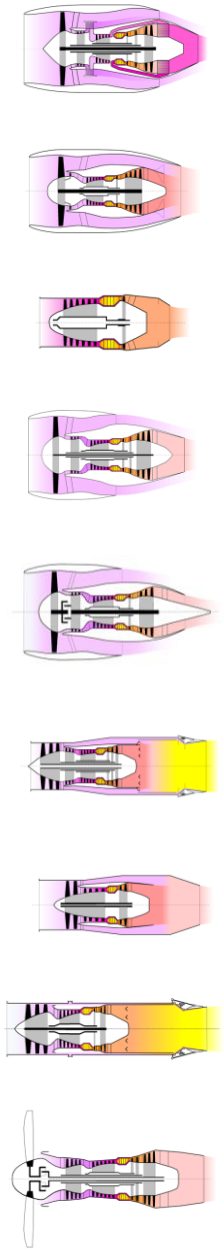
The Need for Thrust Management

Effect of Thrust Differences at Take-off



A strong asymmetric thrust condition could be difficult to counteract with nose wheel steering only, due to limited effectivity of the rudder at low speed.

https://www.aerofly.com/aircraft-tutorials/a350_flightdeck/



The Thermodynamic Cycle of a Turbofan

Station	W kg/s	T K	P kPa	WRstd kg/s
amb		303.15	101.325	
2	881.265	303.15	101.325	903.912
13	813.475	337.73	144.372	618.091
21	67.790	335.75	141.855	52.268
22	67.790	335.75	141.855	52.268
24	67.790	442.44	347.400	24.500
25	67.790	442.44	340.452	25.000
3	65.756	983.39	5106.782	2.410
31	54.232	983.39	5106.782	
4	55.811	1900.00	4851.443	2.993
405	61.234	1825.45	4851.443	3.219
41	63.946	1792.64	4851.443	3.331
43	63.946	1309.02	1002.024	
44	66.657	1296.62	1002.024	
45	68.465	1285.05	981.984	14.919
49	68.465	817.17	127.388	
5	68.691	816.15	127.388	91.952
8	69.369	817.75	126.114	93.889
18	809.408	337.73	143.264	619.760
Bleed	0.000	983.39	5106.762	

Efficiency	isentr	polytr	RNI	P/P
Outer LPC	0.9300	0.9334	0.942	1.425
Inner LPC	0.9350	0.9380	0.942	1.400
IP Compressor	0.9096	0.9201	1.167	2.449
HP Compressor	0.8746	0.9100	2.015	15.000
Burner	0.9995			0.950
HP Turbine	0.9000	0.8822	5.666	4.842
LP Turbine	0.9350	0.9174	1.683	7.709

HP Spl mech Eff	0.9950	Nom Spd	3200 rpm
LP Spl mech Eff	0.9920	Nom Spd	3080 rpm
IPC & LPT		Nom Spd	7701 rpm

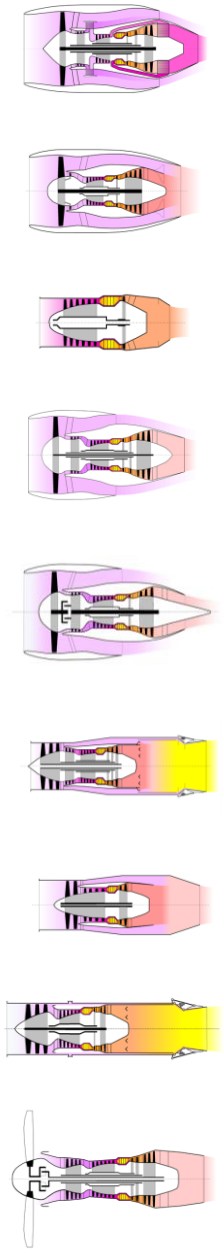
P22/P21=1.0000 P25/P24=0.9800 P45/P44=0.9800

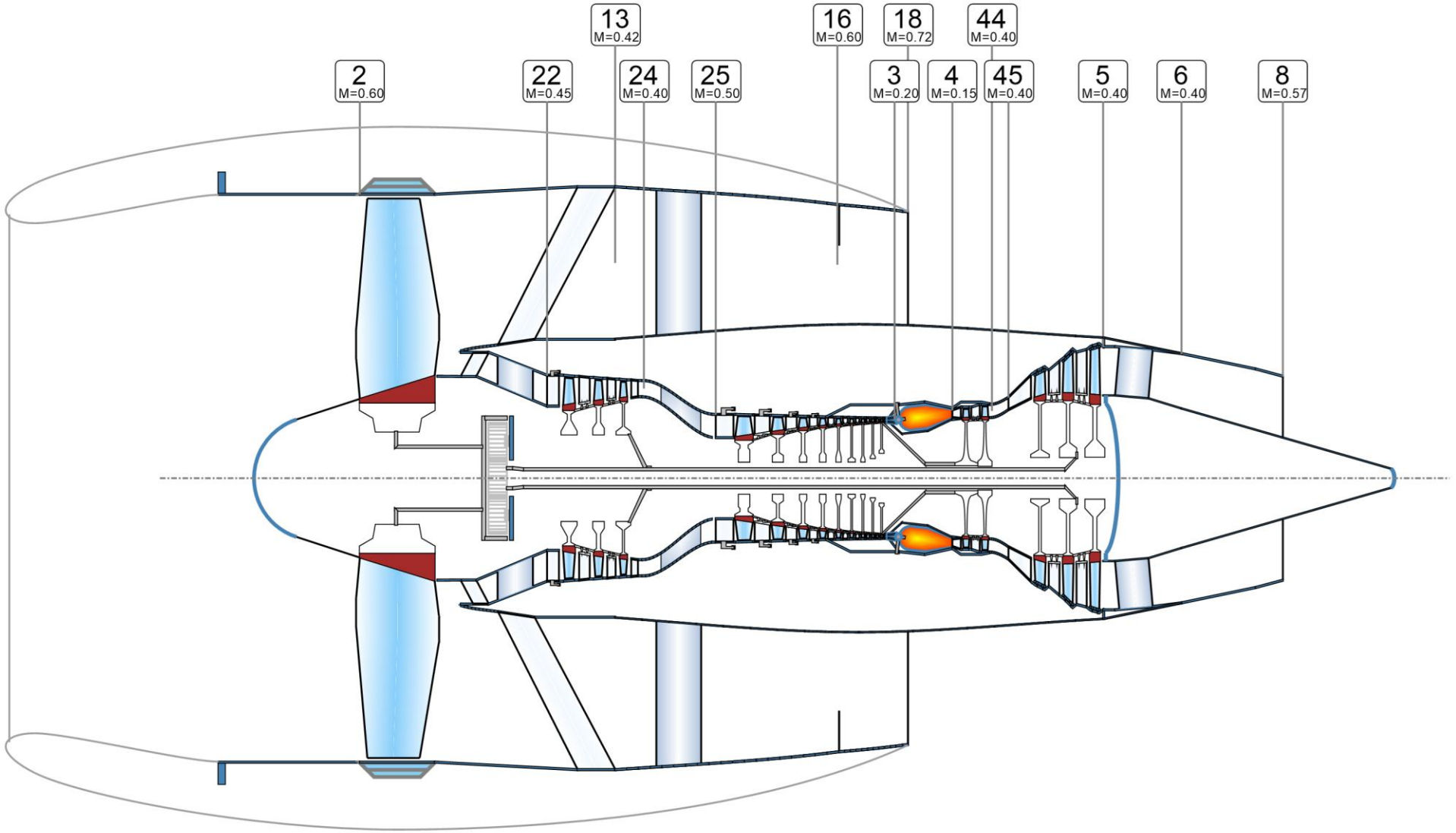
Absolute HP PWX Input			
Corrected HP PWX Input		PwxHRstd	0.0
Corrected LP PWX Input		PwxLRstd	0.0

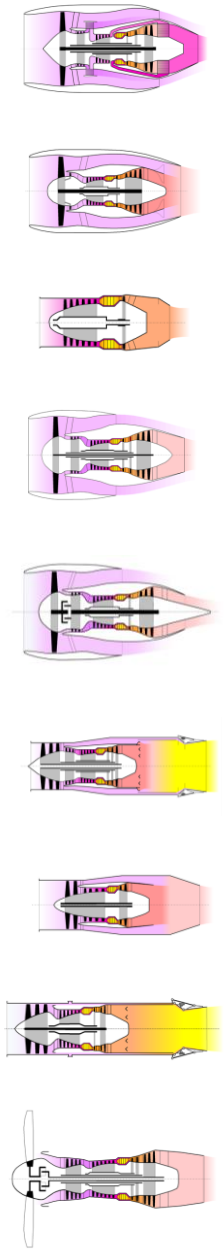
hum [%]	war0	FHV	Fuel
0.0	0.00000	43.124	Generic

SL static, ISA +15.0 C

			CYCLE DESIGN POINT
FN	=	226.66 kN	Net Thrust (50956lbf)
TSFC	=	6.9675 g/(kN*s)	Thrust Specific Fuel Consumption (0.2460lbm/h/lbf)
WF	=	1.57928 kg/s	Fuel Flow
FN/W2	=	257.2 m/s	Specific Thrust
Core Eff	=	0.5032	Core Efficiency
Prop Eff	=	0.0000	Propulsion Efficiency
BPR	=	12.0000	Bypass Ratio
P2/P1	=	1.0000	Inlet Pressure Ratio
P3/P2	=	50.40	Overall Pressure Ratio
P5/P2	=	1.2572	Engine Pressure Ratio
			NGV Exit 2 Stage HPT
P16/P13	=	0.9923	Bypass Duct Pressure Ratio
P16/P6	=	1.13599	Bypass Exit Pressure/Core Exit Pressure
P16/P2	=	1.41390	Bypass Exit Pressure/Engine Inlet Pressure
P6/P5	=	0.99000	Turbine Exit Duct Pressure Ratio
A8	=	0.50534 m²	Geometric Nozzle Throat Area
A18	=	2.93799 m²	Geometric Bypass Nozzle Throat Area
XM8	=	0.57919	Nozzle Throat Mach No.
XM18	=	0.72138	Bypass Nozzle Throat Mach No.
WBLD/W25	=	0.00000	Bleed Air Flow/Mass Flow W25
CD8	=	0.95147	Nozzle Discharge Coefficient
CD18	=	0.94424	Bypass Nozzle Discharge Coefficient
V18/V8,id	=	0.79995	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	=	0.01000	HP Leakage to LPT Exit/Mass Flow W25
Loading	=	100.00 %	Burner Loading in % of the Cycle Design Point Value
WCHN/W25	=	0.12000	HPT Nozzle Guide Vane Cooling Air / W25
WCHR/W25	=	0.04000	HPT Rotor Cooling Air / W25
WCLN/W25	=	0.02667	LPT Nozzle Guide Vane Cooling Air / W25
WCLR/W25	=	0.00333	LPT Rotor Cooling Air / W25
Gear Rat	=	2.50000	Gear Ratio NLPT / NLPC
WLkBy/W25	=	0.00000	HP Leakage to Bypass/Mass Flow W25
PWX	=	50.00 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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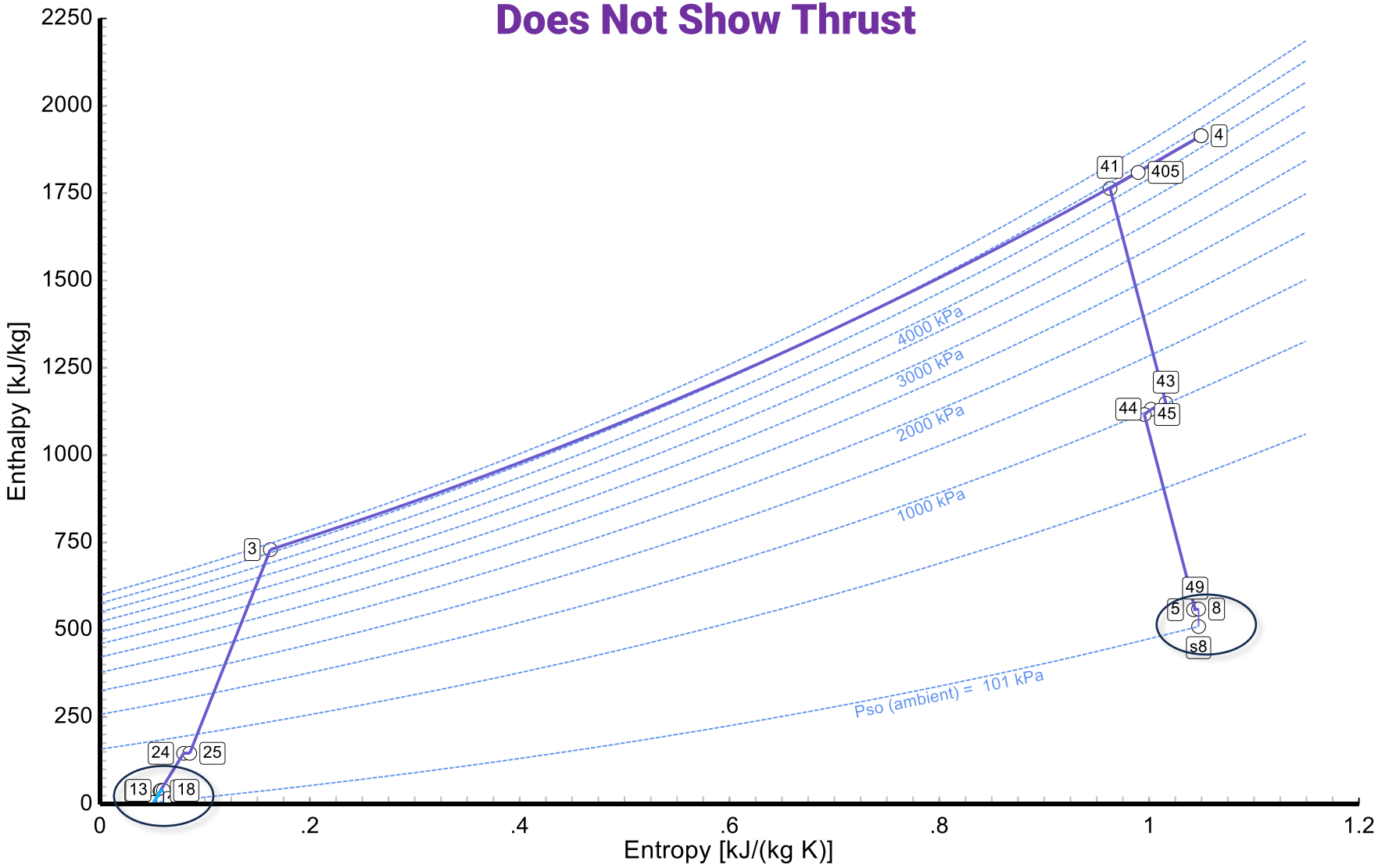
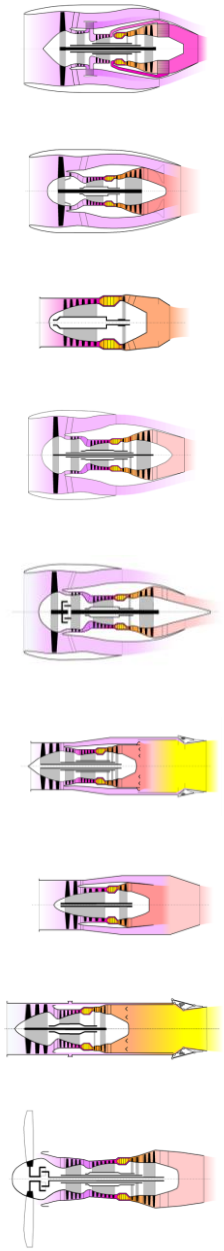
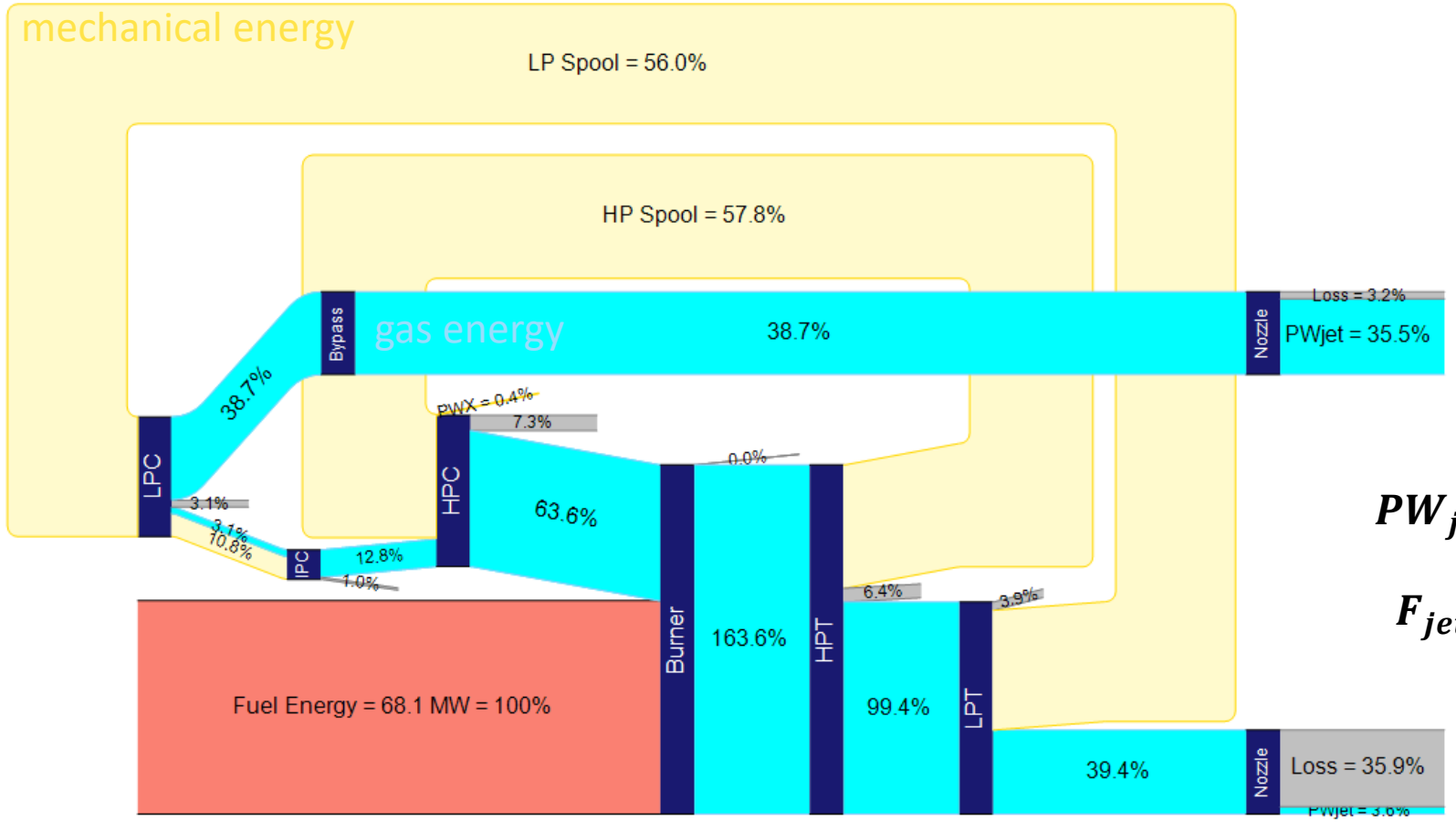
H-S Diagram

Does Not Show Thrust





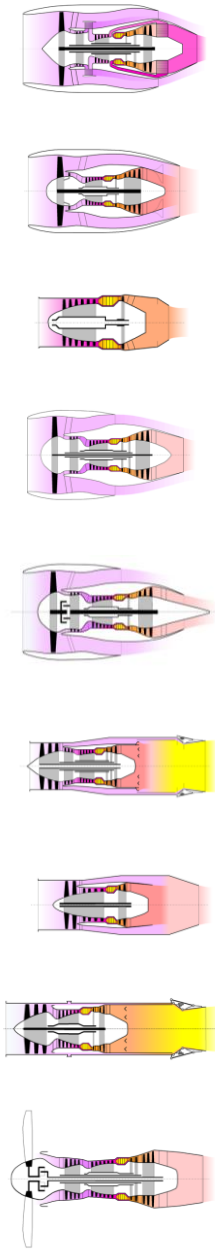
Sankey Diagram
Shows Energy Flows



SL static, ISA +15.0 C

$$PW_{jet} = W * \frac{V^2}{2}$$

$$F_{jet} = W * V$$



About Thrust

Thrust cannot be measured on aircraft

- We have to look at a substitute

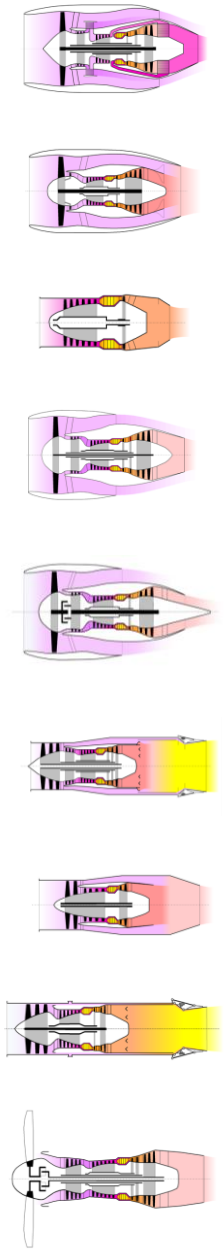
Which measurable parameter best correlates with thrust?

- It should be independent from manufacturing tolerance

Let’s conduct a Monte Carlo study

- Create an off-design model of a high bypass ratio turbofan
- Apply statistically distributed modifiers to component efficiency and flow capacity
- Analyse the resulting thrust scatter

Simulating Engine Manufacturing with a Monte Carlo Study



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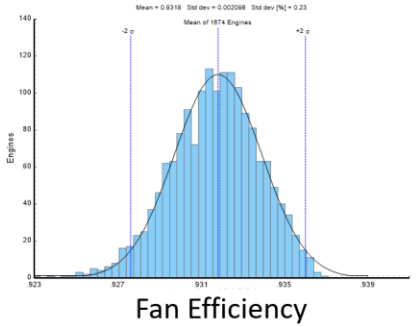
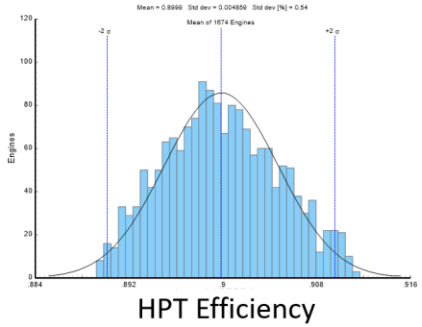
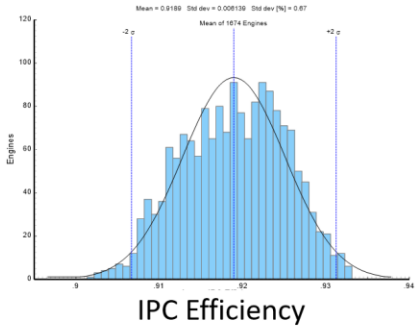
Input



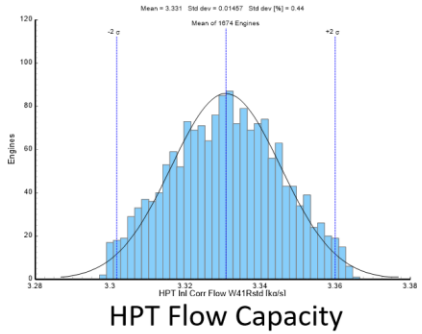
Fan Efficiency



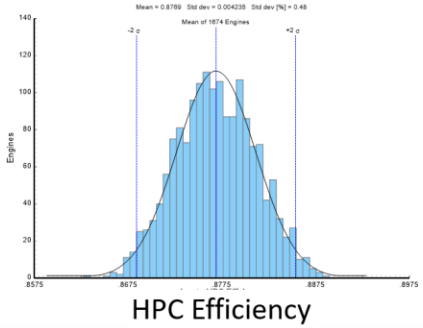
HPT Efficiency



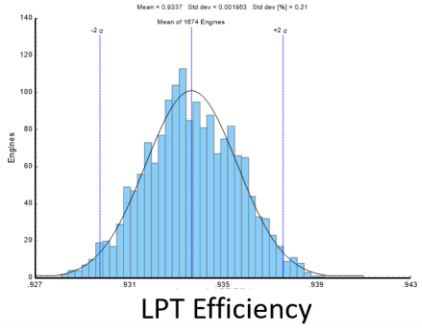
IPC Efficiency



HPT Flow Capacity

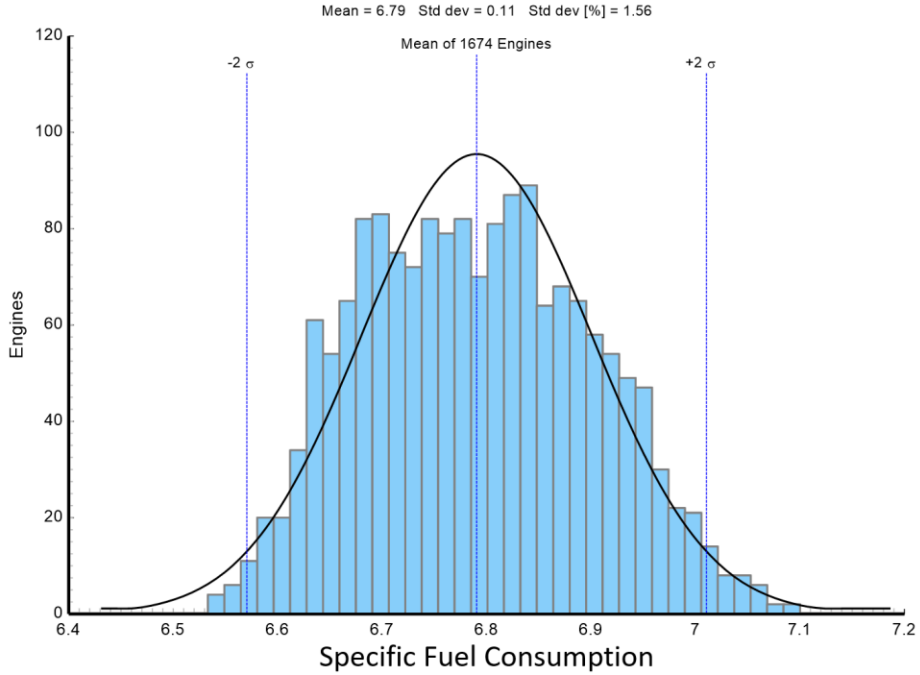


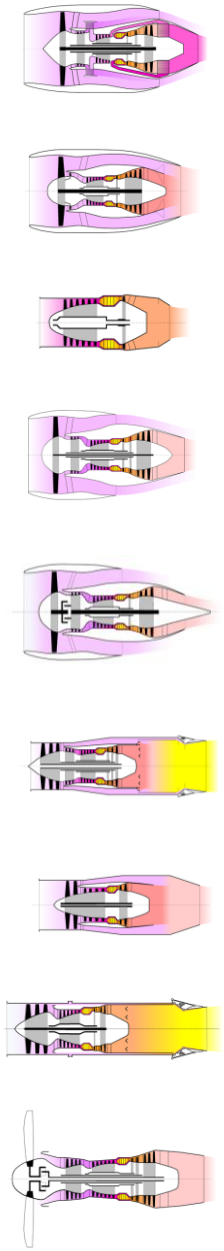
HPC Efficiency



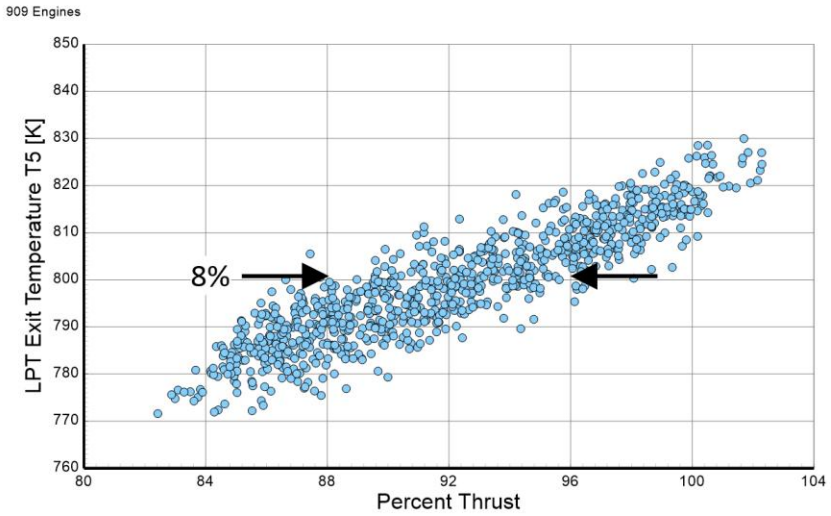
LPT Efficiency

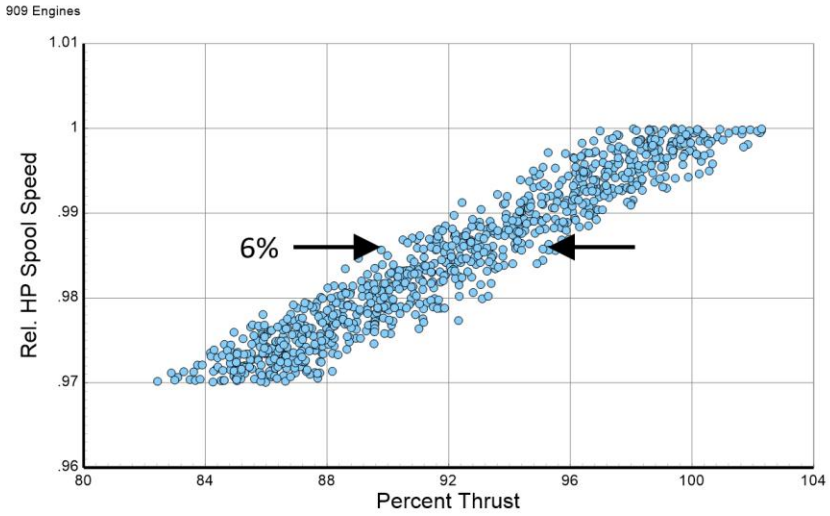
Result

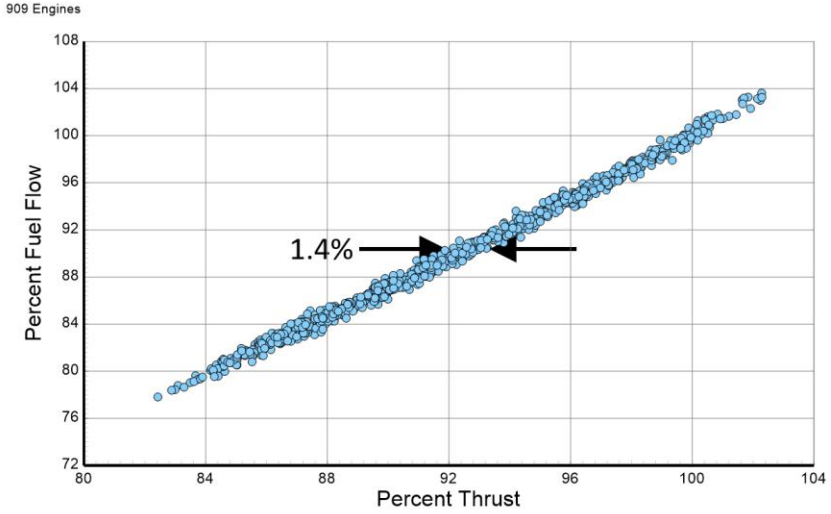


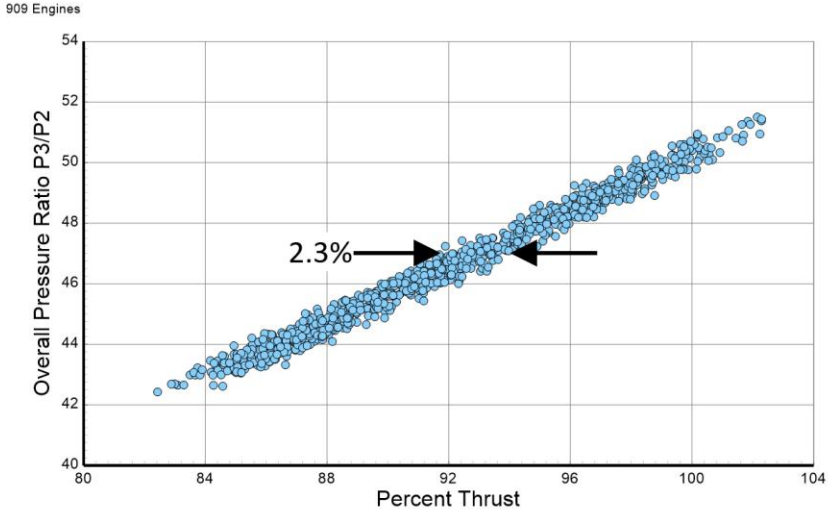


Thrust Measurement Substitutes

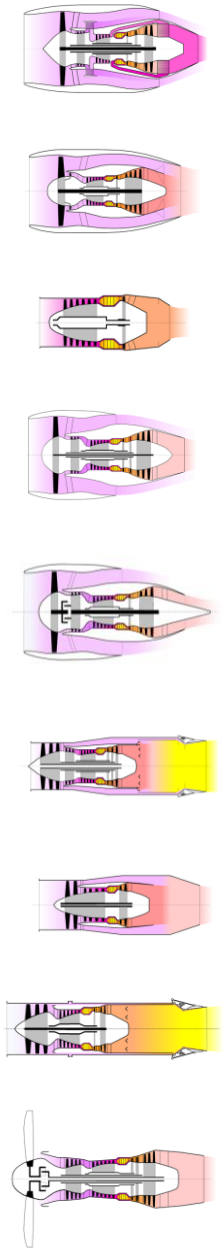




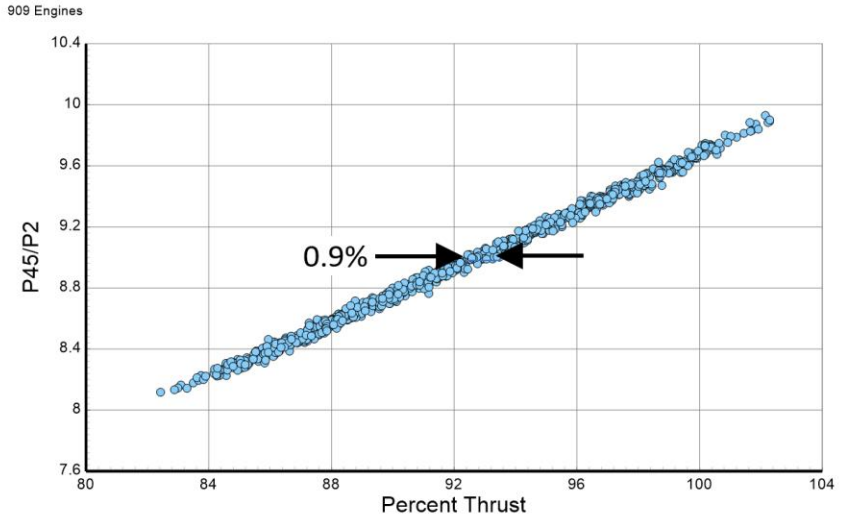


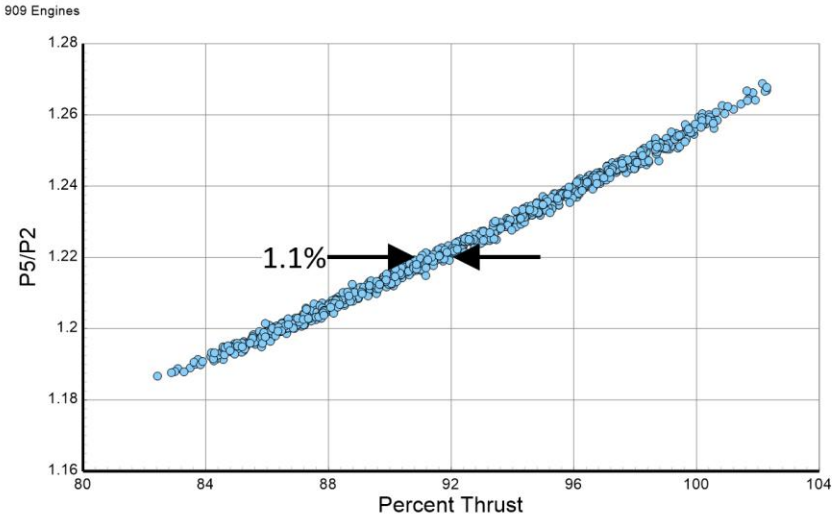


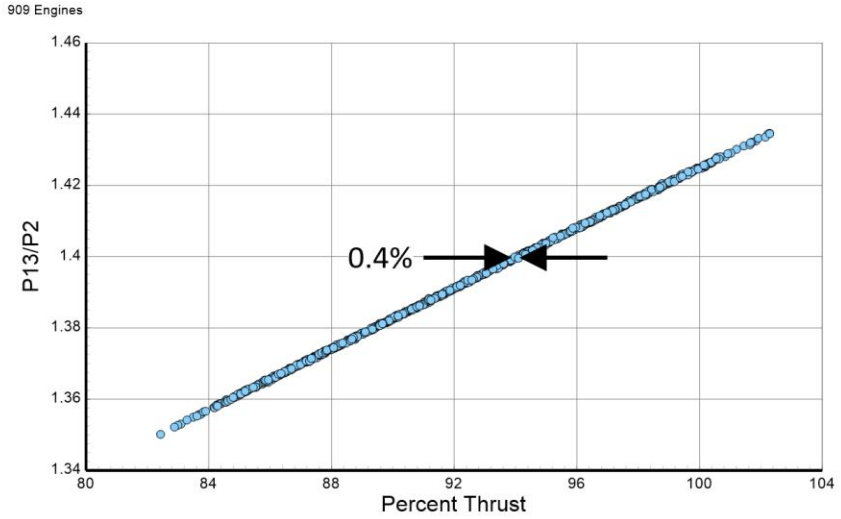
HP Spool Speed = 97 … 100%

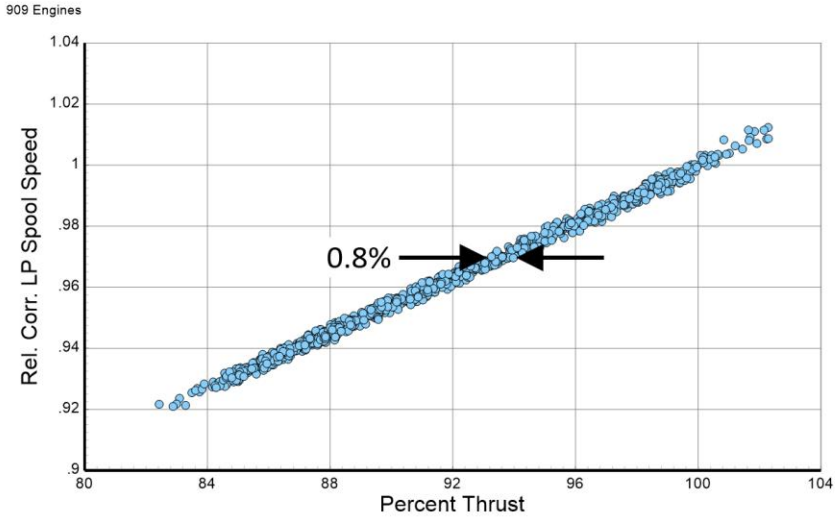


More Thrust Measurement Substitutes

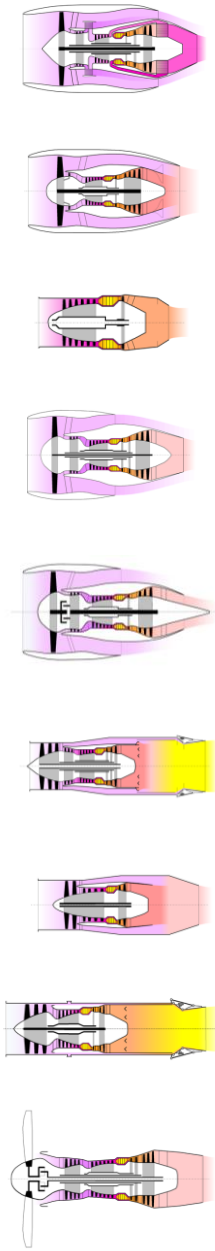








HP Spool Speed = 97 … 100%



The Preferred Thrust Setting Parameters

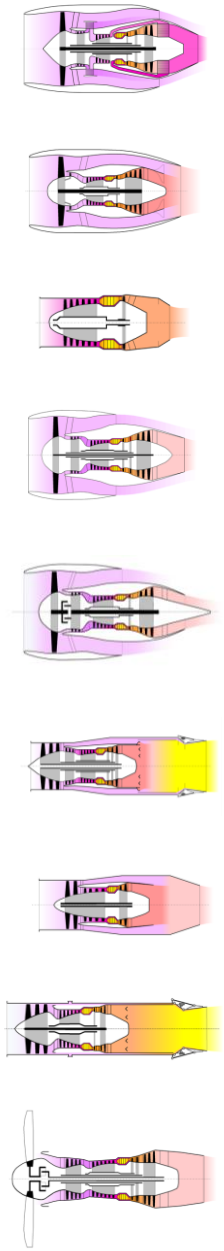
Percent of Fan Reference RPM (%N_1)

- The percentage of the reference rotation speed of the fan (GE and CFMI)
- The thermodynamic parameter is corrected fan speed N_{1corr} ($N_1/\sqrt{\Theta_2}$)

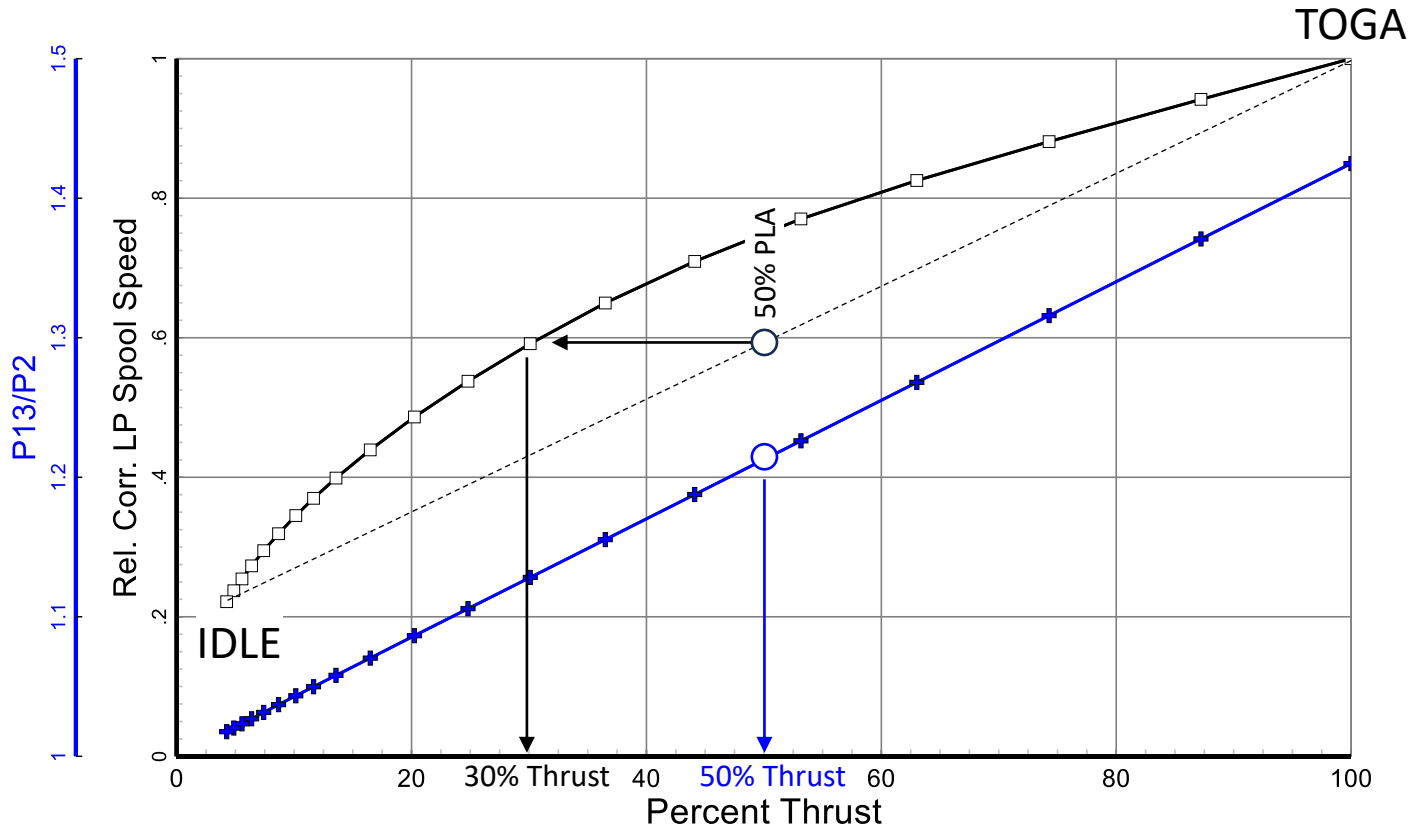
Engine Pressure Ratio (EPR)

- The ratio of the total pressure at the exhaust of the fan to the total pressure in front of the fan
- N_1 is the parameter for the thrust setting in degraded mode.

$\Theta_2=T_2/288.15K$



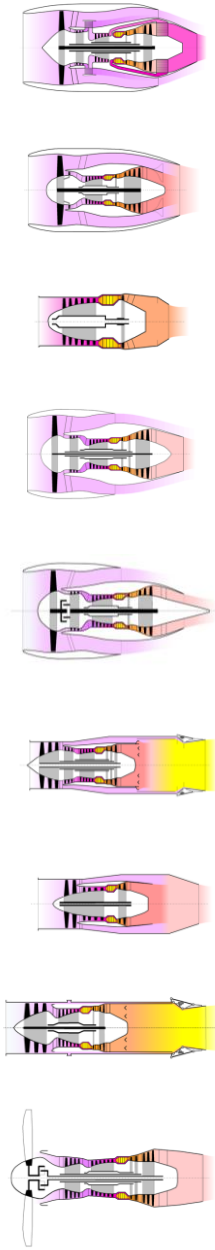
Correlations with Thrust



EPR is proportional to fan pressure ratio P_{13}/P_2. It gives the pilot a more linear response than N_1

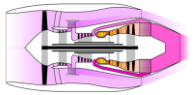
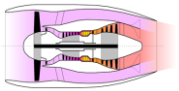
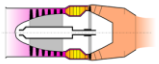
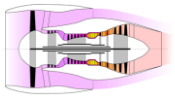
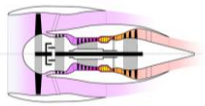
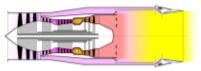
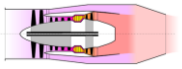
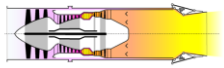
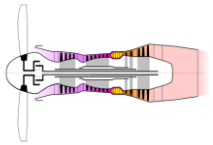
While a thrust lever at the halfway position in an EPR engine gives 50% of maximum thrust,

an N_1 engine may only give 30% of the total thrust, despite that the engine N_1 being halfway to maximum.



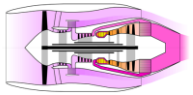
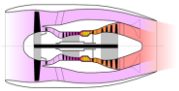
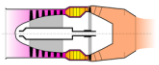
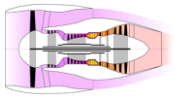
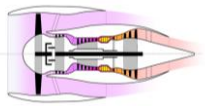
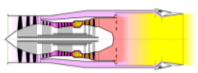
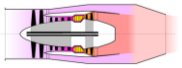
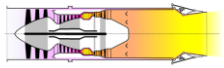
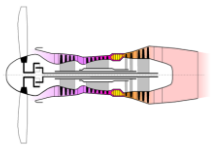
N_1 has Some Advantages

- N_1 is a single measurement
- EPR is derived from two measurements and therefore more liable to error/miscalculation.
- EPR becomes less accurate for engines with a very high bypass ratio because the fan pressure ratio decreases as the bypass ratio increases.

New Cockpit Design Approach…

- Traditionally thrust is not indicated in the cockpit.
- Airbus A380 (Trent 900 or GP7000)/A350(Trent XWB) display % THRUST as thrust parameter to the pilots.
- 0% THRUST equals windmilling thrust.
- 100% THRUST equals **T**ake-**O**ff/**G**o-**A**round (TOGA), bleed off.
- THRUST is based upon N_1.

Outline

Constant thrust, independent from engine-to-engine variations and deterioration

Wing-mounted Engines

Thrust

- Thrust Setting Parameters
- Engine Pressure Ratio
- Spool Speed

Ratings

- Flat Rating
- Generating Schedules
- Derating
- Idle

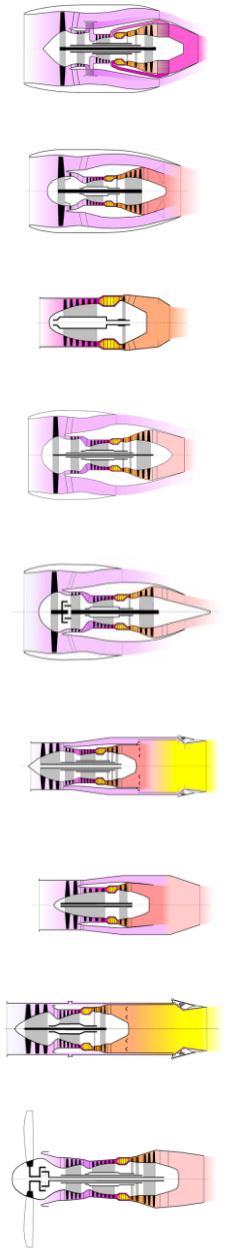
Exhaust Gas Temperature

- Deterioration
- EGT Margin

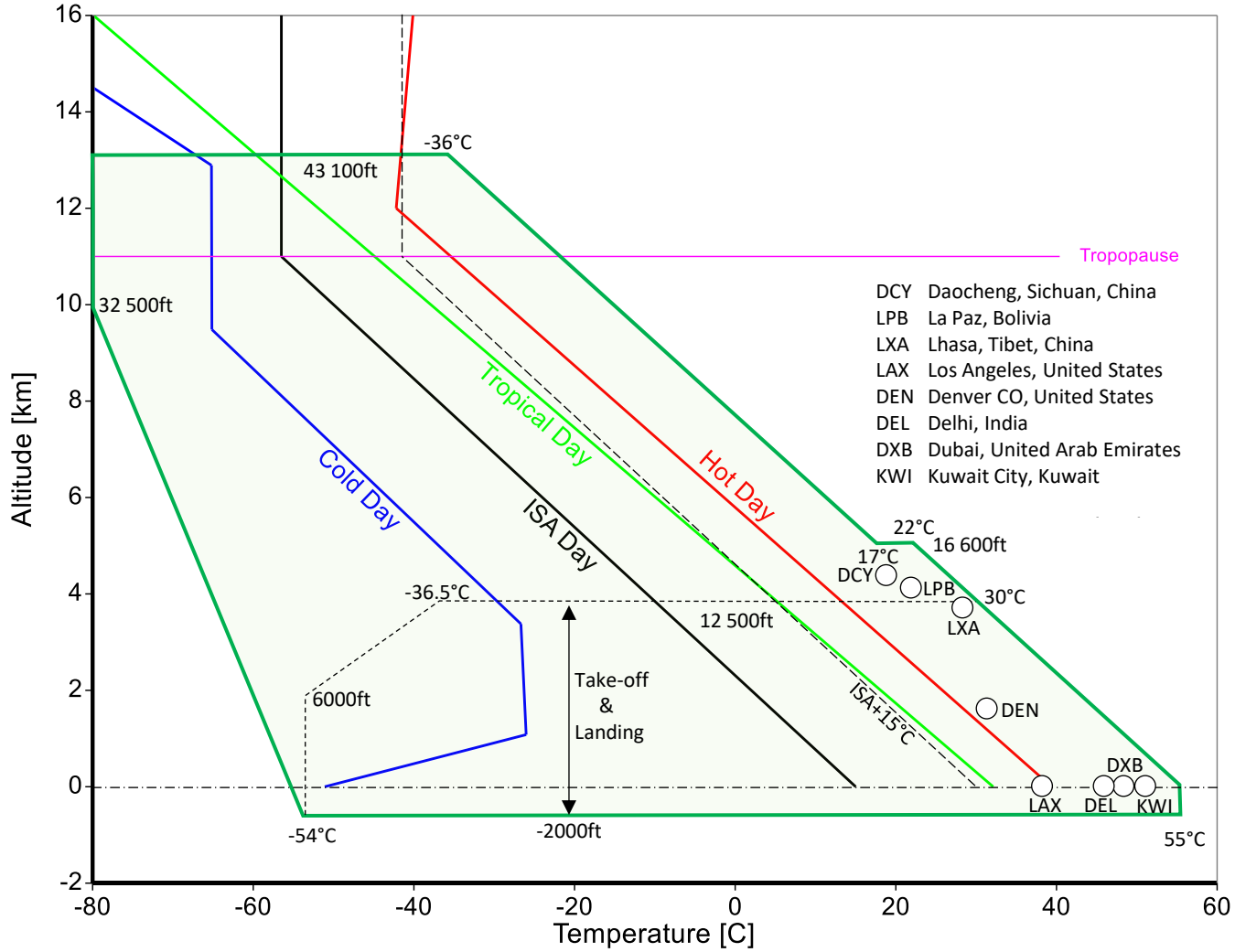
The Cockpit

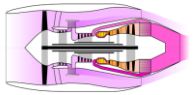
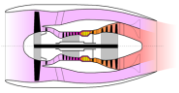
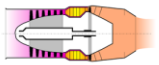
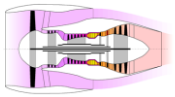
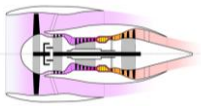
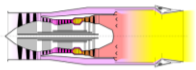
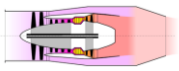
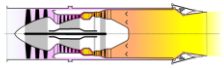
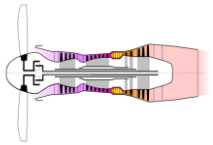
- A320
- A350

Transient



Typical Environmental Envelope



Limitations on Maximum Thrust

Pressure differential across the engine case at station 3:

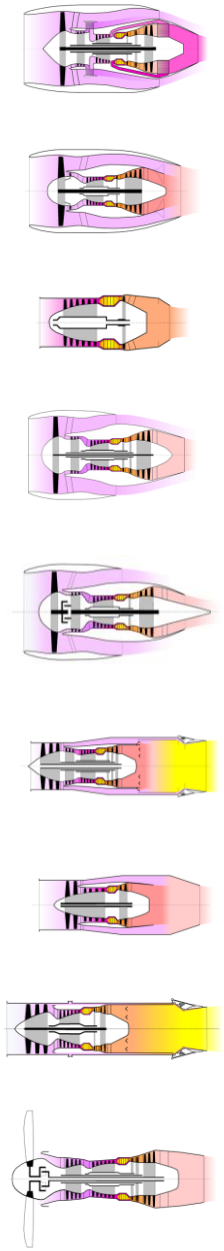
- Modern engines have compression ratios of as high as 50:1. Therefore, if ambient pressure is 100kPa the pressure inside the engine can be as high as 5000kPa; a differential pressure of as much as 4900kPa.

Turbine inlet temperature

- This limitation is required to avoid exceeding design maximum temperatures of the materials in the hottest section of the engine.

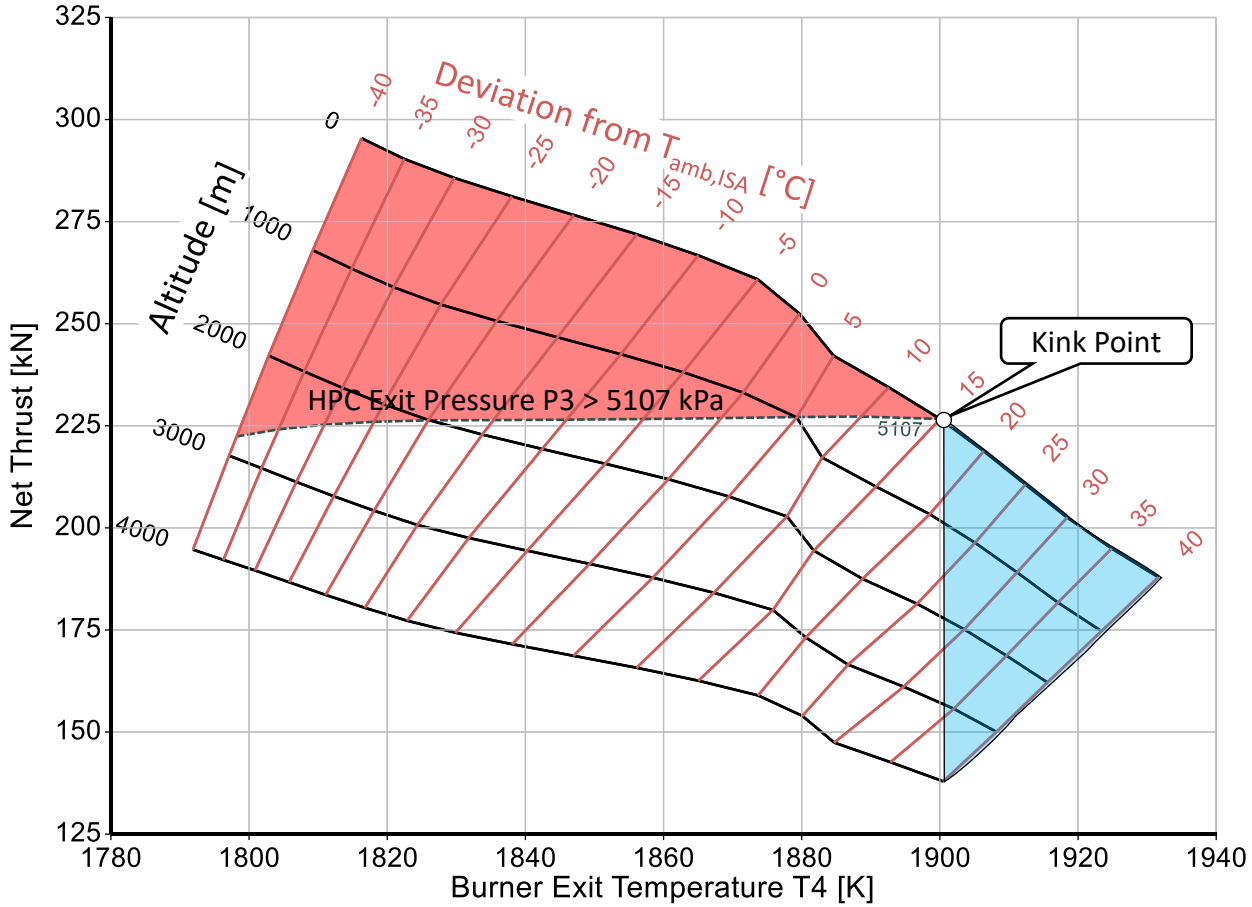
Fan speed (N_1) and core speed (N_2)

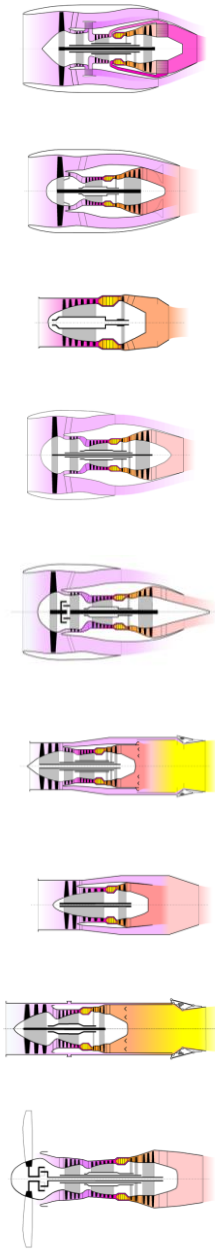
- High centrifugal forces at the rim of a disk can also limit the maximum allowable thrust.



Thermodynamic Potential

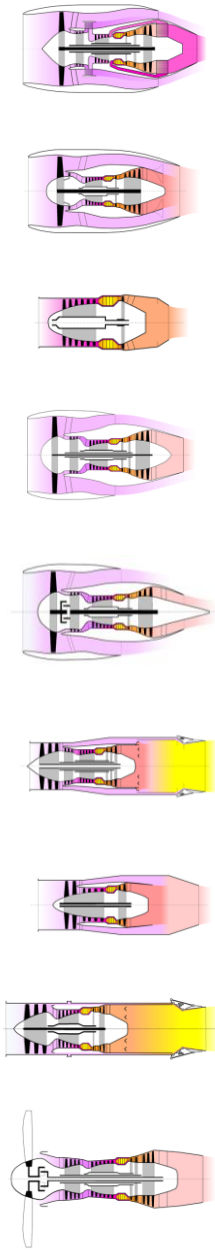
Thrust for 100% HP Spool Speed





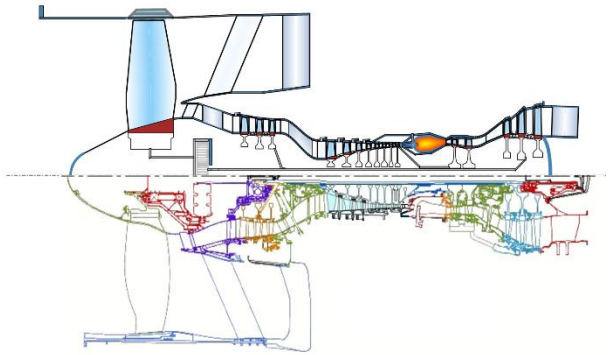
Flat Rating

- Engine manufacturers define the guaranteed maximum thrust of an engine based on its maximum limits (e.g. EGT, N_1, N_2) and up to a defined Outer Air Temperature OAT. This OAT is called the flat rate temperature.
  - It is also commonly called corner point temperature, breakpoint temperature, or kink point temperature.
  - Above this OAT value, the engine control manages the thrust to maintain a constant EGT.
- The maximum thrust and flat rate temperature are selected so that a new or overhauled engine has a sufficient EGT margin to the EGT redline.
  - This will enable the engine to sustain a certain amount of engine wear and still be capable of producing its maximum thrust rating without reaching the EGT redline.
- An OAT of 30°C at sea level (ISA +15°C) is usually defined at max take-off by engine manufacturers as a compromise for the flat rate temperature.



Technical Terms

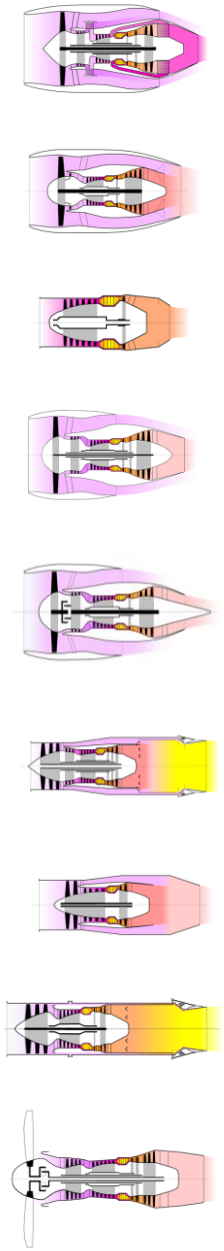
Engine



- Non-dimensional performance
  - Temperature and pressure ratios
  - Internal Mach numbers
- Operating condition
  - T_2 (inlet total temperature, °K)
  - P_2 (inlet total pressure)
  - P_{amb} (ambient pressure)
  - Spool speed

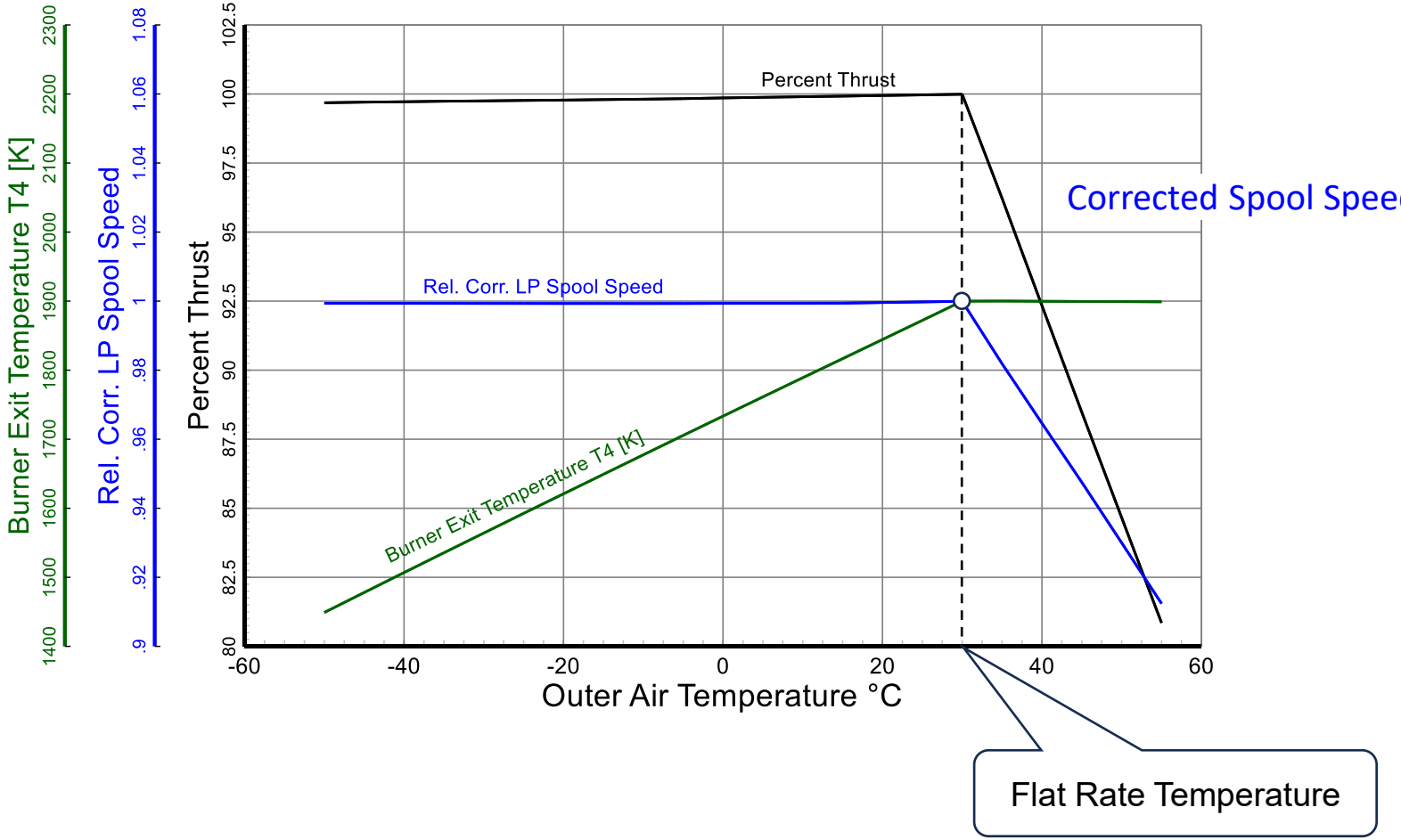
Aircraft

- Flight velocity (speed)
- Pressure altitude
- OAT (Outer Air Temperature, °C)
- Flight Mach number



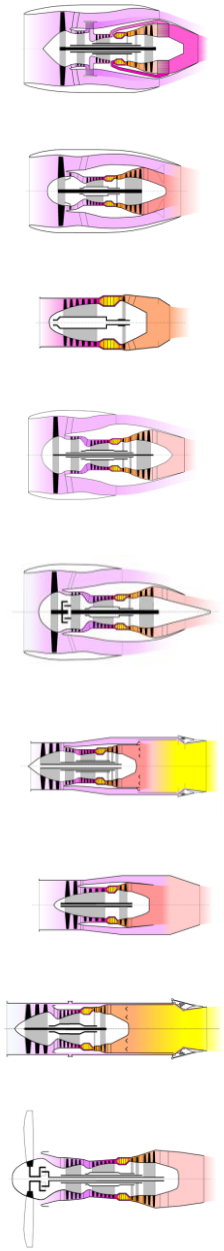
Flat Rating

Thrust, N_{Lcorr} and Burner Exit Temperature T_4 @ Sea Level

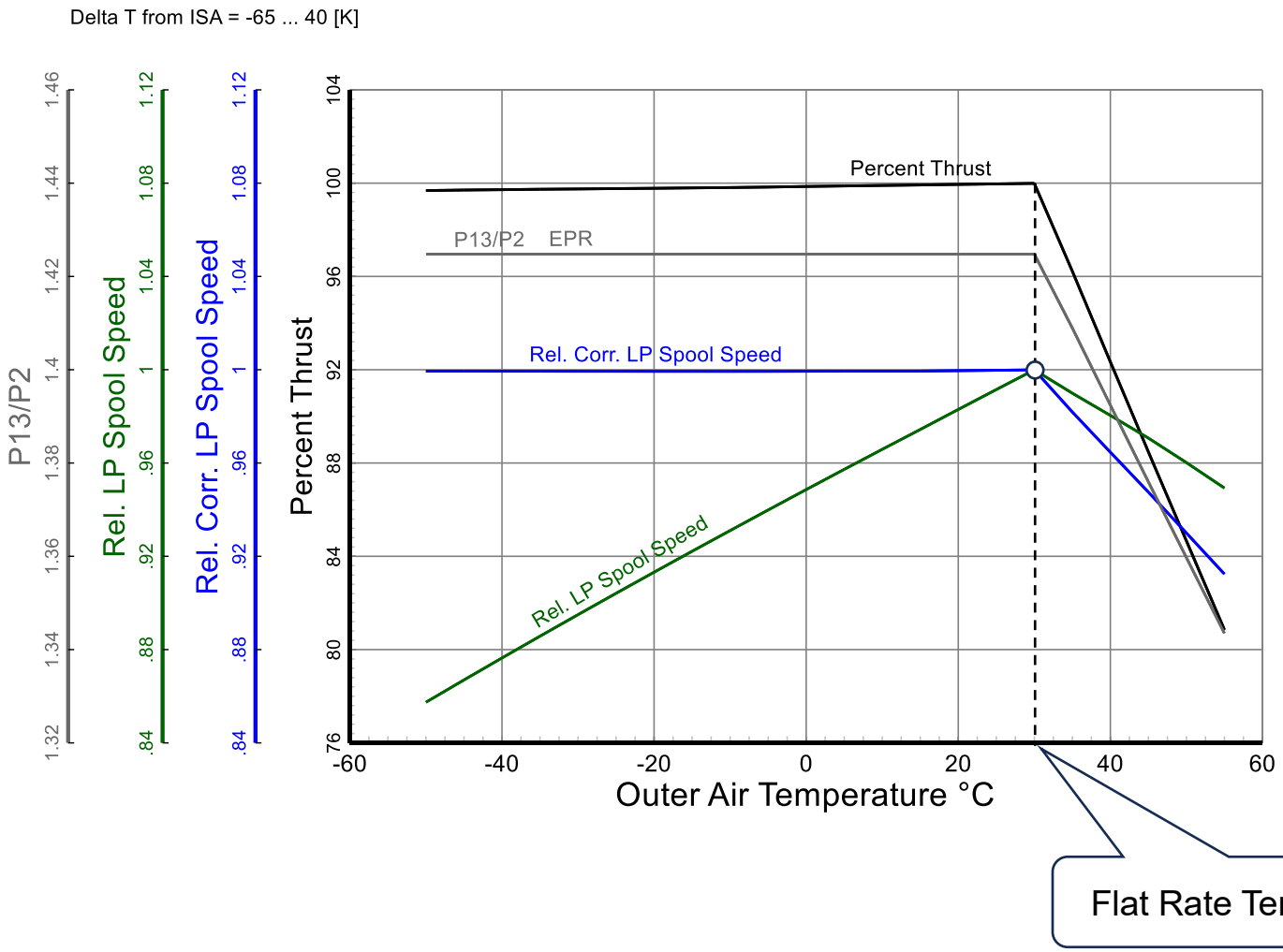


$$\text{Corrected Spool Speed} = \frac{N_L}{\sqrt{\Theta_2}}$$

$$\Theta_2 = \frac{T_2}{288.15K}$$

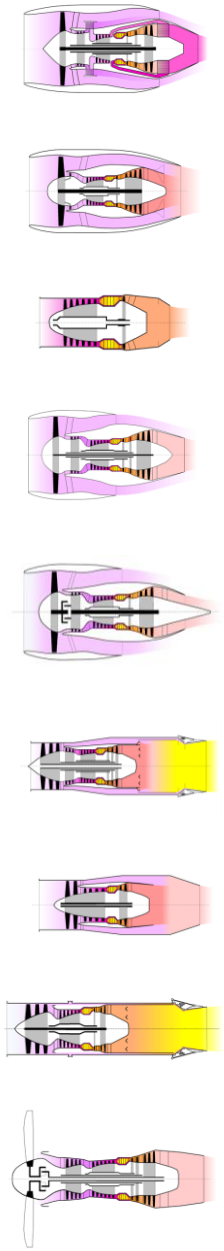


EPR and $N_L/\sqrt{\Theta}$ Represent Thrust



Instead of $\frac{N_1}{\sqrt{\Theta_2}}$

N_1 is used in practice



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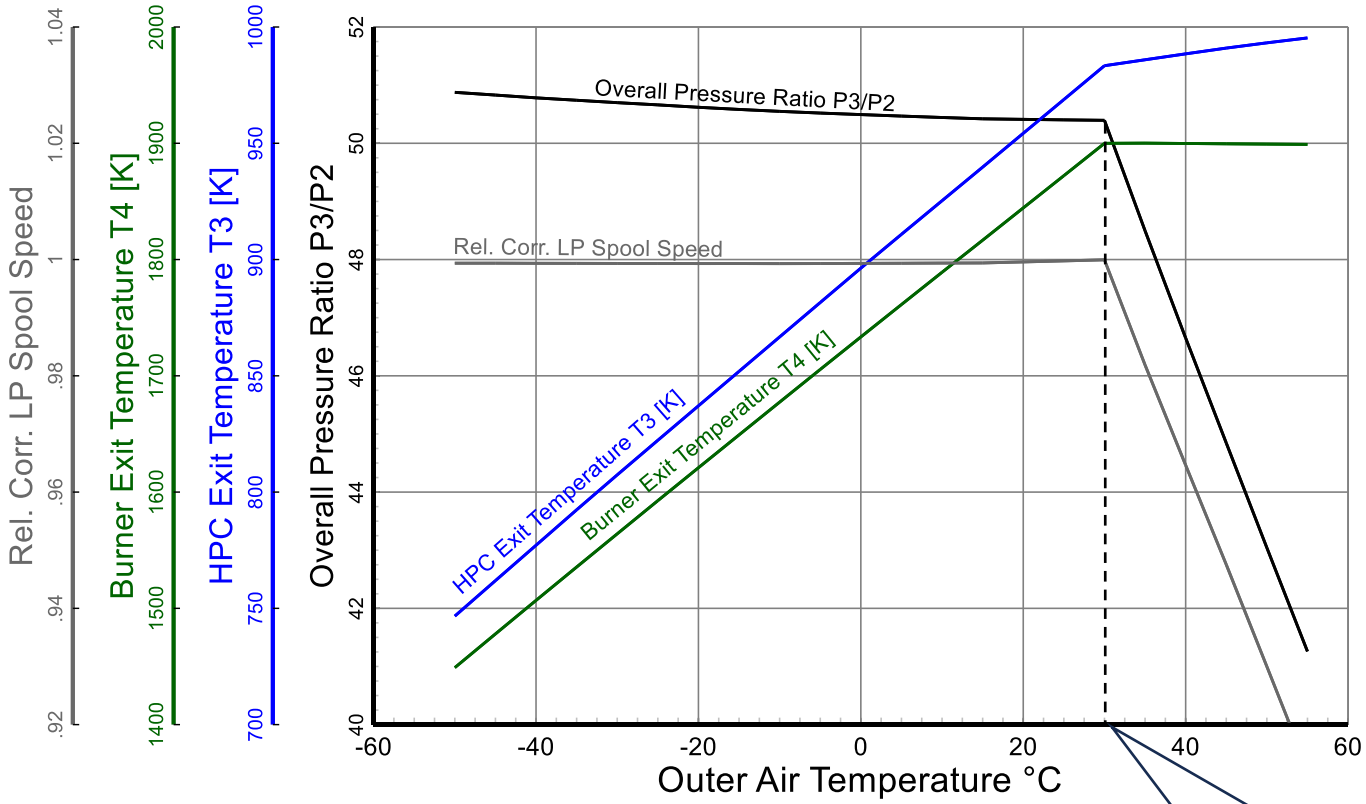
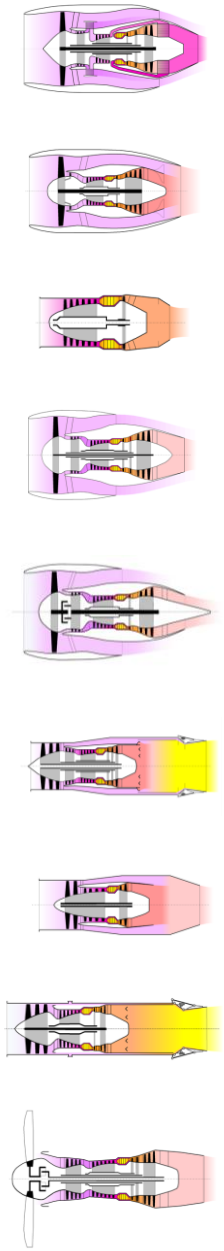
Flat Rating

HPC Exit Temperature T_3



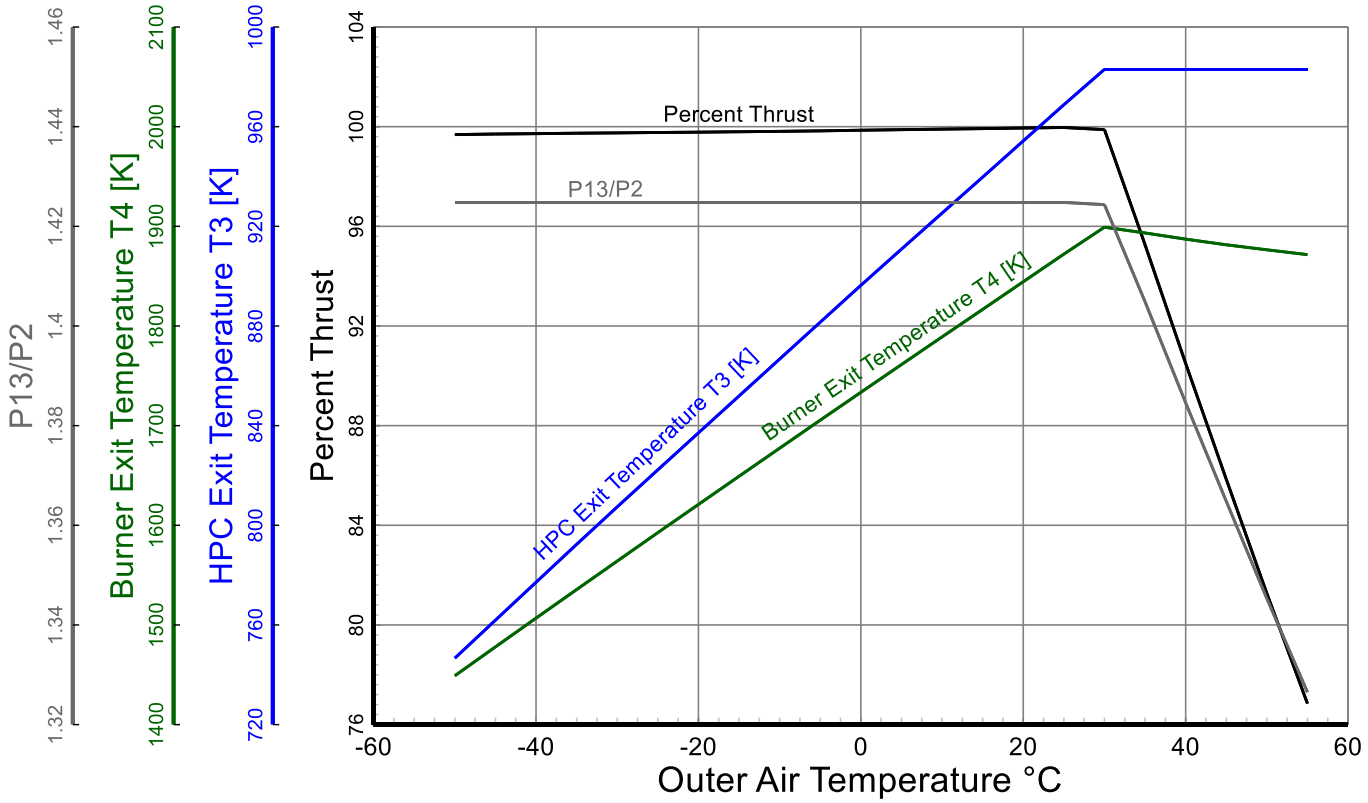
HPC Exit Temp. T_3 increases

when Burner Exit Temp. T_4 is kept constant

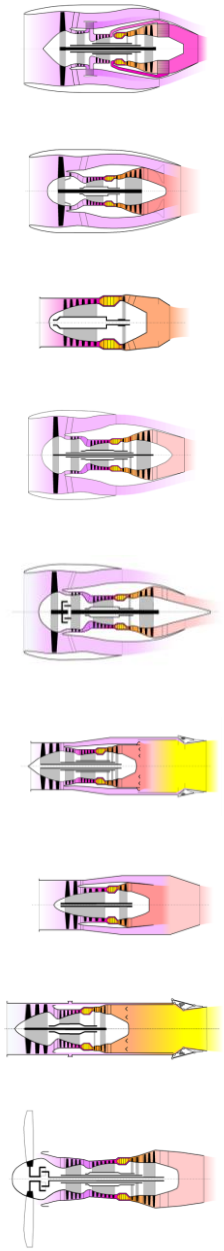


Flat Rating

HPC Exit Temperature T_3 Limited

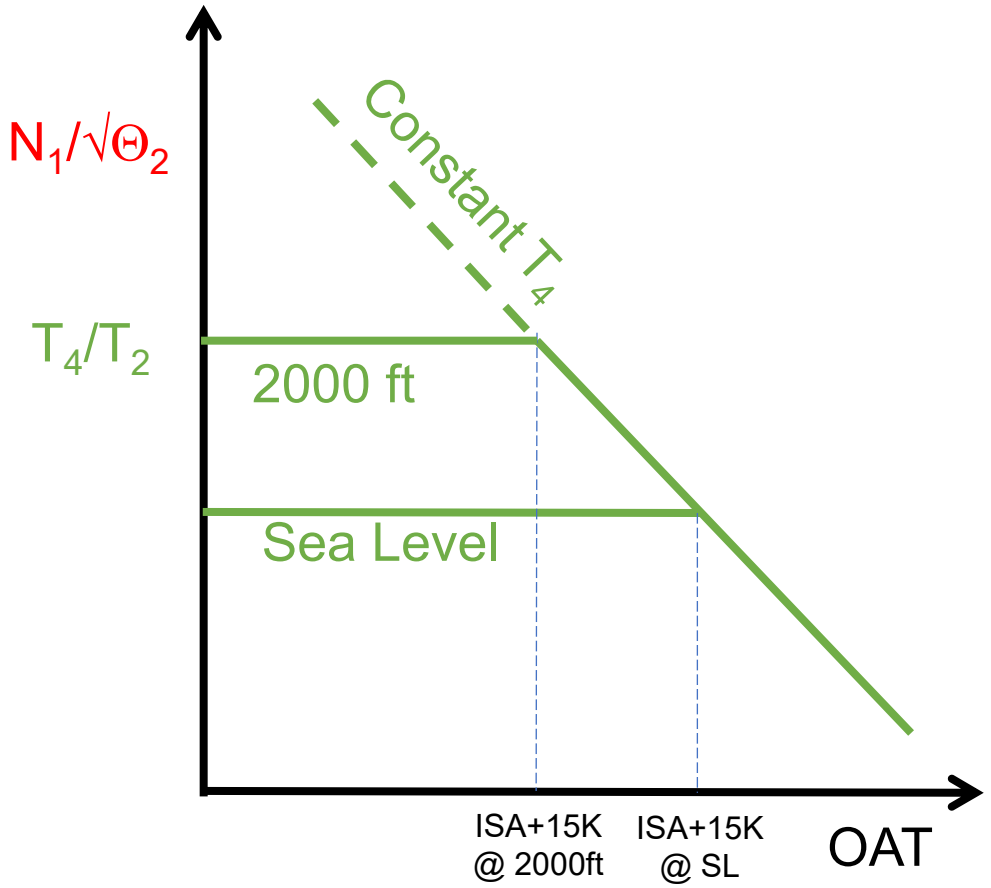


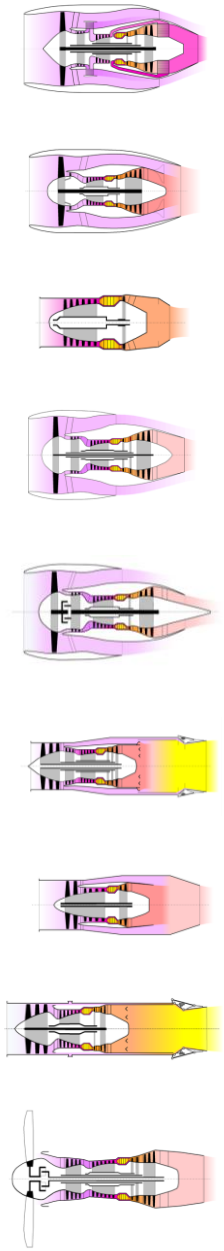
T_3 can be a limit at low altitude.



$N_1/\sqrt{\Theta_2}$ at Altitude

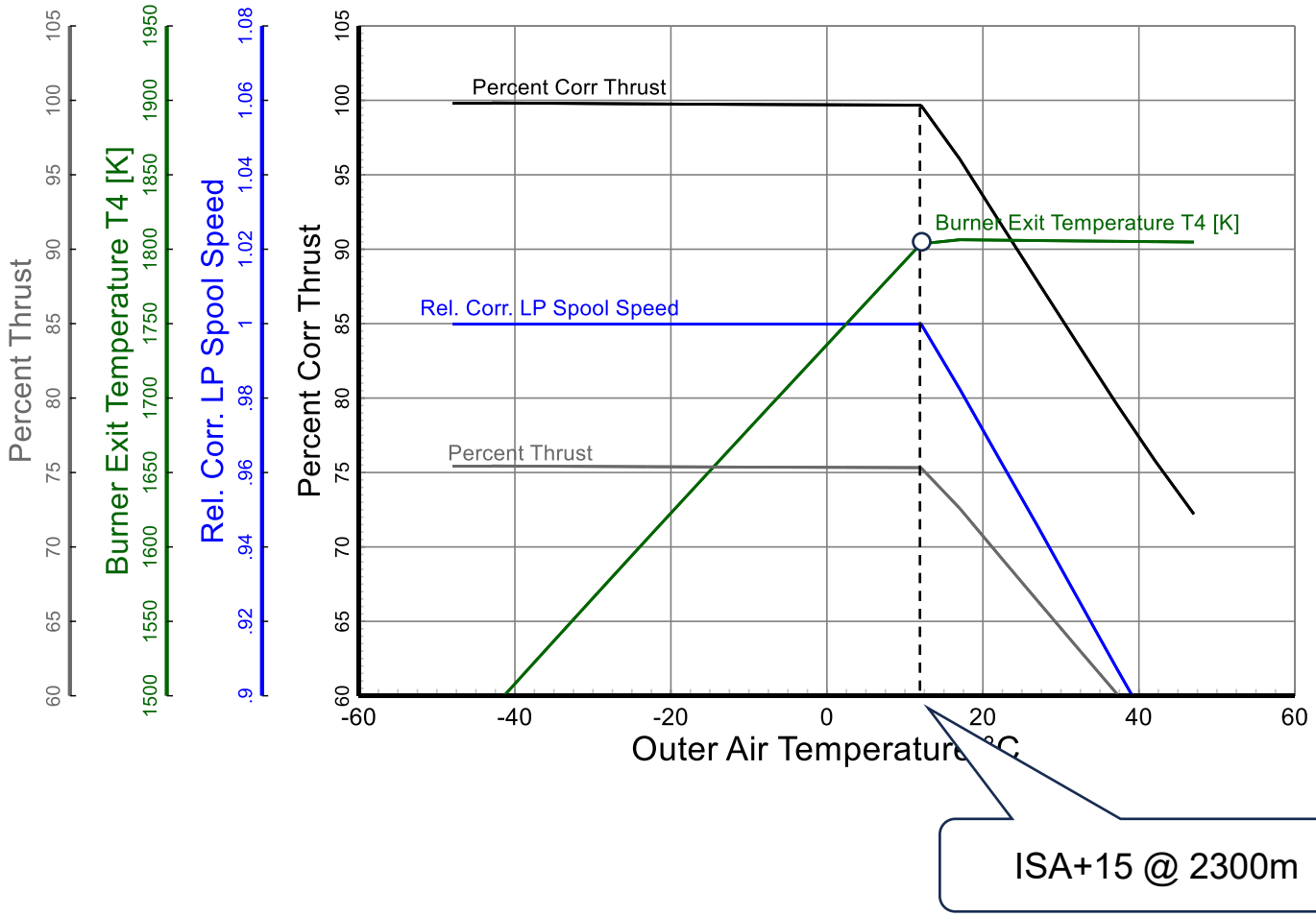
- Thrust at increasing altitude is defined as the intersection between the constant T_4 line and the OAT ISA + 15°K at altitude
- This means increasing non-dimensional condition with altitude since T_2 decreases and thus T_4/T_2 increases
- $N_1/\sqrt{\theta_2}$ changes in proportion to T_4/T_2 , it increases with altitude





Flat Rating @ 2300m

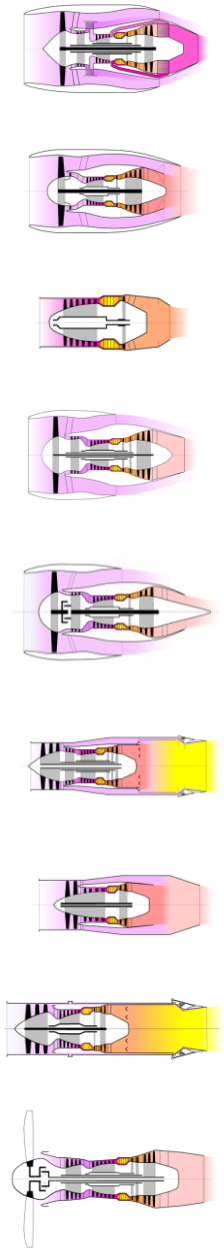
Max $N_L/\sqrt{\Theta}$ =100% Burner Exit Temperature =1805K



Corrected Thrust

$$F_{corr} = \frac{F}{\delta}$$

$$\delta_2 = \frac{P_2}{101.325kPa}$$



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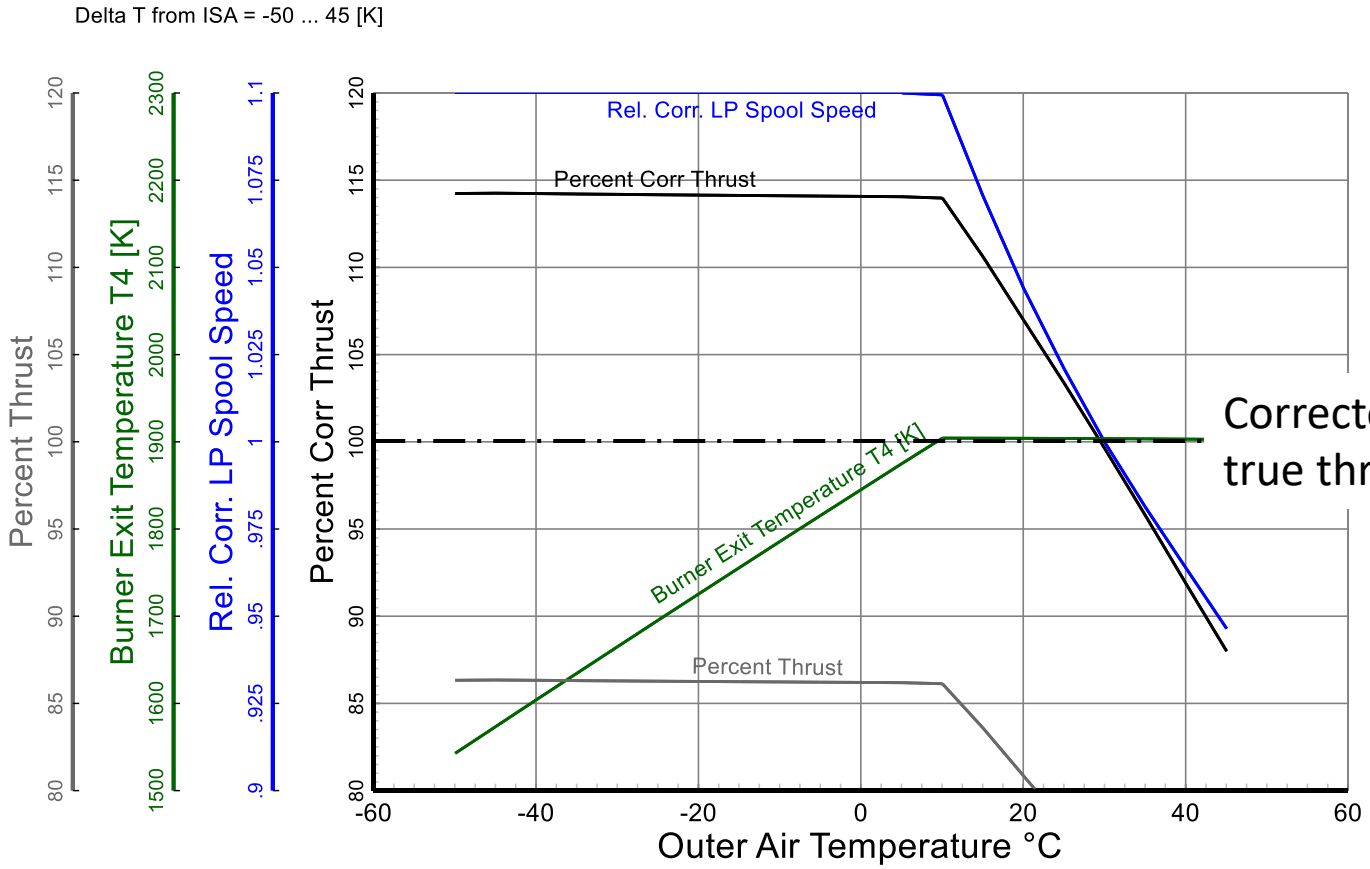
Flat Rating @ 2300m

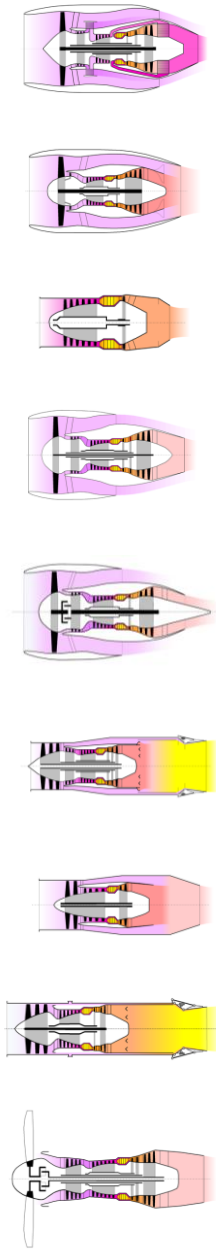
Max $N_L/\sqrt{\Theta}$ =110% Burner Exit Temperature =1900K



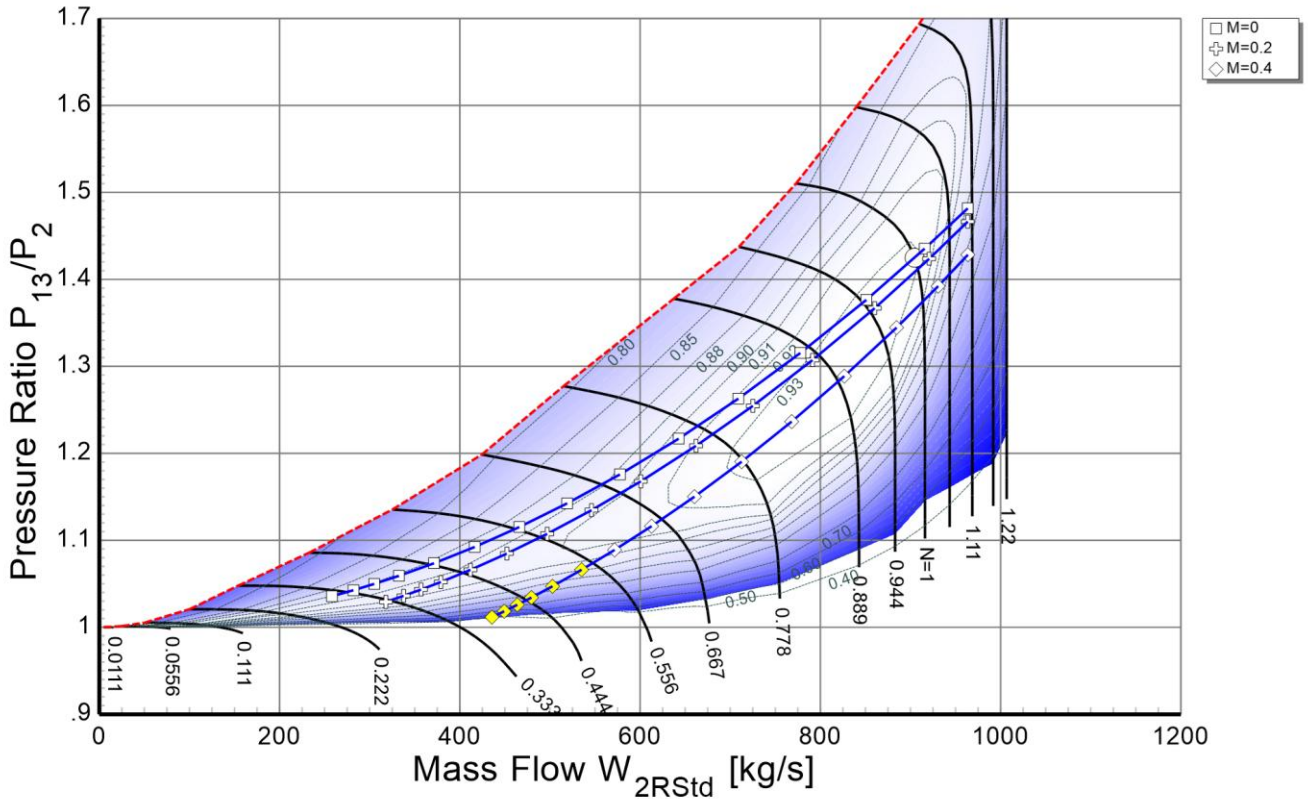
Corrected thrust F/δ_2 increases, true thrust F decreases

$$\Theta_2 = \frac{T_2}{288.15K}$$

$$\delta_2 = \frac{P_2}{101.325kPa}$$

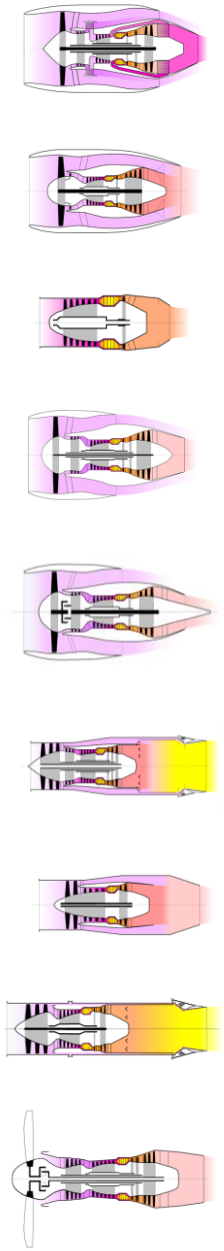


Schedules Must be a Function of Flight Mach Number



Fan operating lines , i.e. the correlations between mass flow, pressure ratio and corrected speed, change with flight Mach number.

P_2/P_{amb} is a measure of flight Mach number



Outline

Constant thrust, independent from engine-to-engine variations and deterioration

Wing-mounted Engines

Thrust

- Thrust Setting Parameters
- Engine Pressure Ratio
- Spool Speed

Ratings

- Flat Rating
- Generating Schedules
- Derating
- Idle

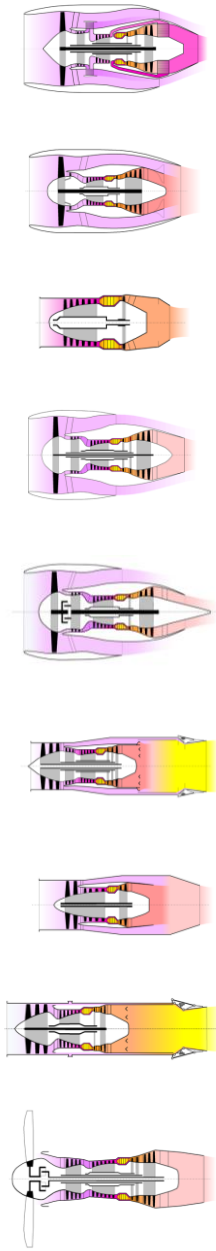
Exhaust Gas Temperature

- Deterioration
- EGT Margin

The Cockpit

- A320
- A350

Transient



The Thrust Rating Parameter is an Umbrella Covering all Limiters

HP Turbine Inlet Temperature T_4

LP Turbine Inlet Temperature T_{45}

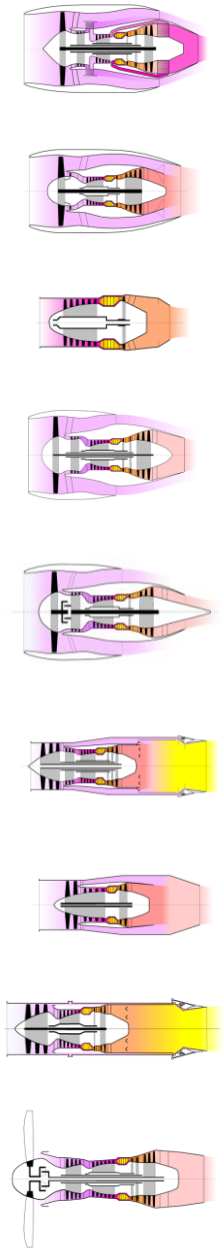
Compressor Exit Temperature T_3

Burner Inlet Pressure P_3

Fan Speed N_1

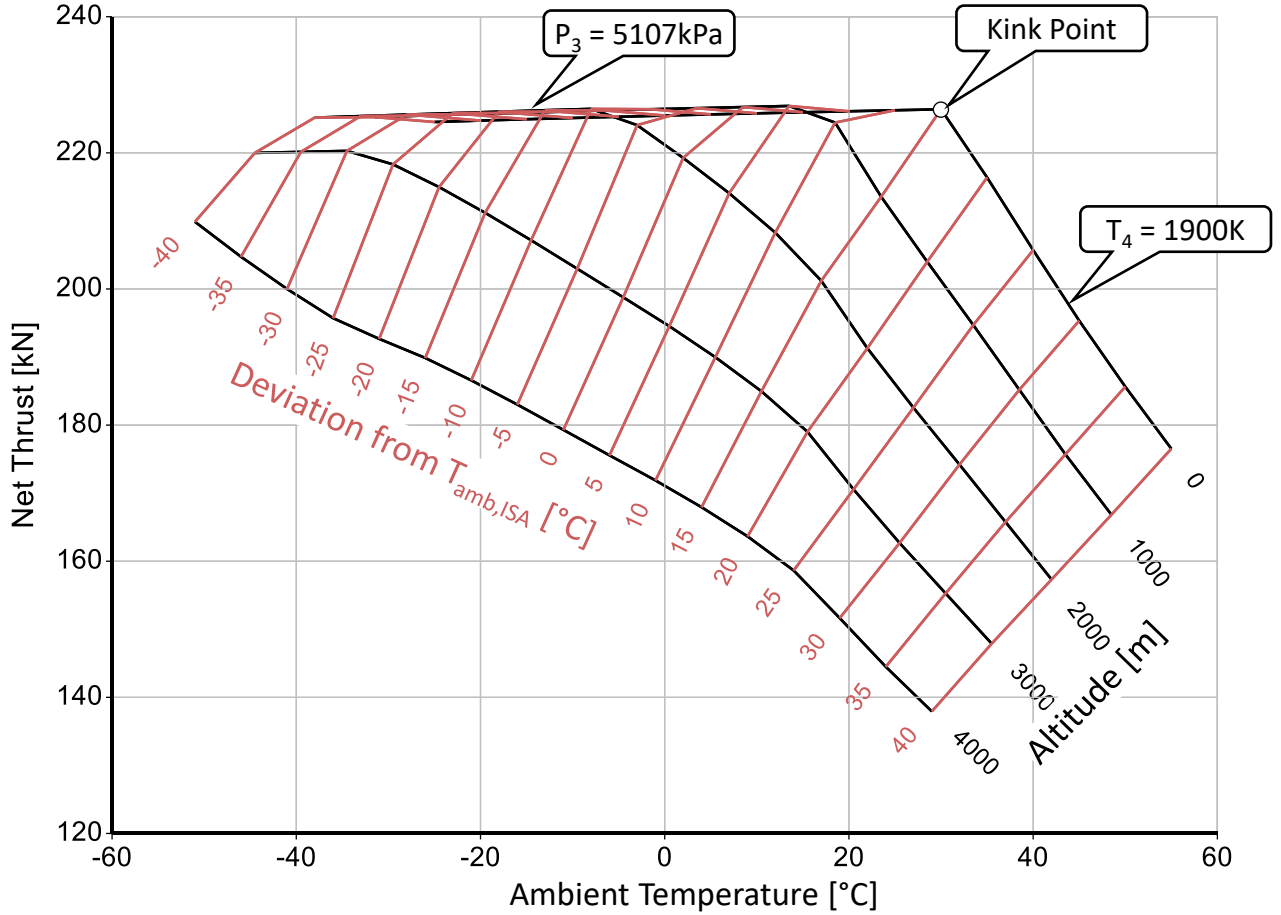
Gas Generator Speed N_{GG}

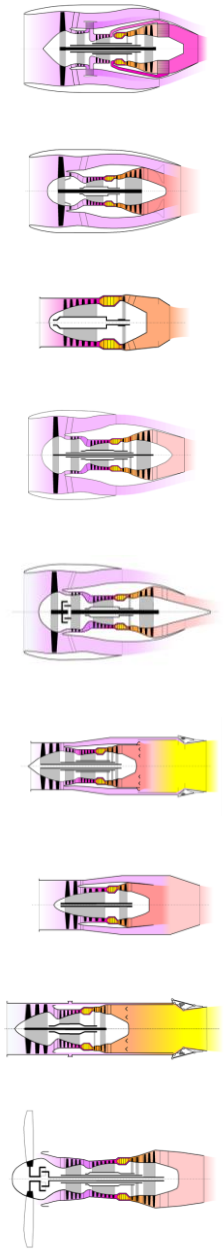
Fan Corrected Speed $N_1/\sqrt{\Theta_2}$



Thrust with P_3 and T_4 Limitation

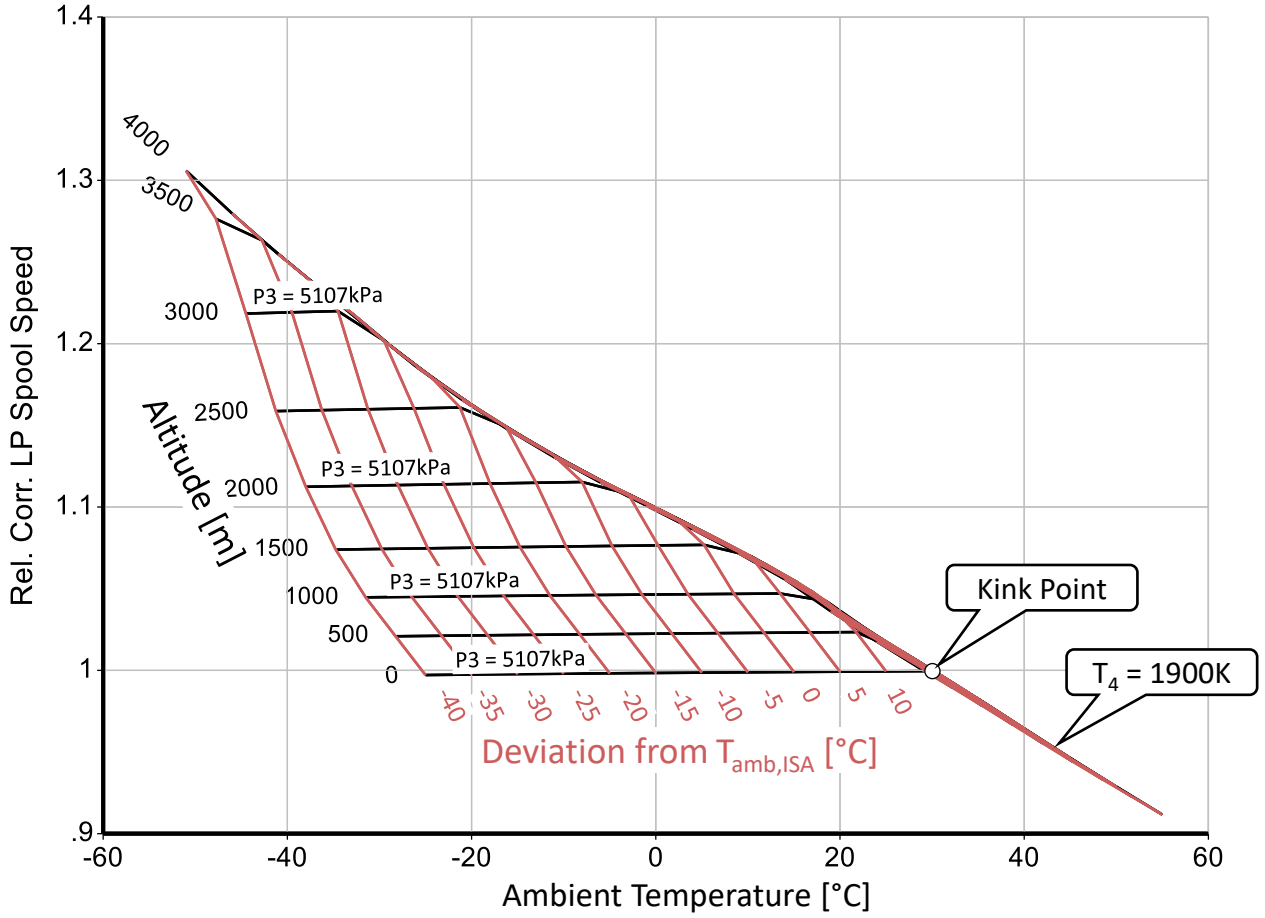
$P_3 \leq 5107kPa$ $T_4 \leq 1900K$

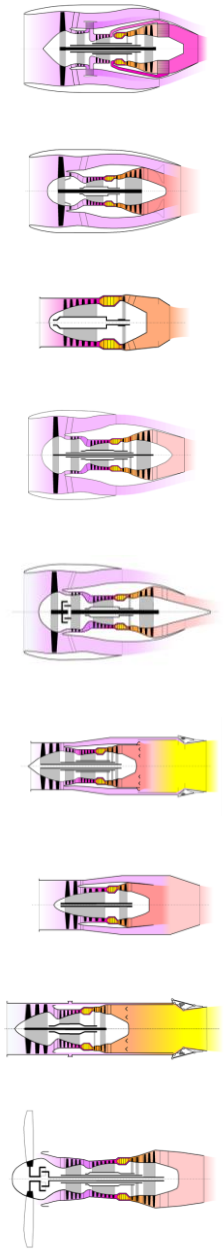




Relative $N_1/\sqrt{\Theta_2}$ With P_3 and T_4 Limits Only

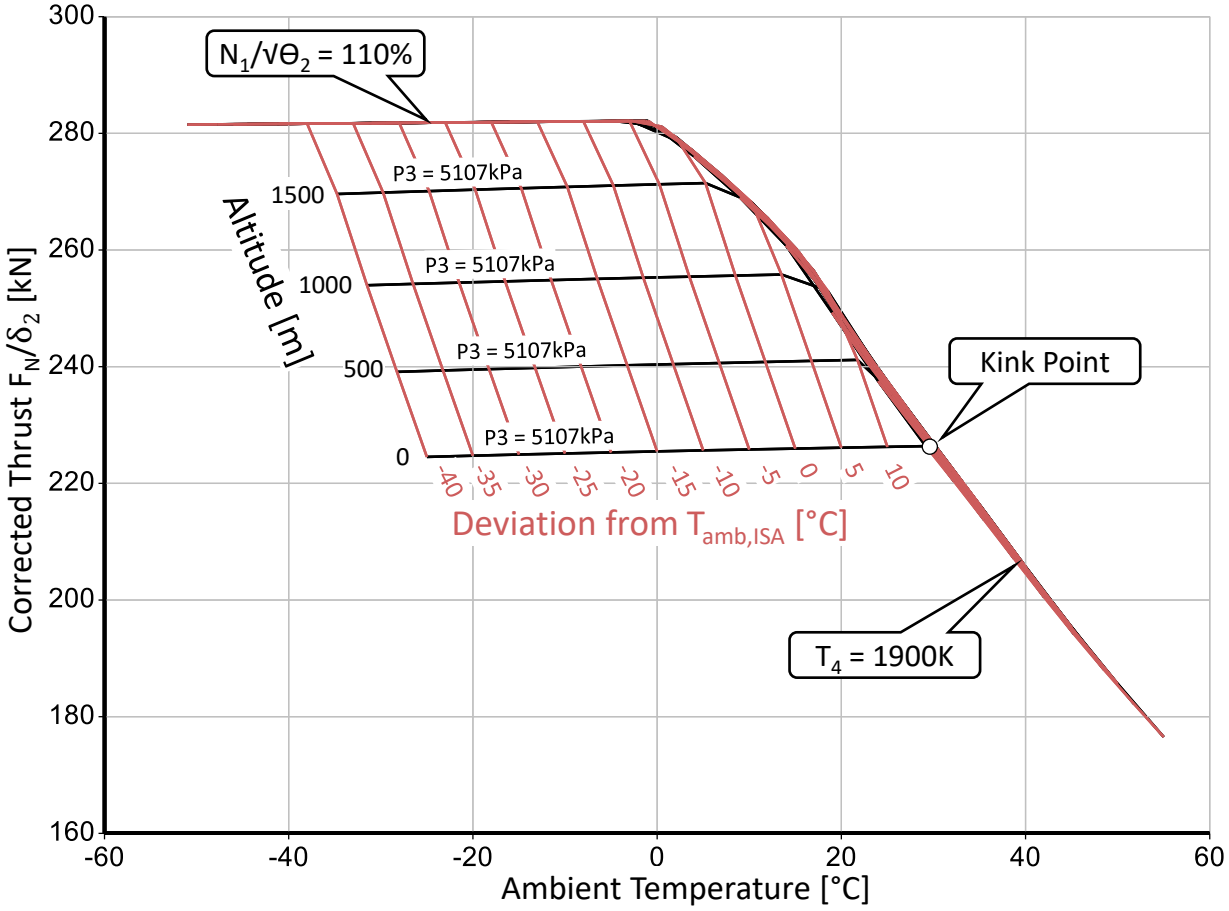
$P_3 \leq 5107kPa$ $T_4 \leq 1900K$

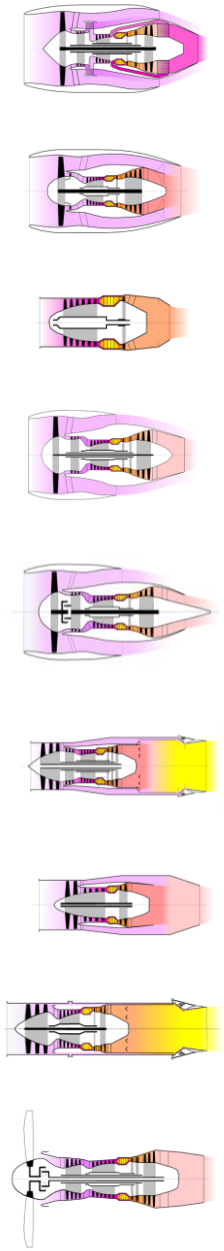




Corrected Thrust F/δ_2 With P_3, T_4 and $N_1/\sqrt{\Theta_2}$ Limits

$P_3 \leq 5107kPa$ $T_4 \leq 1900K$ $N_1/\sqrt{\Theta_2} \leq 110\%$





Corrected Thrust F/δ_2 with P_3, T_4 and $N_1/\sqrt{\Theta_2}$ Limits

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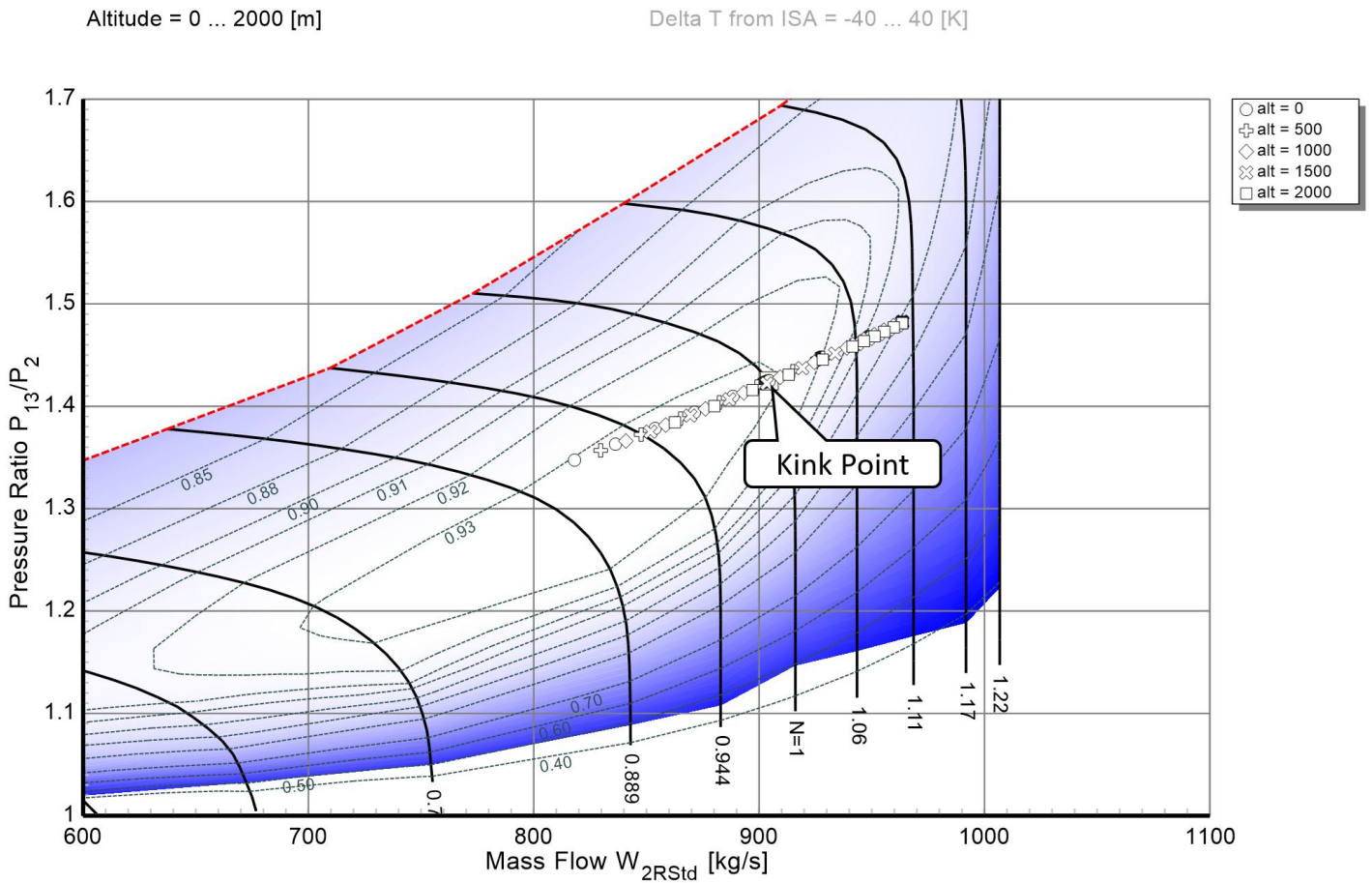
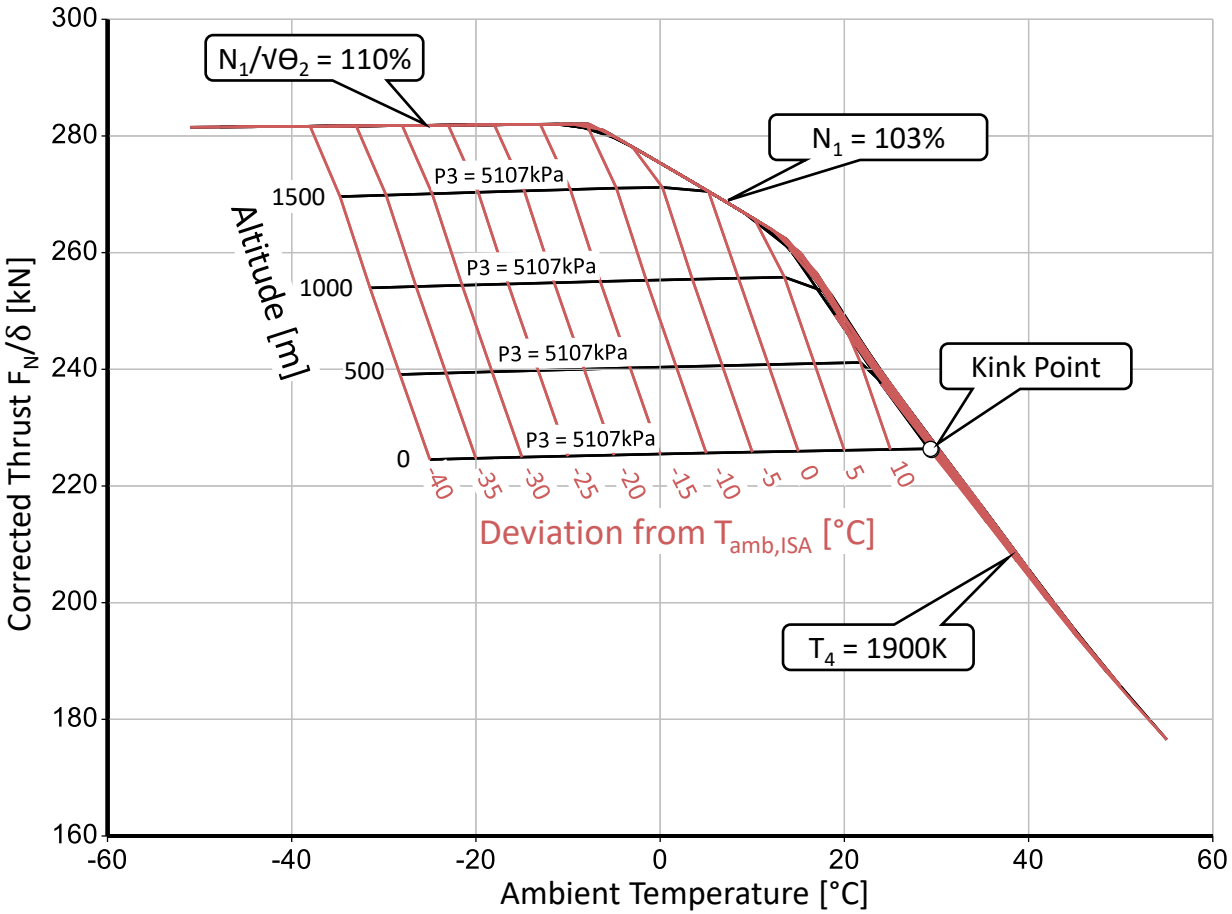
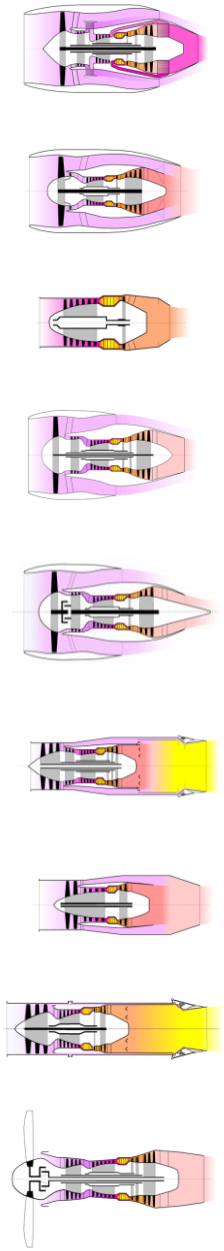


Corrected Thrust F/δ_2 with P_3, T_4, $N_1/\sqrt{\Theta_2}$ and Absolute N_1 Limits

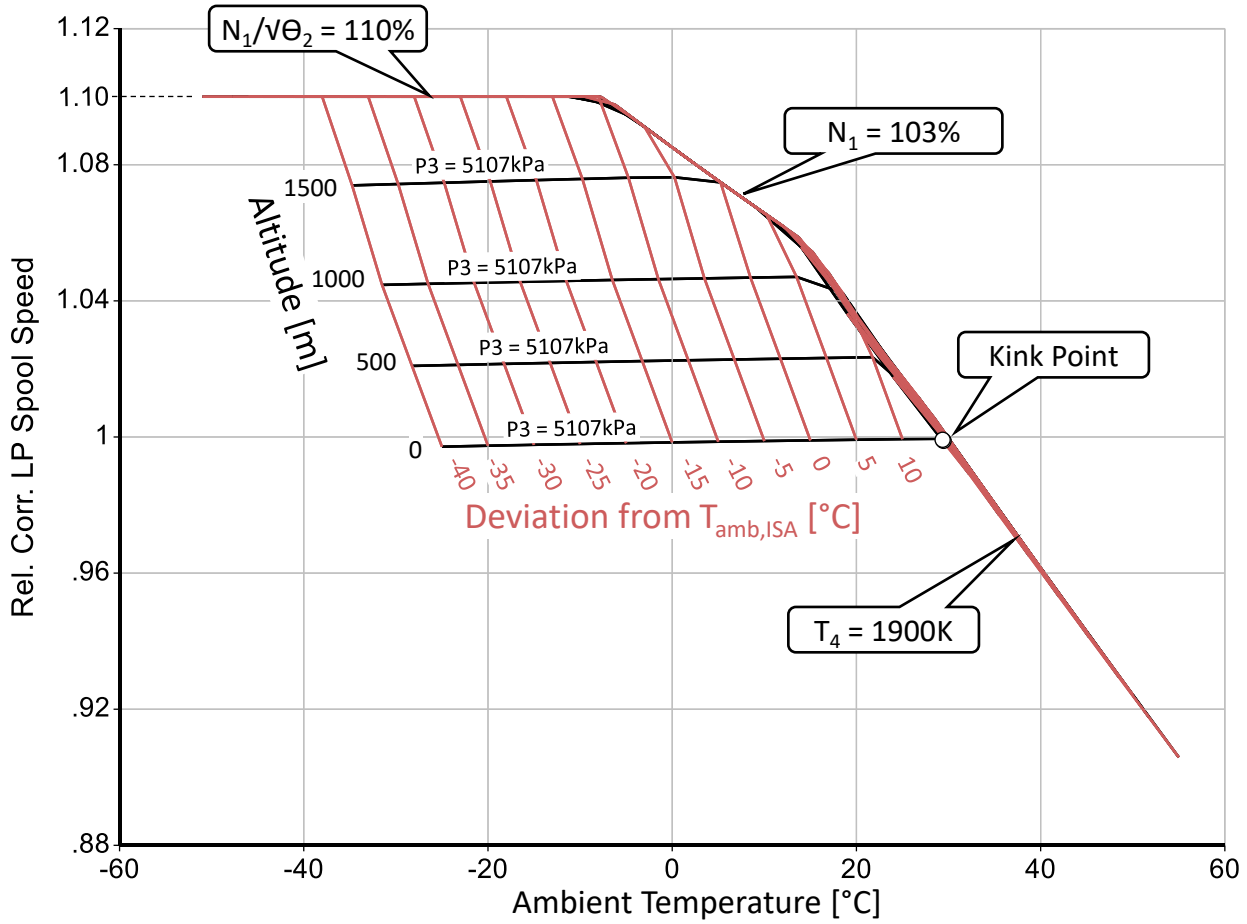
$P_3 \leq 5107kPa$ $T_4 \leq 1900K$ $N_1/\sqrt{\Theta_2} \leq 110\%$ $N_1 \leq 103\%$

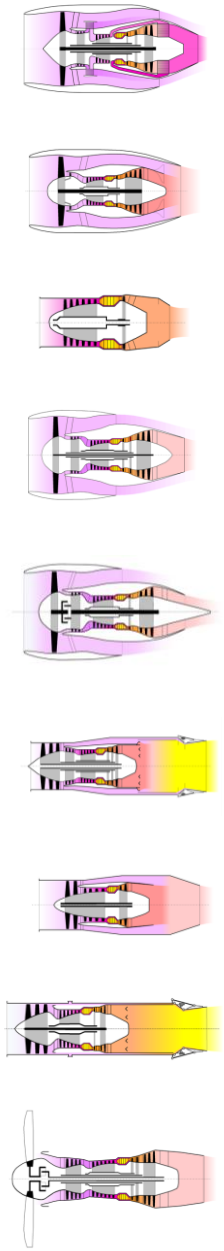




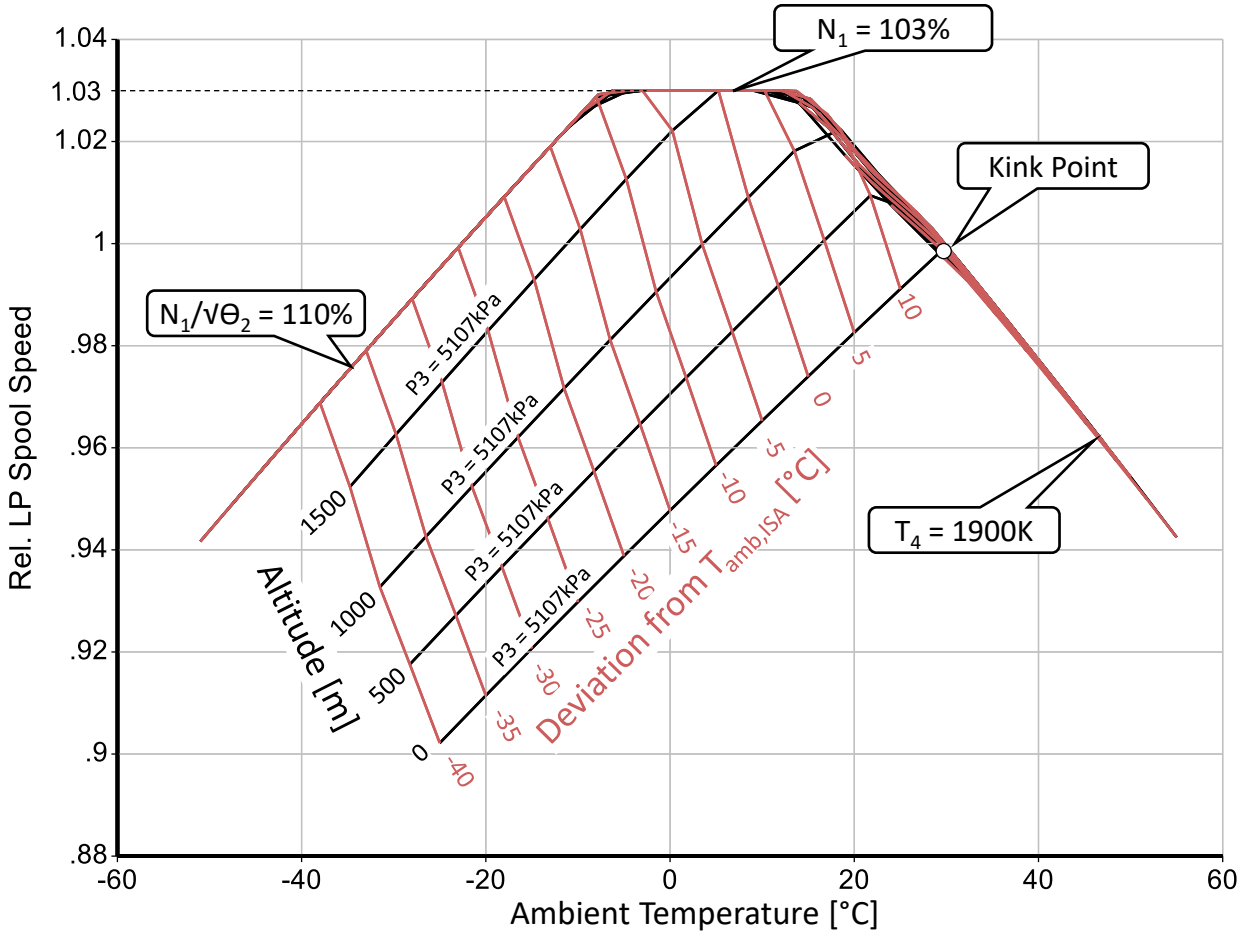
Relative $N_1/\sqrt{\Theta_2}$ with P_3, T_4, and N_1 Limits

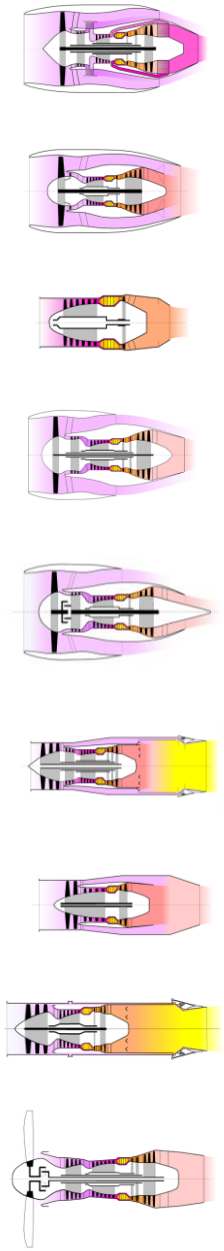
$P_3 \leq 5107kPa$ $T_4 \leq 1900K$ $N_1/\sqrt{\Theta_2} \leq 110\%$ $N_1 \leq 103\%$



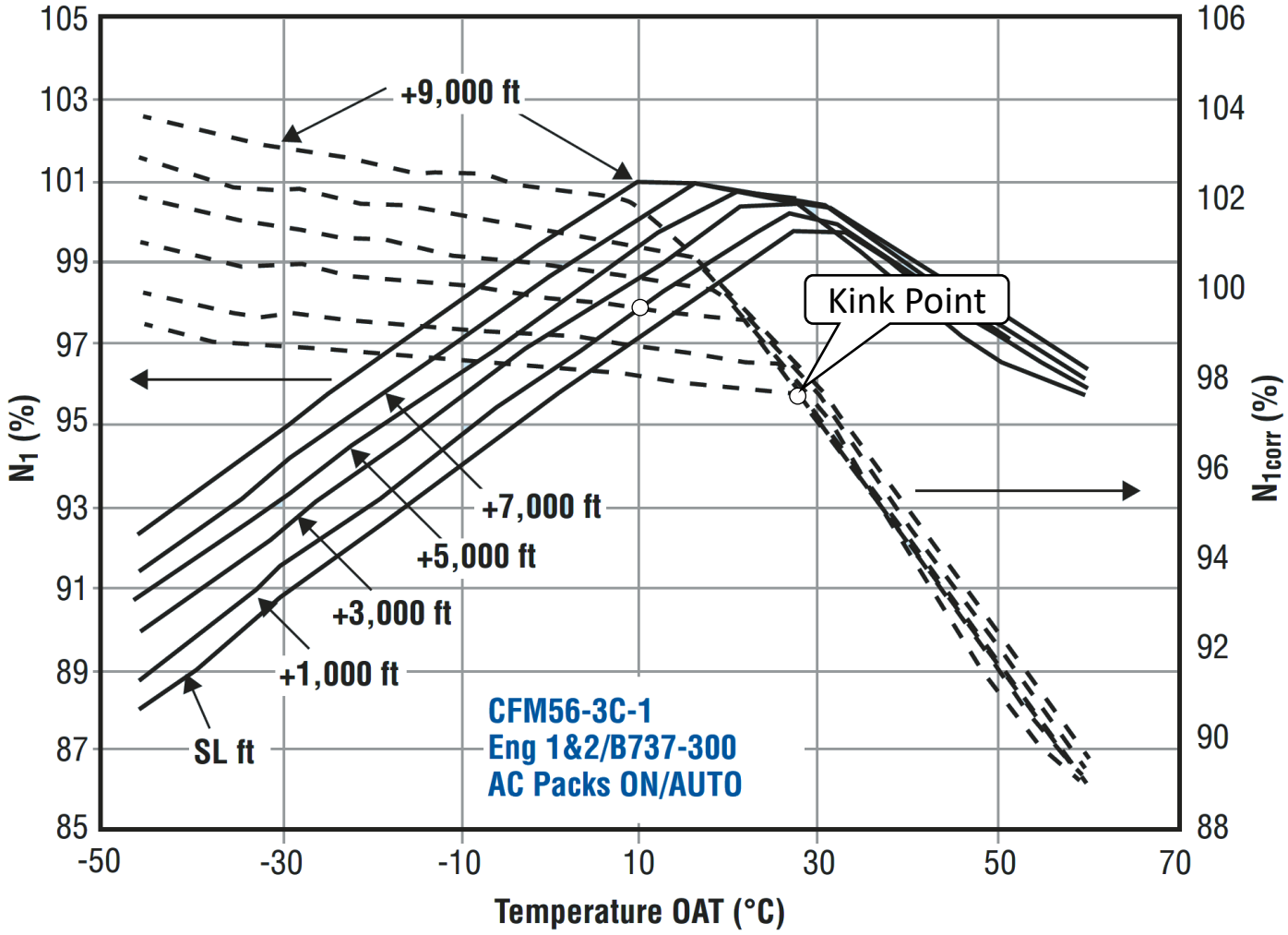


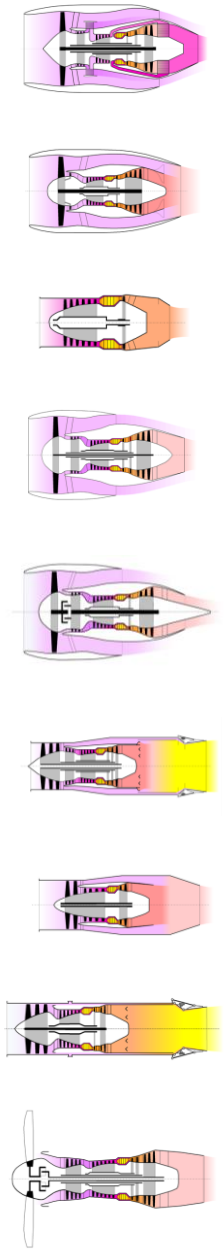
Take-off N_1 in the Engine Controller



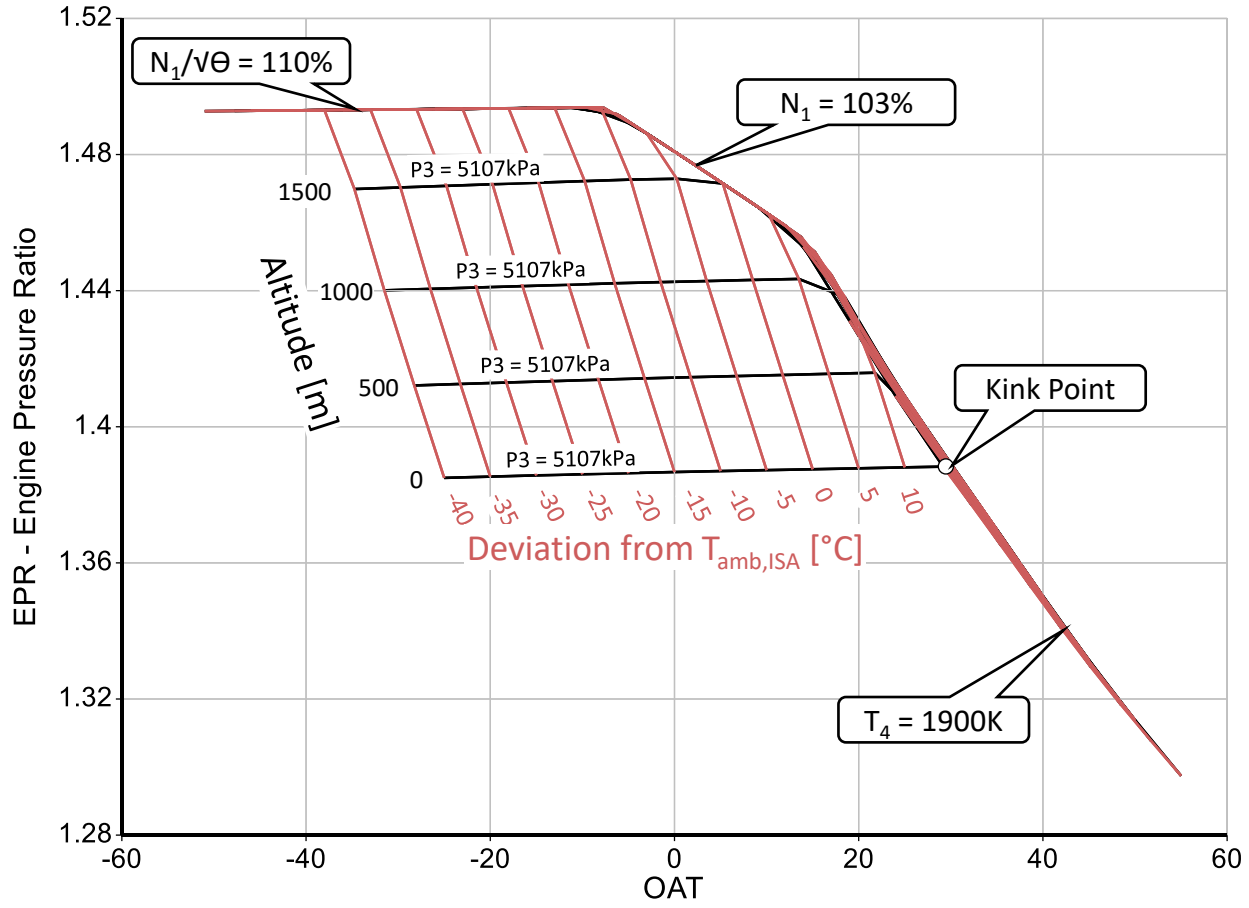


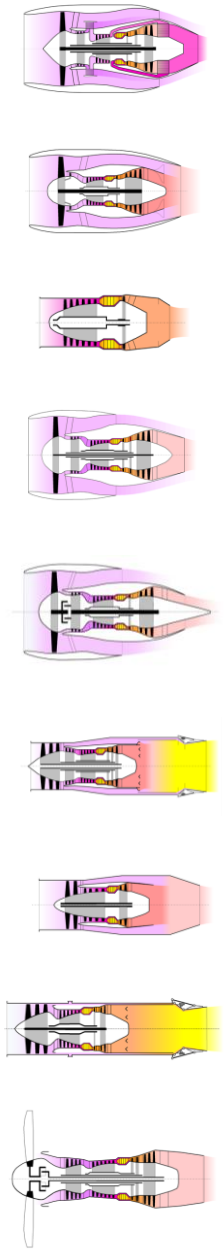
Take-off Schedule for a CFM56-3 on the Boeing 737-300



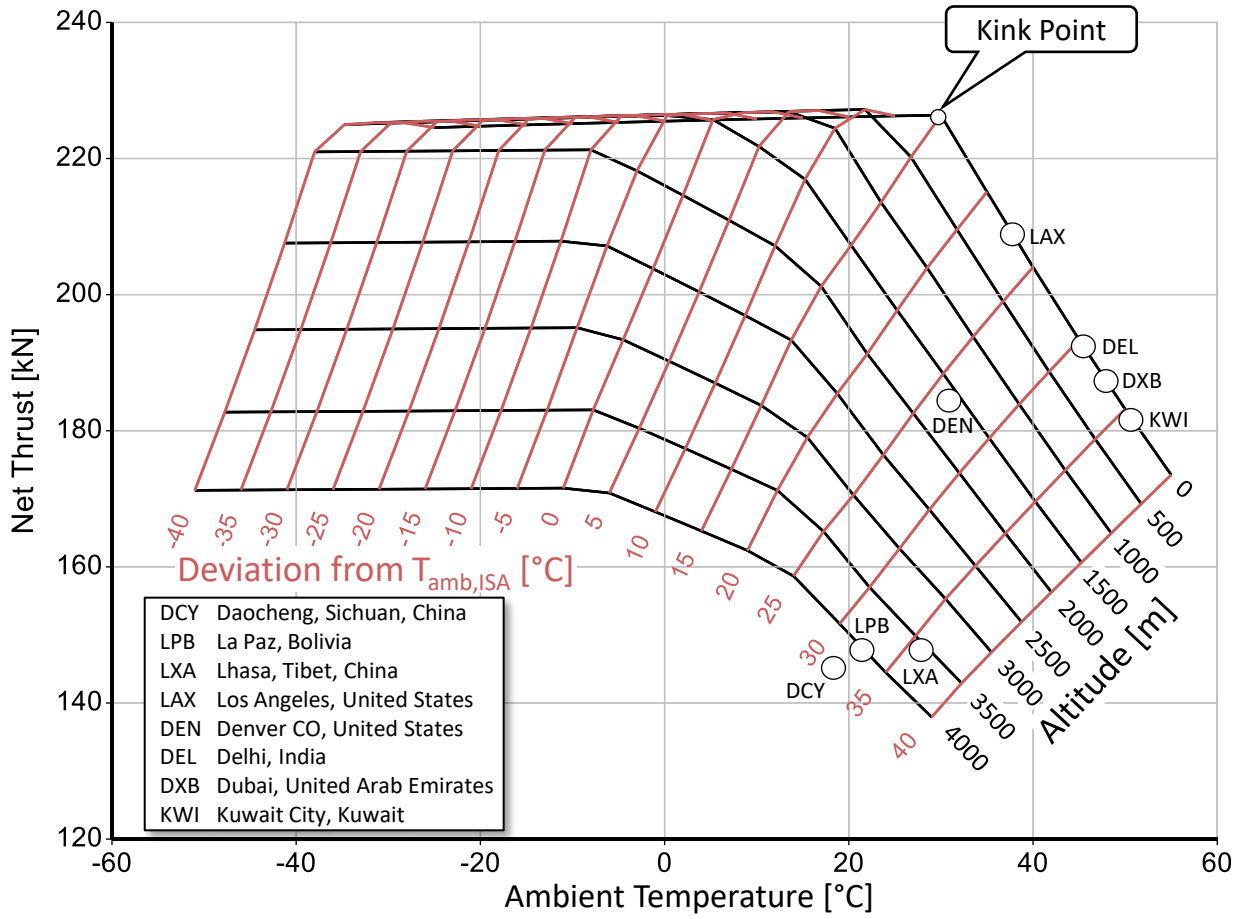


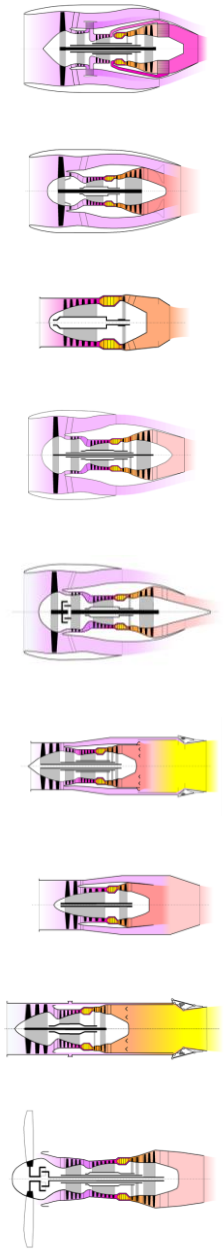
Take-off EPR in the Engine Controller



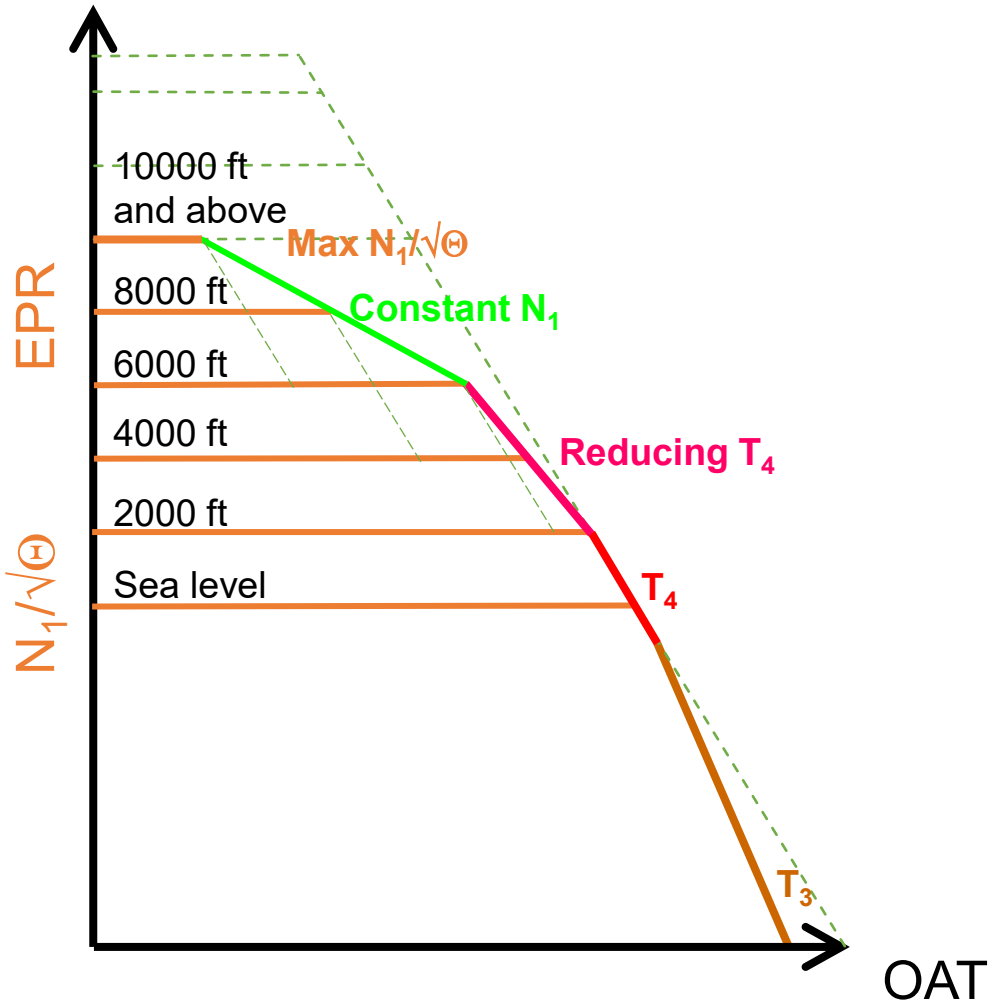


Absolute Take-off Thrust in the Aircraft Environmental Envelope



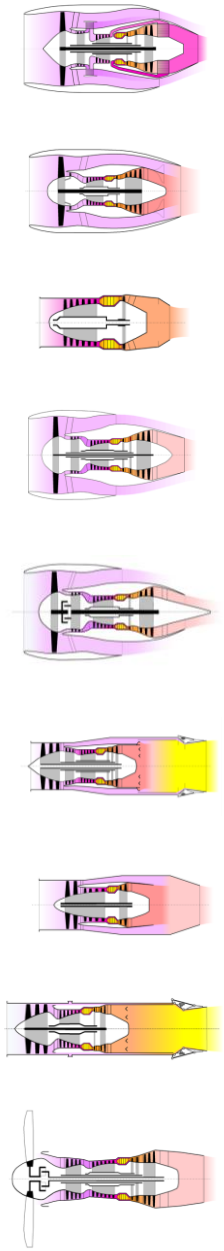


Optimizing the Take-off Schedule



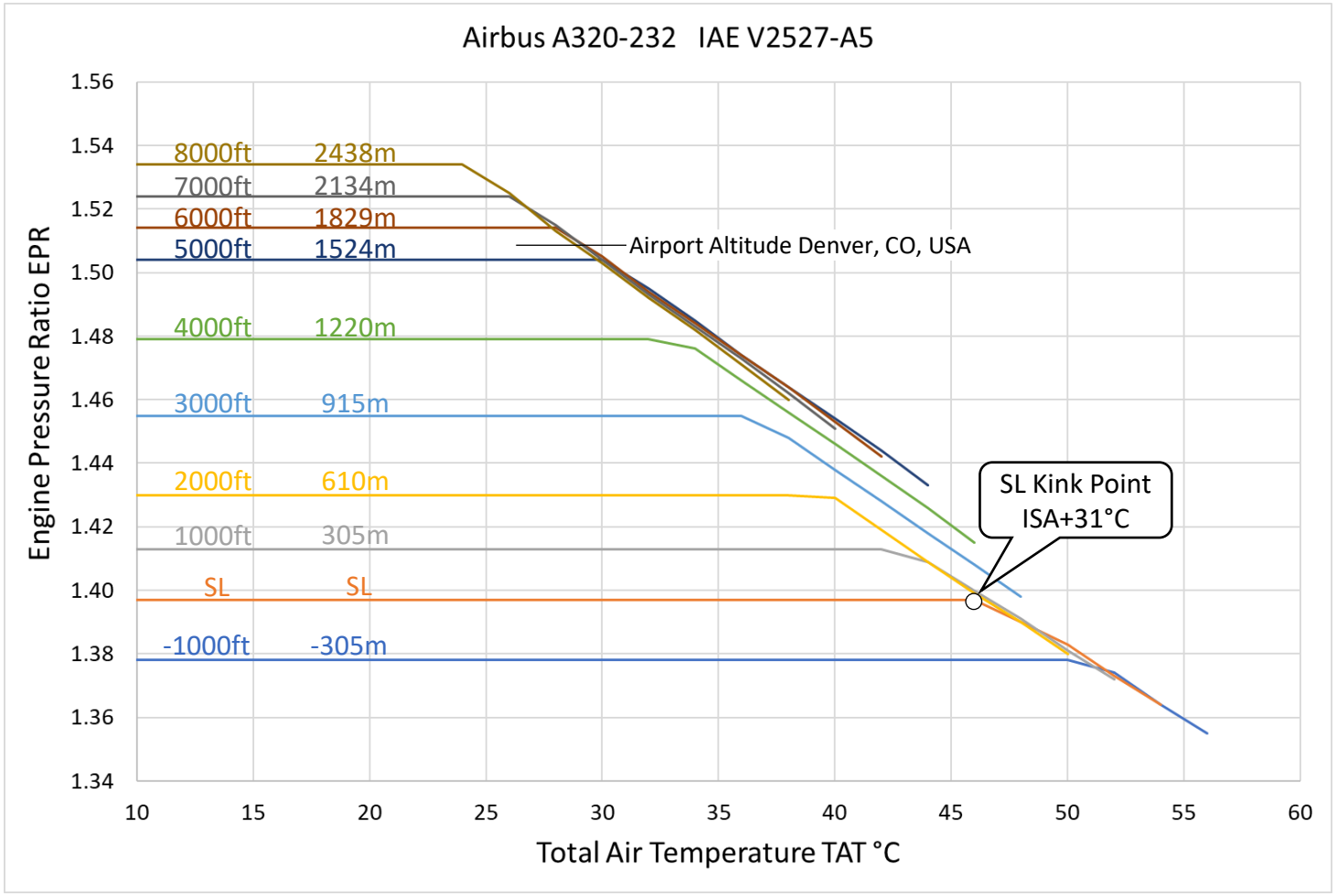
Source: RR

- To optimise the use of the mechanical capability of the engine, a more complex rating structure can be created
- Maximum constant T_4 is restricted to -1000 ft to 2000 ft, where most of the world's major airports are, maximising the use of the T_4 capability
- At higher inlet temperatures the slope of a constant T_3 will result in reduced T_4
- At higher Altitudes progressively reduce the T_4 to ensure that peak conditions occur around normal operating altitudes
- Most of the world's major airports are below 6000 ft and there is little value in offering high thrusts above 6000 ft
  - Therefore, N_1 can be used to define the rating above 6000 ft
- There are **very** few significant airports above 10000 ft and the rating can be limited to a constant non-dimensional condition above 10000 ft



Airbus A320-232 Take-off EPR

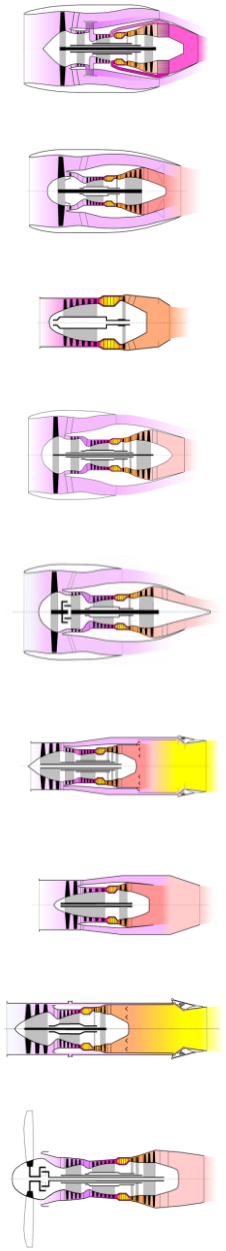
IAE V2527-A5



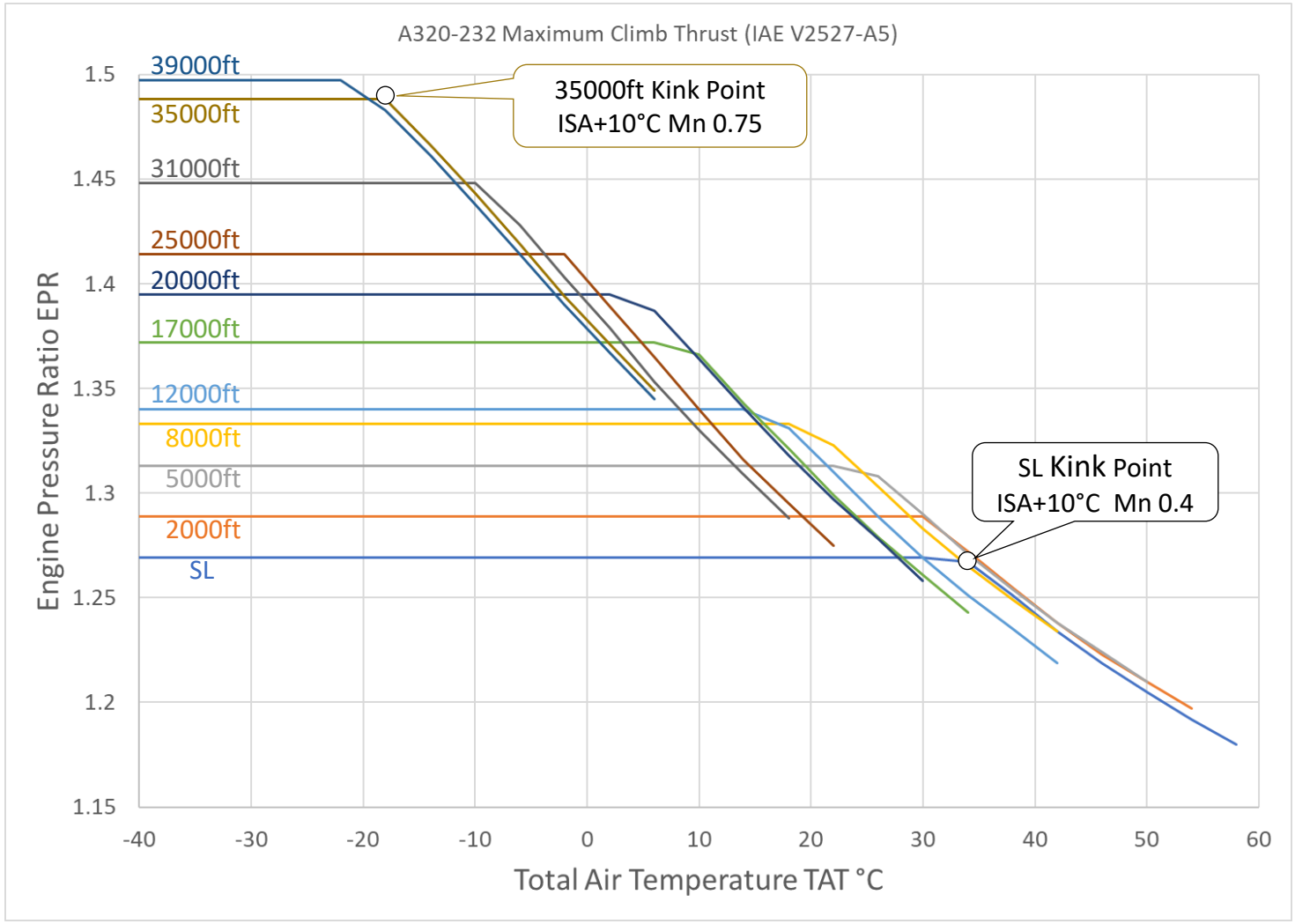
A320 Takeoff Thrust Setting - EPR

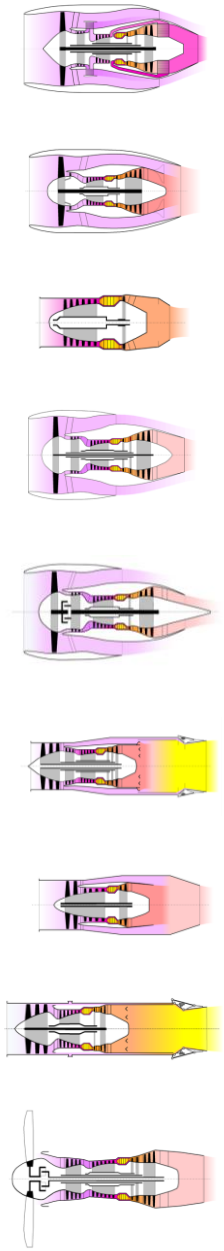
EPR settings in shaded area are for FLEX EPR only.

TAT (°F/°C)	Pressure Altitude (Feet)										
	-1000	SL	1000	2000	3000	4000	5000	6000	7000	8000	8500
158/70	1.295	1.294	-	-	-	-	-	-	-	-	-
154/68	1.303	1.303	1.301	-	-	-	-	-	-	-	-
151/66	1.312	1.311	1.310	1.307	-	-	-	-	-	-	-
147/64	1.320	1.320	1.318	1.316	1.323	-	-	-	-	-	-
144/62	1.329	1.329	1.327	1.325	1.332	1.339	-	-	-	-	-
140/60	1.337	1.337	1.336	1.334	1.341	1.348	1.354	-	-	-	-
136/58	1.346	1.346	1.345	1.343	1.351	1.358	1.364	1.363	-	-	-
133/56	1.355	1.355	1.354	1.352	1.360	1.367	1.374	1.372	1.371	-	-
129/54	1.364	1.364	1.363	1.362	1.369	1.377	1.383	1.382	1.381	1.379	-
126/52	1.374	1.373	1.372	1.371	1.379	1.386	1.393	1.392	1.391	1.389	1.388
122/50	1.378	1.383	1.381	1.380	1.388	1.396	1.403	1.402	1.401	1.399	1.398
118/48		1.390	1.391	1.390	1.398	1.405	1.413	1.412	1.411	1.409	1.408
115/46		1.397	1.400	1.399	1.408	1.415	1.423	1.422	1.421	1.419	1.418
111/44			1.409	1.409	1.418	1.426	1.433	1.432	1.431	1.429	1.428
108/42			1.413	1.419	1.428	1.436	1.444	1.442	1.441	1.440	1.438
104/40				1.429	1.438	1.446	1.454	1.453	1.451	1.450	1.448
100/38				1.430	1.448	1.456	1.464	1.464	1.462	1.460	1.459
97/36					1.455	1.466	1.474	1.474	1.473	1.471	1.469
93/34						1.476	1.485	1.484	1.483	1.482	1.480
90/32						1.479	1.495	1.494	1.493	1.492	1.491
86/30							1.504	1.505	1.504	1.503	1.501
82/28								1.514	1.515	1.513	1.512
79/26									1.524	1.525	1.523
75/24										1.534	1.533
72/22											1.537
68/20											
50/10											
32/0											
-4/-20											
-40/-40											
-76/-60	1.378	1.397	1.413	1.430	1.455	1.479	1.504	1.514	1.524	1.534	1.573

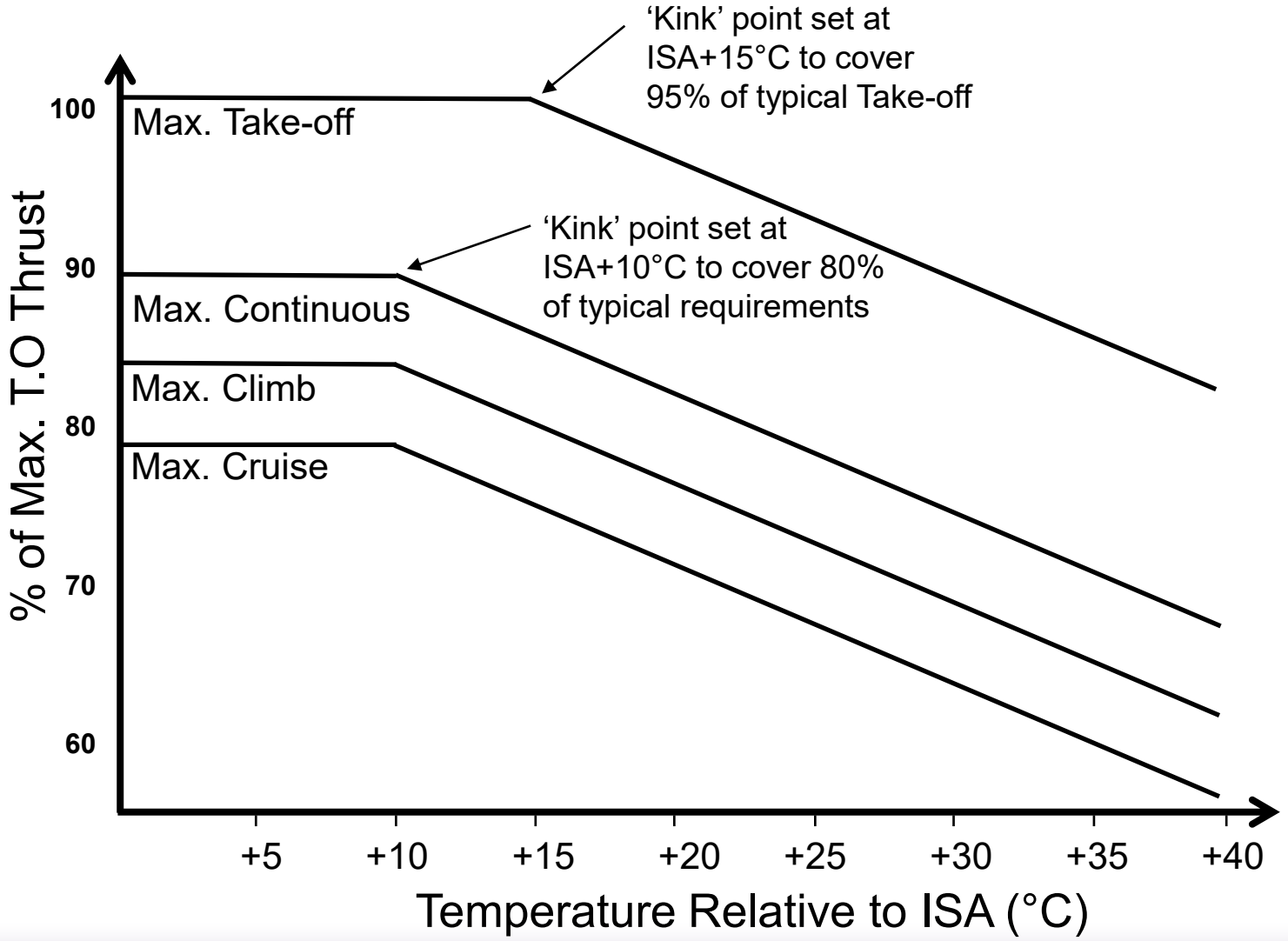


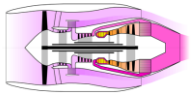
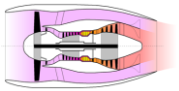
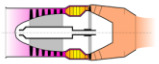
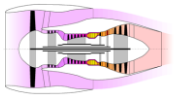
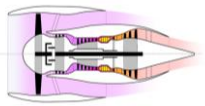
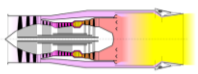
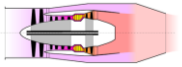
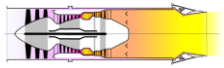
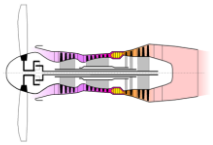
Airbus A320-232 Max Climb IAE V2527-A5





Relationship Between Ratings for a Typical Turbofan



Outline

Constant thrust, independent from engine-to-engine variations and deterioration

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- Spool Speed

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- Idle

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- Deterioration
- EGT Margin

The Cockpit

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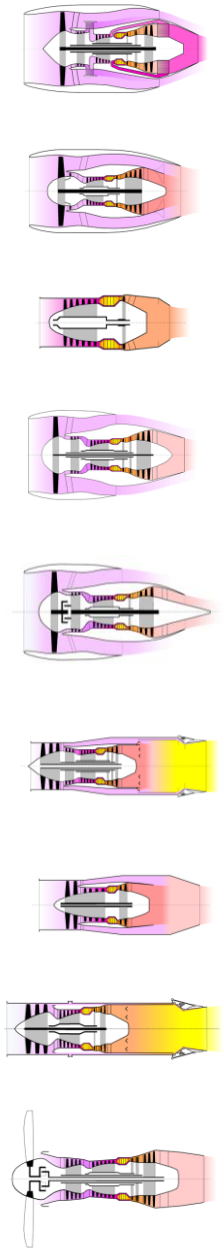
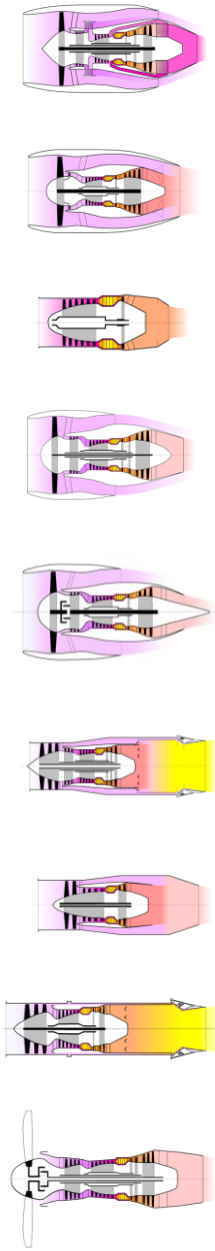


Reduced Take-off Thrust

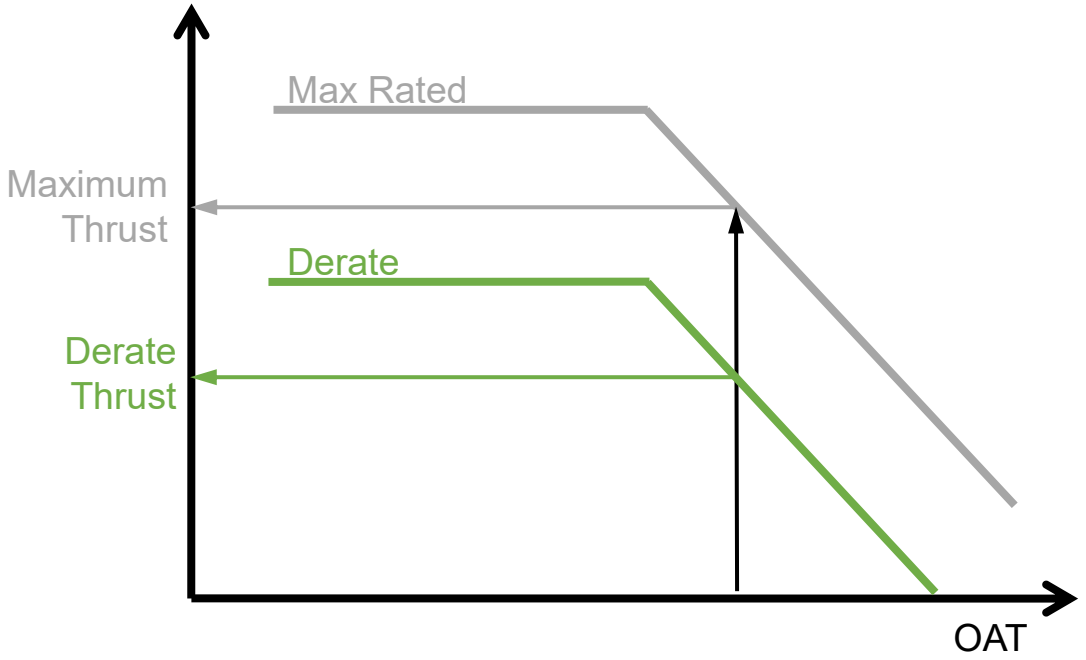
Benefits of Reduced Thrust

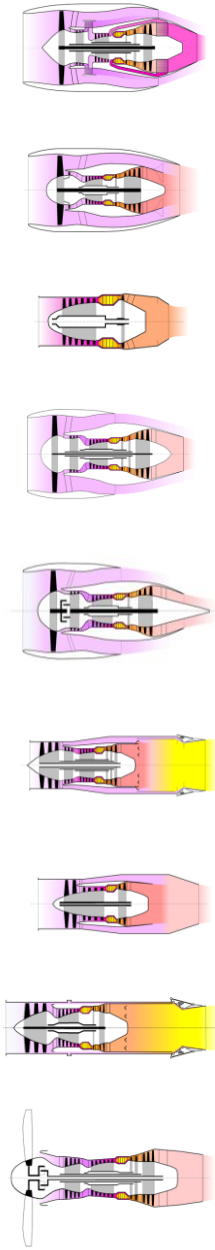
- Lower Take-off EGT
- Fewer operational events due to high EGT
- Lower fuel burn over on-wing life of engine
- Lower maintenance costs
- EGT Margin decreases more slowly
  - SFC increase kept at low rate
  - Better engine performance retention, longer engine life on wing
- Shop visit rate decreases



Derate

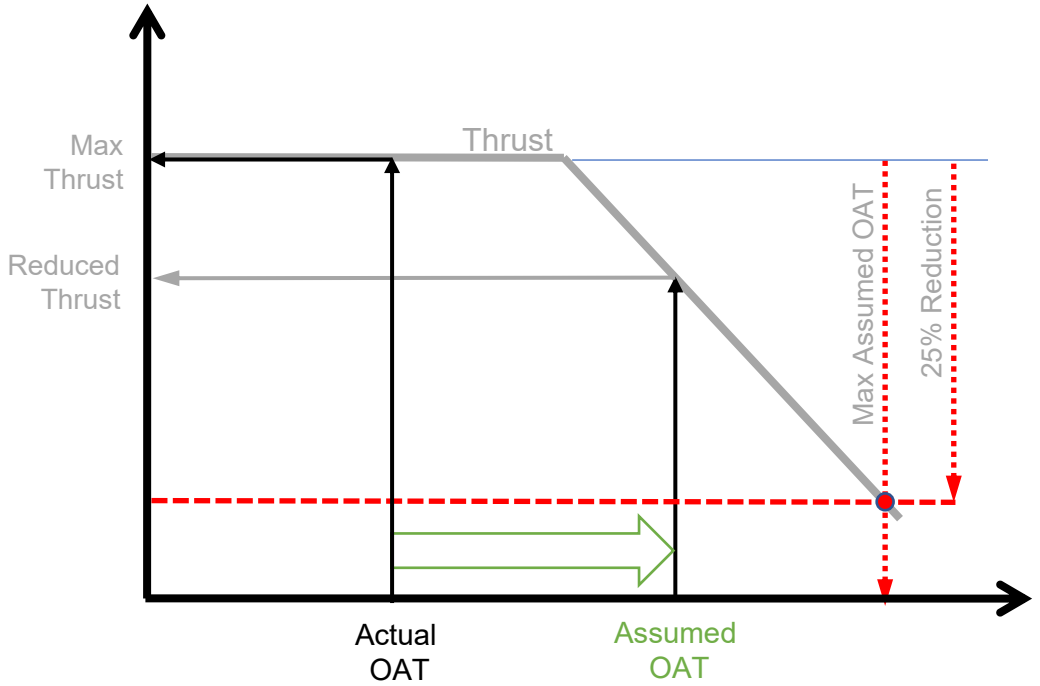
- Operating the engine at a derate is similar to having a less powerful engine on the airplane
- A derate is a separate, certified, thrust setting, requiring separate performance charts to be available for its use
- When operating at a derate, the reduced thrust level is a new maximum, and may not be exceeded
- Derates may be used only if the expected take-off weight is low enough to permit the use of reduced thrust equal to or below the level of derate

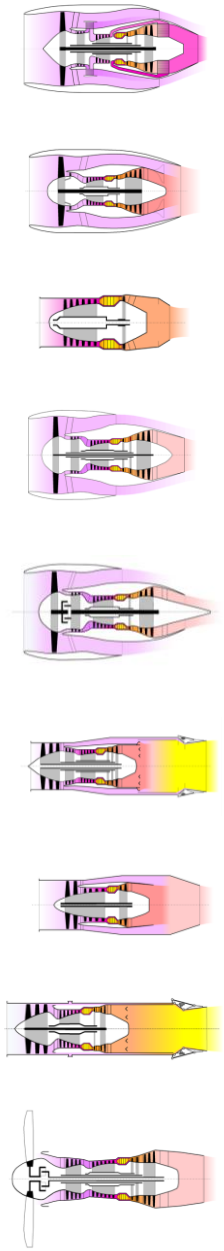




Assumed Temperature (FLEX)

- The assumed temperature method tricks the engine into thinking the weather outside is much hotter than it actually is
- The maximum temperature that meets all take-off performance requirements at the actual take-off weight is the maximum allowable assumed OAT
- Maximum of 25% thrust reduction
- If necessary, the crew can push the throttles into the Take-off/Go-around (TOGA) detent and request full power.





Outline

Constant thrust, independent from engine-to-engine variations and deterioration

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- Spool Speed

Ratings

- Flat Rating
- Generating Schedules
- Derating
- Idle

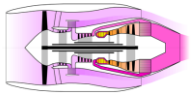
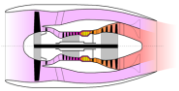
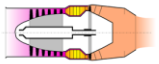
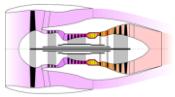
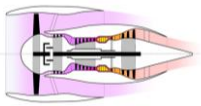
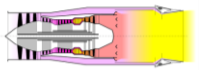
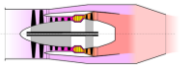
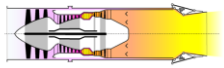
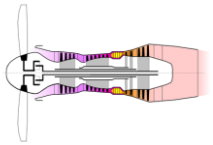
Exhaust Gas Temperature

- Deterioration
- EGT Margin

The Cockpit

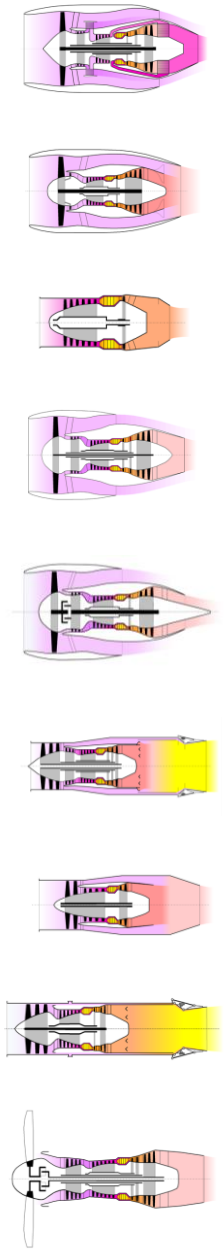
- A320
- A350

Transient

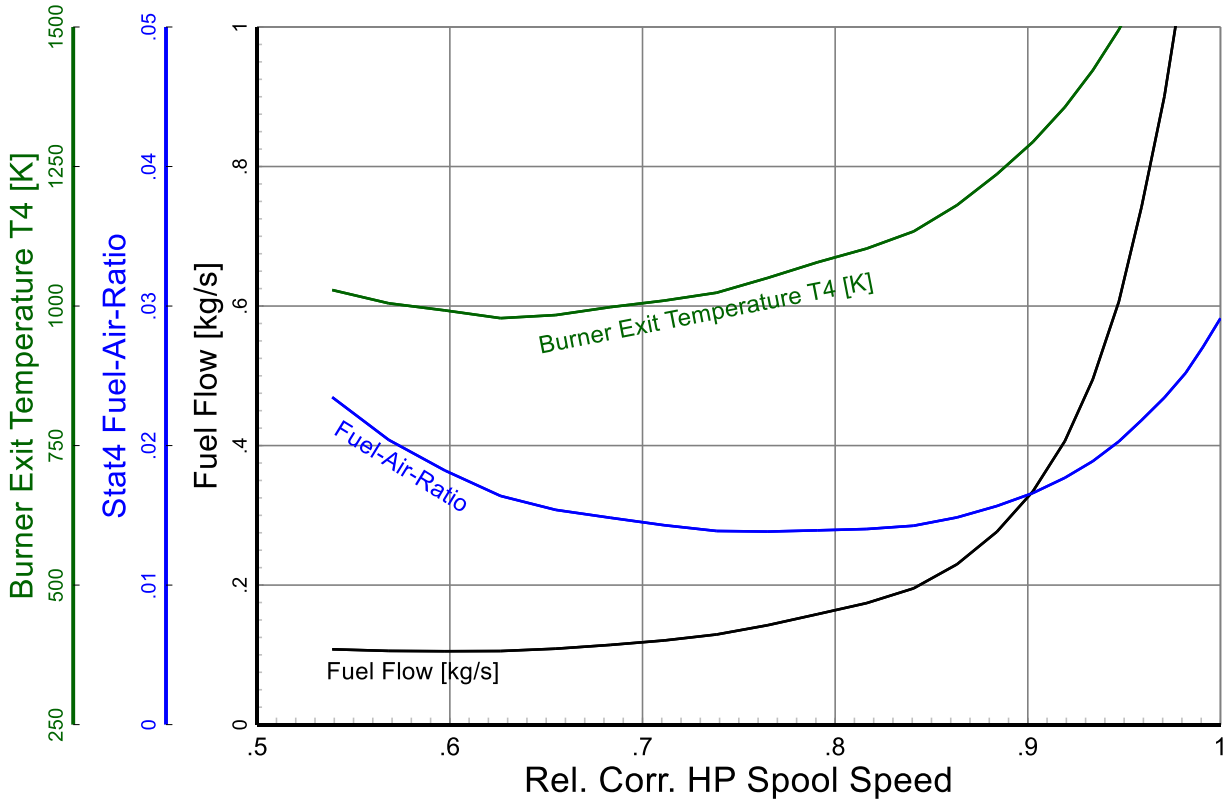










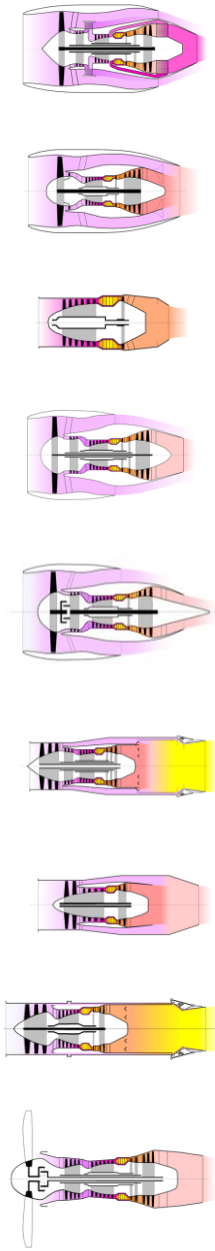
Idle Ratings

- Simplest definiton of idle is the minimum non-dimensional condition $N_H/\sqrt{\Theta_2}$ for stable operation
- Engine and aircraft requirements impose additional requirements which result in complex idle rating definitions
- Idle Ratings usually result in different settings for ground and flight operations, each with additional sophistication to meet specific requirements



Minimum $N_H/\sqrt{\theta_2}$ for Stable Operation





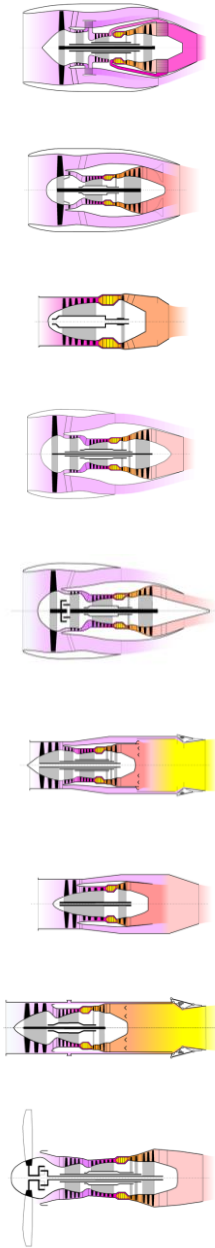
Flight Idle Issues

Descent Rate

- the aircraft is most efficient when at cruise conditions
- minimise the distance covered at climb or descent !
- steepest possible descent, limited by airspeed
- low idle thrust maximises descent angle

Approach speed

- aircraft must be stable at approach airspeed on the glideslope
- to capture and maintain the glideslope minimum available thrust must correspond to an airspeed less than the defined approach airspeed



More Flight Idle Issues

Minimum Cabin Pressure

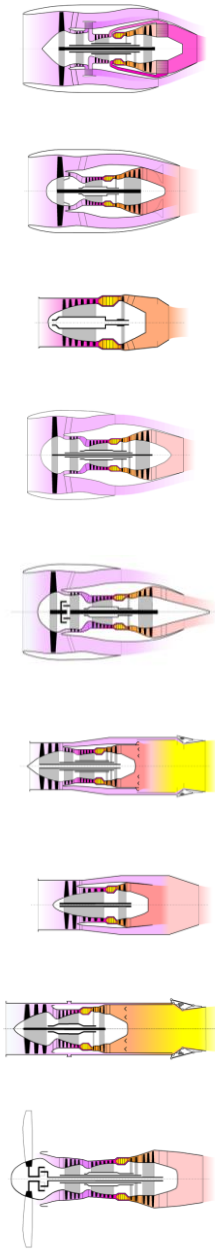
- the minimum cabin pressure requirement is constant with altitude, representing an increasing non-dimensional condition as altitude increases

Go-around Acceleration Times

- the aircraft certified field performance is influenced by the requirement to achieve a 3.2 degree climb gradient within 8 seconds of initiating a go-around manoeuvre
- typically, if less than 95% of take-off thrust is available, maximum allowable take-off weight will be reduced below other limitations
- to meet the acceleration time, engine minimum operating condition is raised

Anti-icing Requirements

- the aircraft anti-icing system typically requires air flow rate and temperature higher than that available at minimum idle conditions
- can raise basic level or include a “reset” when anti-icing is selected



Ground Idle Issues

Taxi thrust

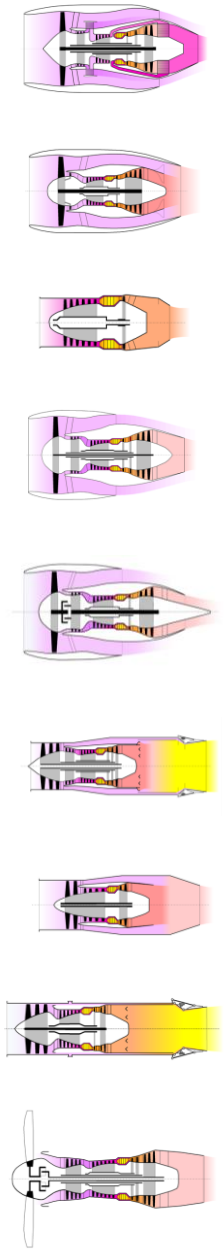
- once the aircraft is moving, idle thrust is normally well above the thrust required to taxi at normal speeds
- high thrust results in excessive brake wear
- handling on ice covered taxiways can be a problem
- Generator ‘on line’ speed

Fuel burn

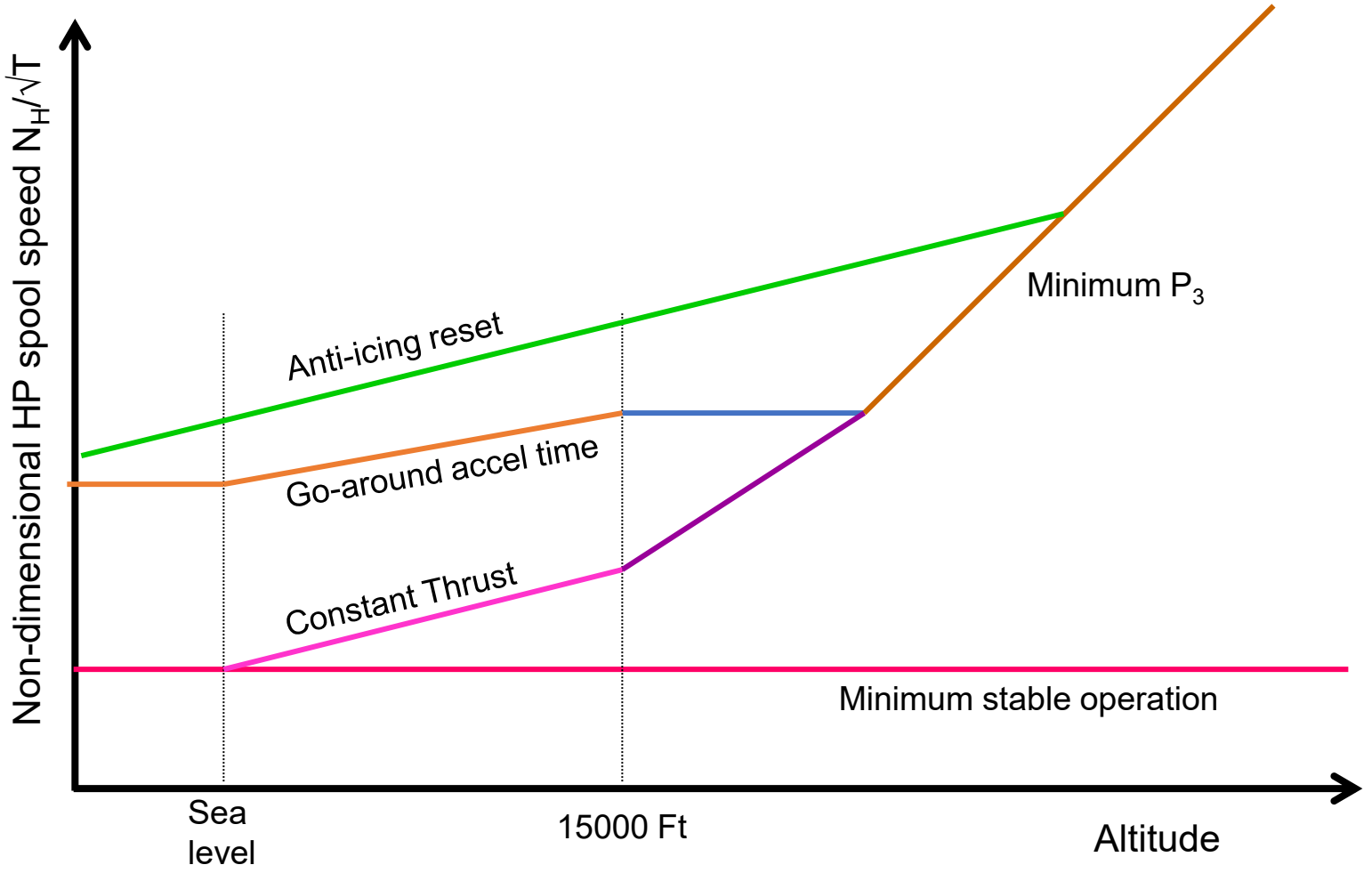
- all fuel burned whilst at idle on the ground is wasted
- generates pollution

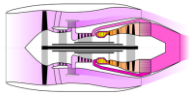
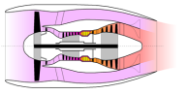
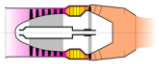
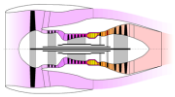
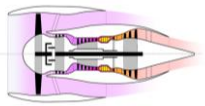
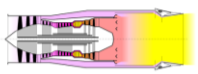
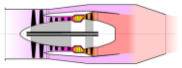
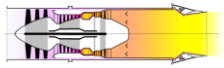
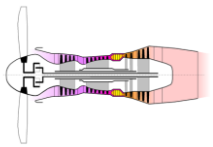
Landing roll

- idle thrust has a small but measurable effect on landing roll distance



Overall Idle Characteristics



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- EGT Margin

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- A350

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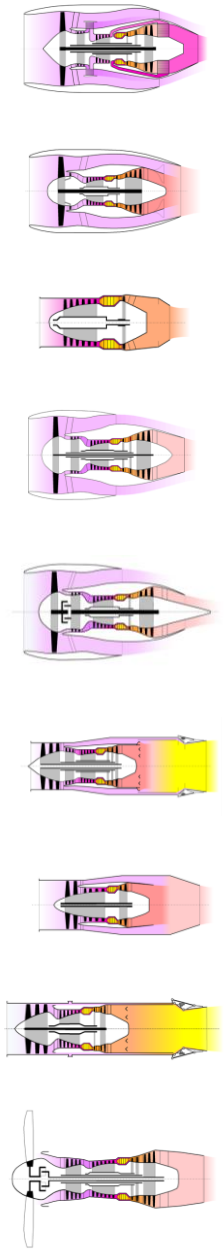
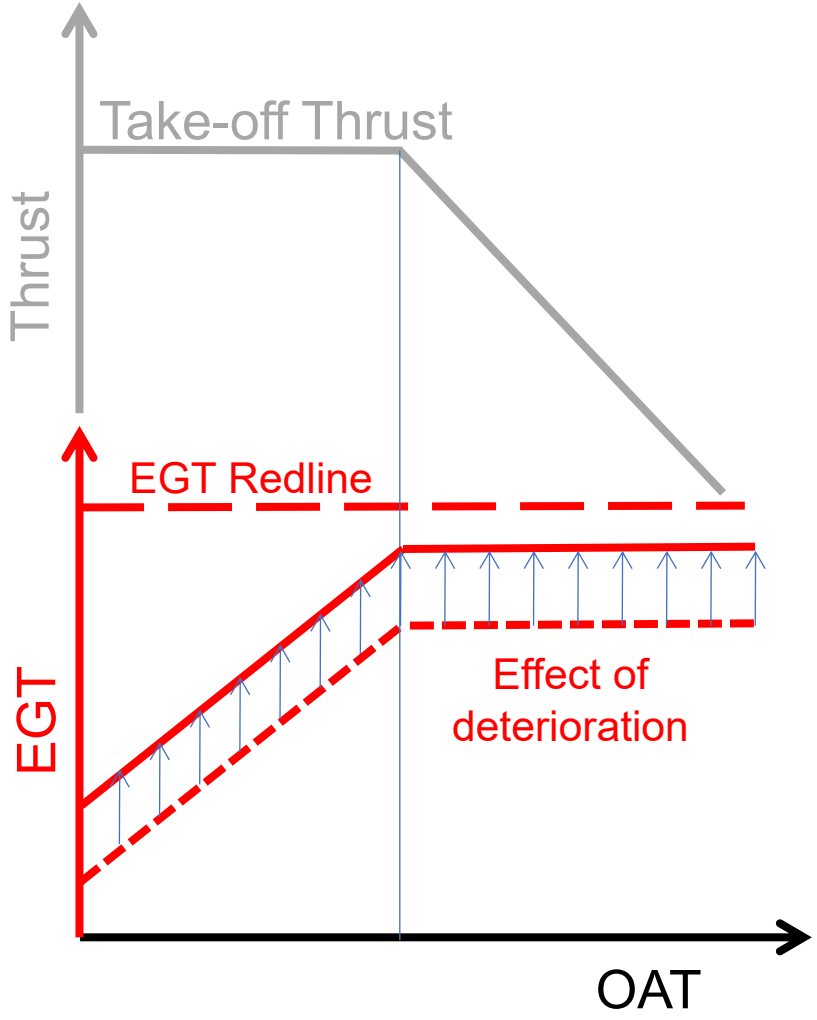
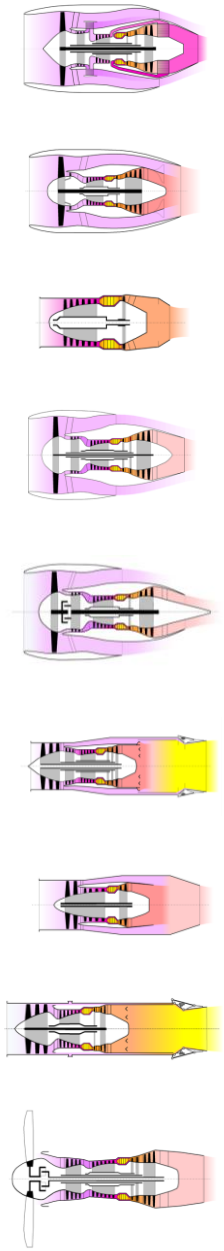


Exhaust Gas Temperature (EGT)

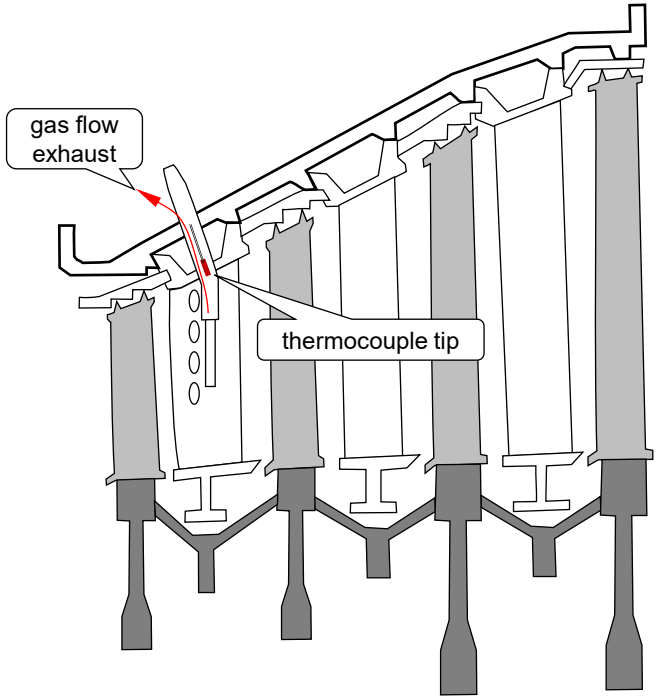


- As an engine deteriorates with age, it needs to run at higher temperatures in order to produce the same take-off thrust
- EGT margins to redline are reduced
- Eventually, the engine will reach its redline limit and need to be removed for maintenance

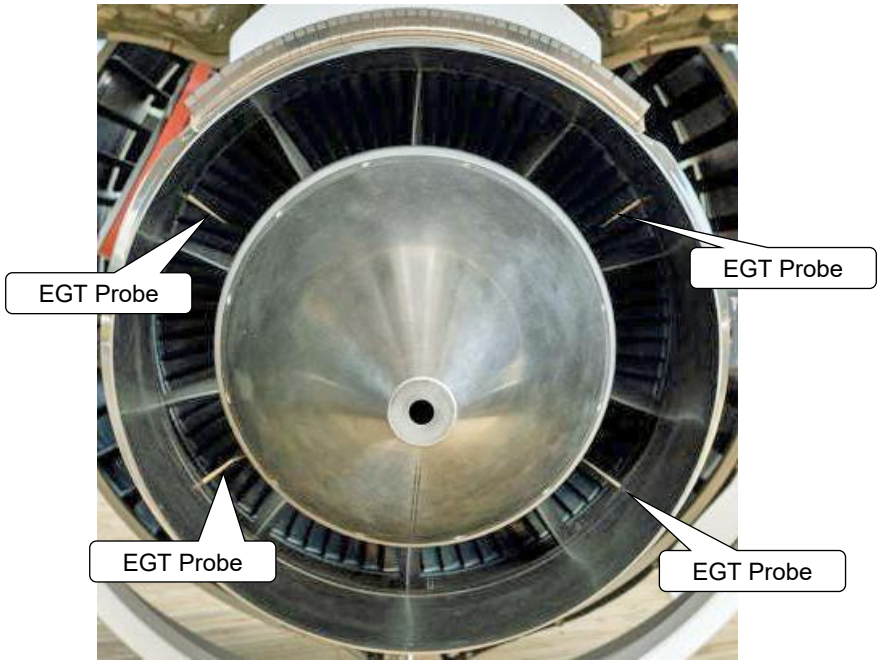


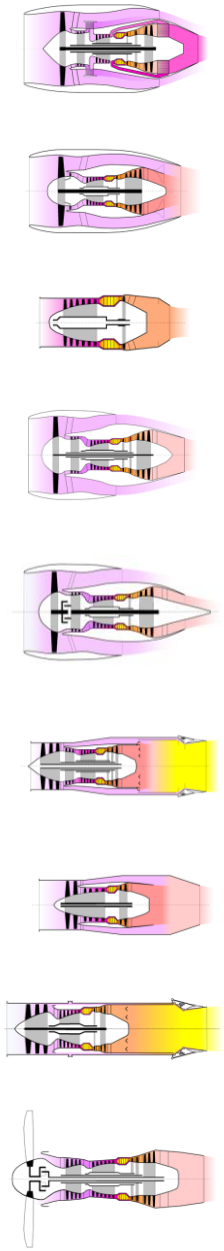
Exhaust Gas Temperature (EGT) Measurement

CFM56-3



PW Geared Turbofan





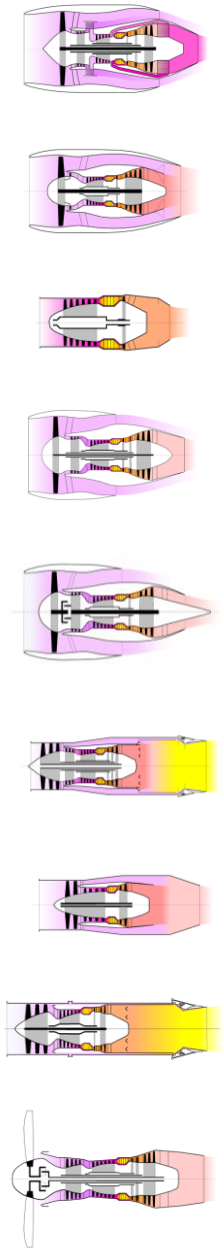
Thrust Setting Parameters and Engine Deterioration

- New CFM56-7B engines can have initial EGT margins as high as 130°C for lower-rated models, while higher-rated models generally start with 80–105°C of margin.

- Engines deteriorate…
  - Blade tip and labyrinth seal wear
  - Erosion and fouling
  - Loss of component efficiencies

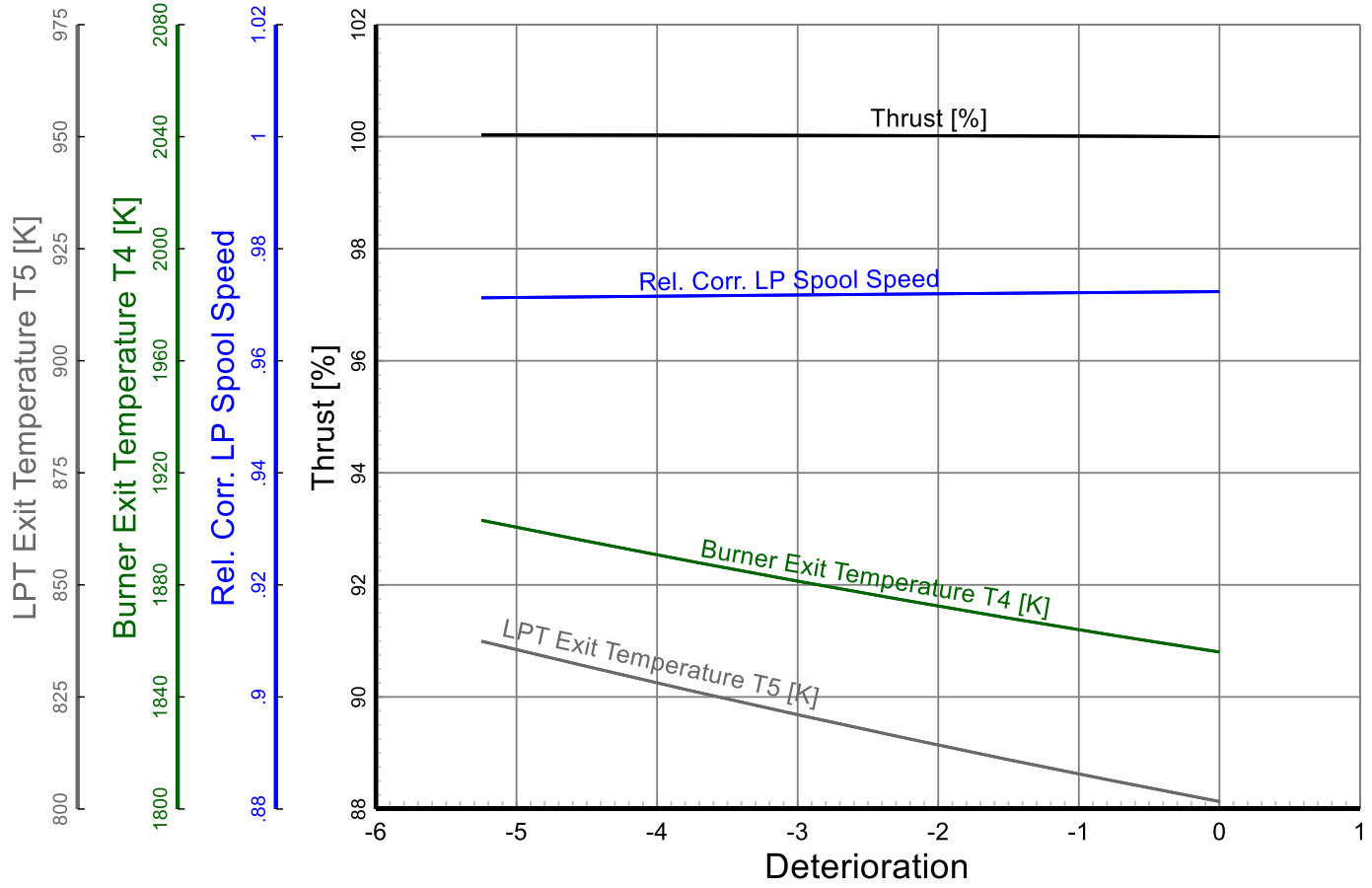
- However, thrust should remain constant
  - This requires an increase in turbine inlet temperature
  - EGT Margin reduces

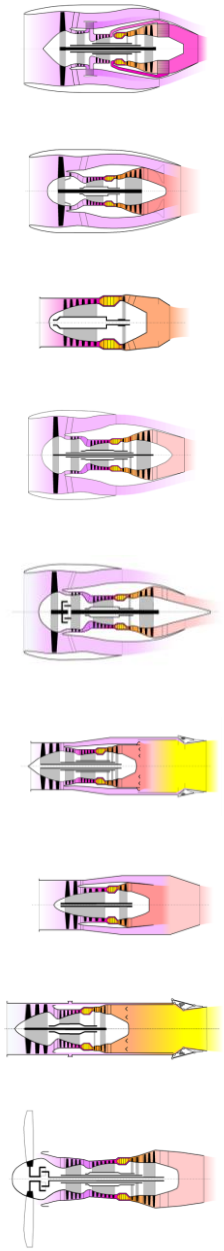
- Keeping EPR or $N_L/\sqrt{\Theta}$ constant yields constant thrust



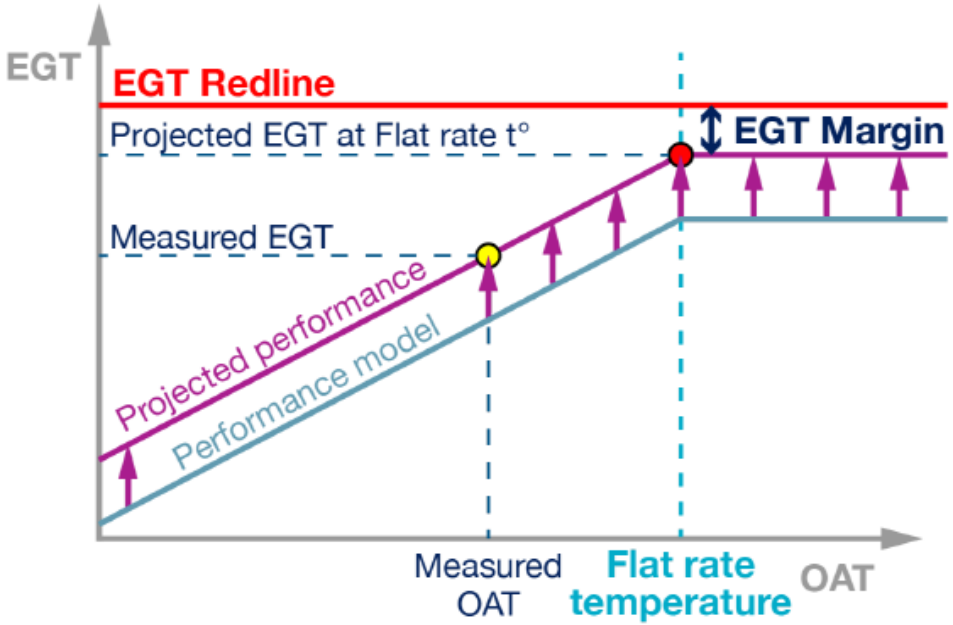
Effect of Deterioration

Constant EPR

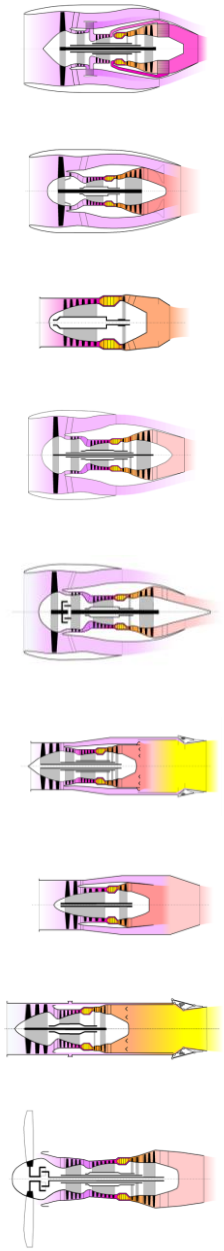




How to Determine the EGT Margin

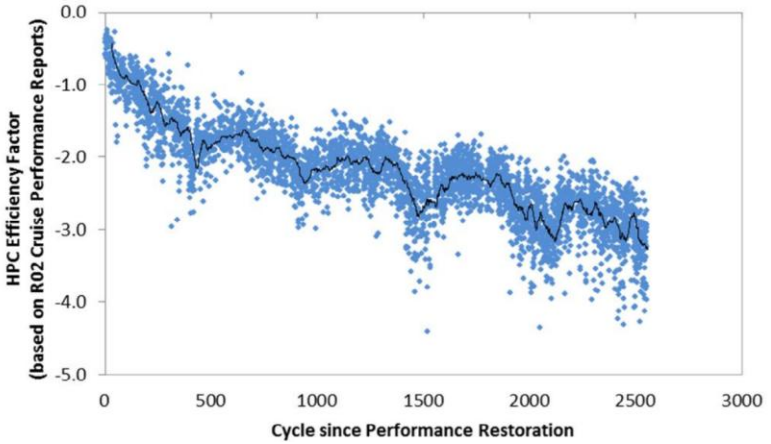


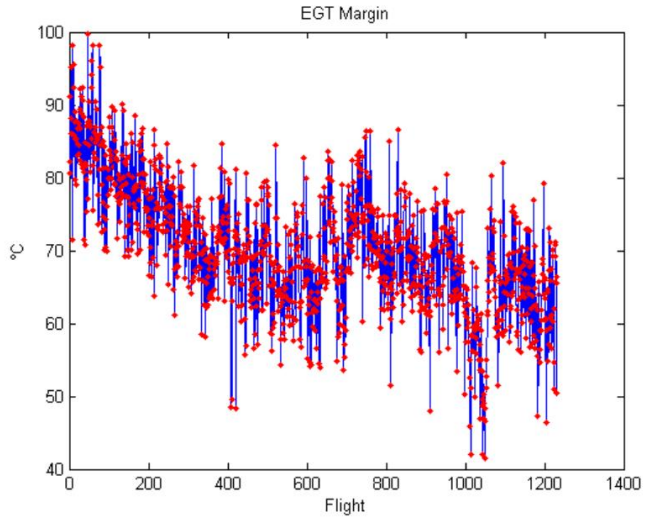
- Each time a takeoff is performed with TOGA thrust, the ECM tool takes a snapshot of the engine parameters and of the external conditions (e.g. OAT, pressure).
- The tool then uses this measurement to calculate a delta vs the engine performance model and project it to the worst condition to determine the projected EGT of the engine.
- The difference between this projected EGT and the EGT redline value is the current EGT margin of the engine.

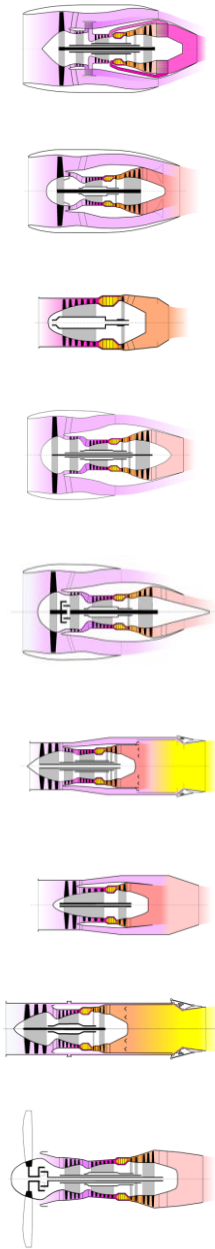


Monitoring Engine Performance Degradation

- The Operator should check the maximum thrust (TOGA) by performing full-rated takeoffs at regular intervals, in order to detect a reduced EGT margin
- Avoid fitting two performance limited engines to the same aircraft
- Maintenance should inform Flight Operations and request that flight crews perform a takeoff with TOGA thrust when it is necessary to ensure an accurate computation of the EGT margin.
- Regular engine washes will remove particles from the compressor such as dirt, oil, sand, and salt that reduce the engine efficiency.

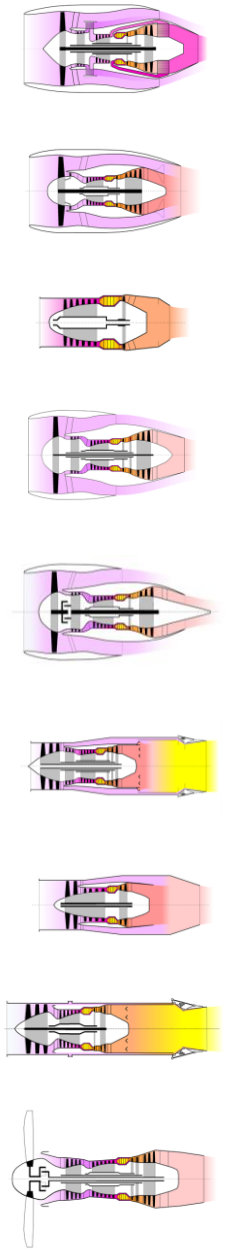




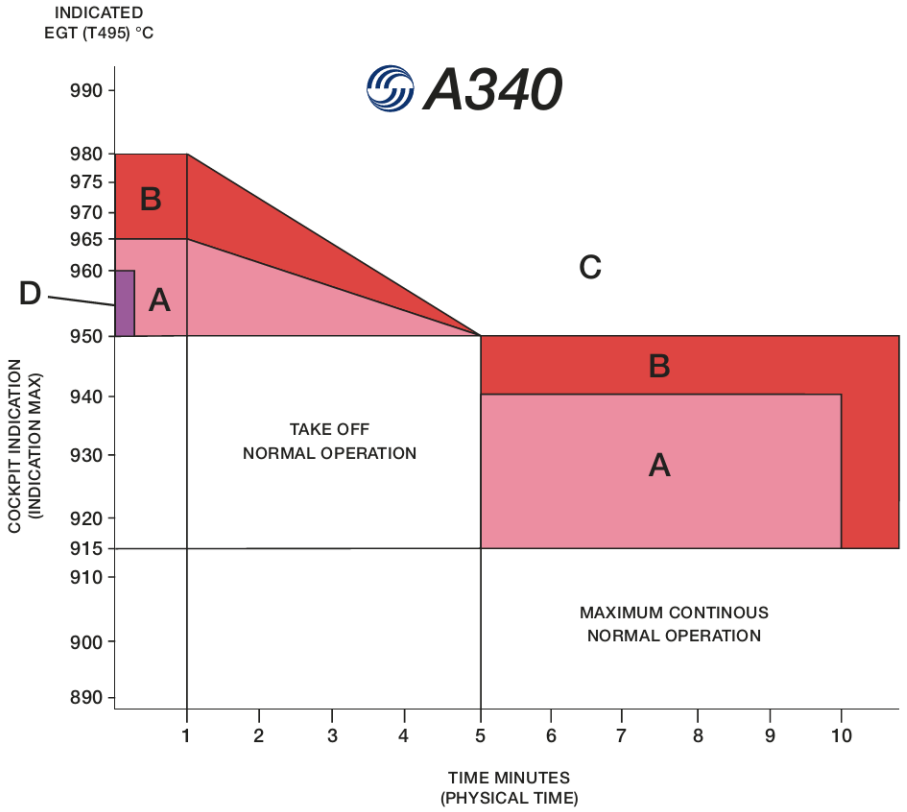


The EGT Redline is Not a “hard” Limit

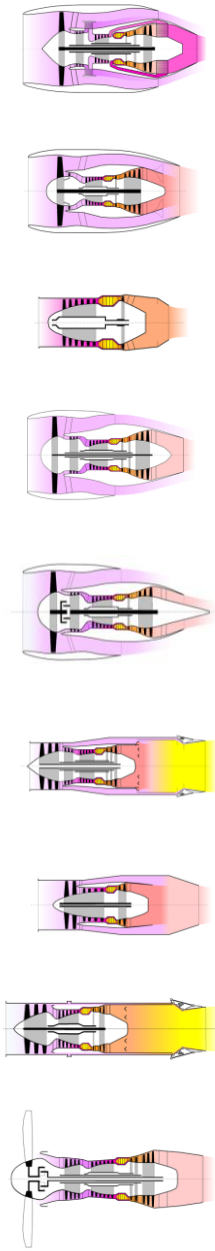
- In the absence of severe damage, an engine is capable of operating above the EGT at the cost of accelerated engine wear.
- This is demonstrated during the engine certification tests.
- An EGT overlimit requires maintenance.
- After an EGT overlimit, inspection and troubleshooting are necessary to identify the root cause of the overlimit and assess the engine’s health.



Allowance for CFM56-5C EGT Over Limits



D	EGT over limit of less than 10°C and lasting less than 20 seconds are permitted, without any requested maintenance action
A	Inspection and troubleshooting are required. Maximum of 20 over limit occurrences are allowed before engine removal
B	Inspection required. If the root cause is not identified, borescope inspection is required. 20 over limit occurrences in area A & B combined or 10 in area B alone are allowed before engine removal
C	Remove the engine and return to shop. One non-revenue flight is allowed if no damage occurs beyond serviceable limits.



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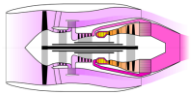
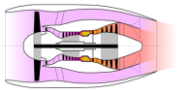
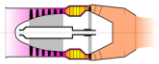
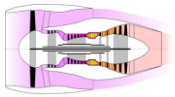
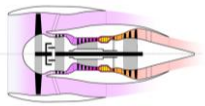
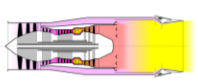
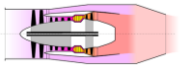
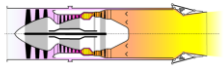
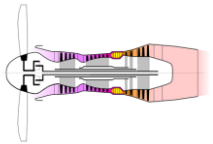
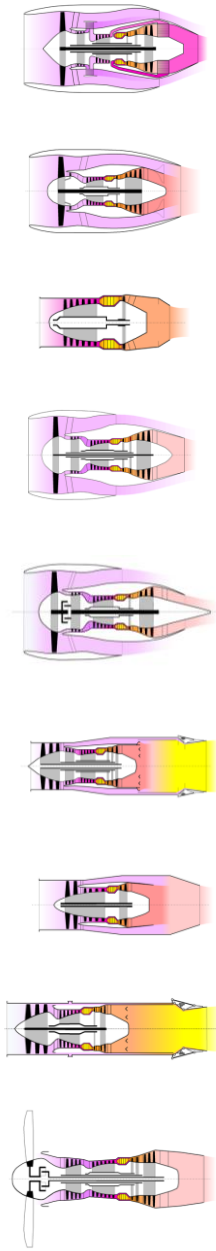
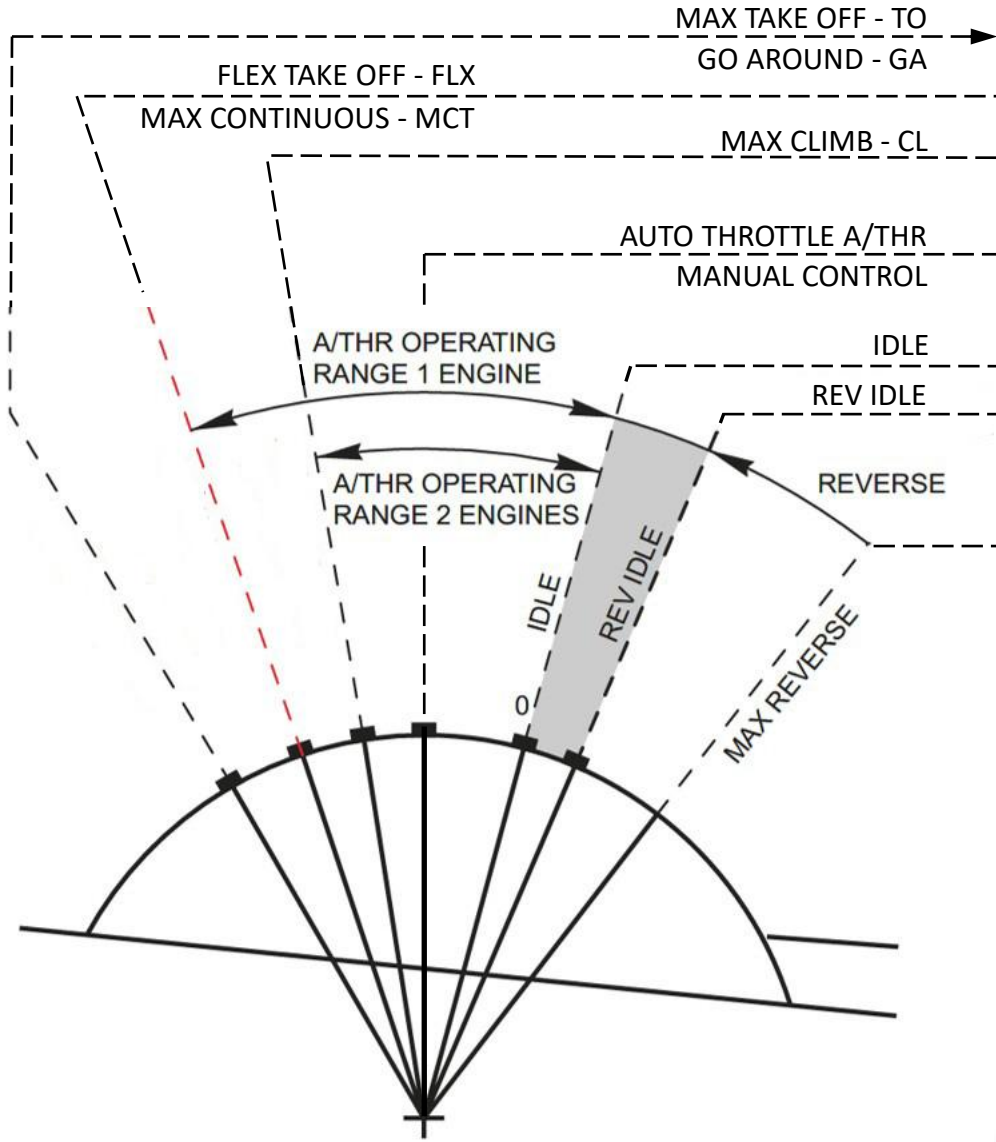
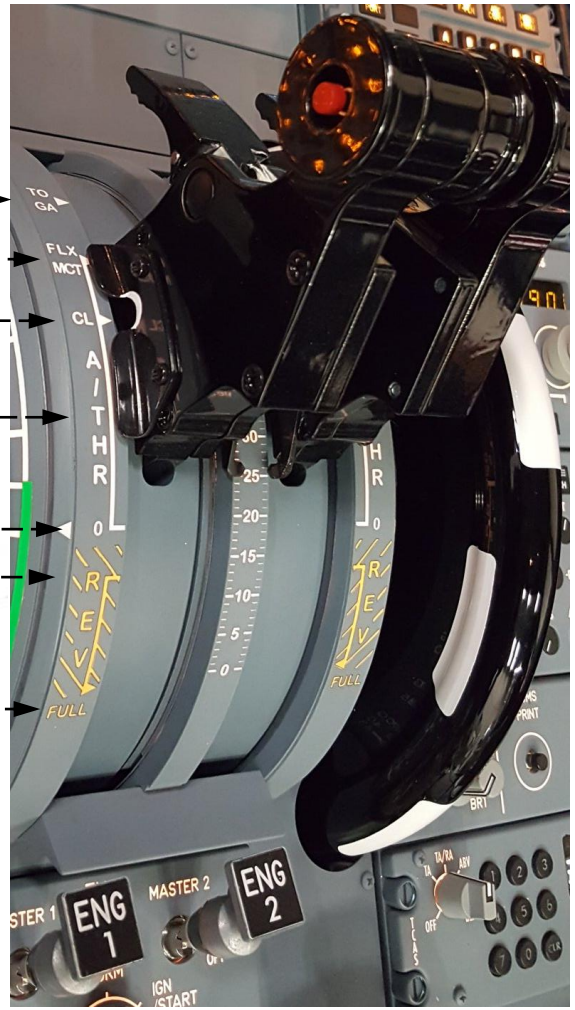
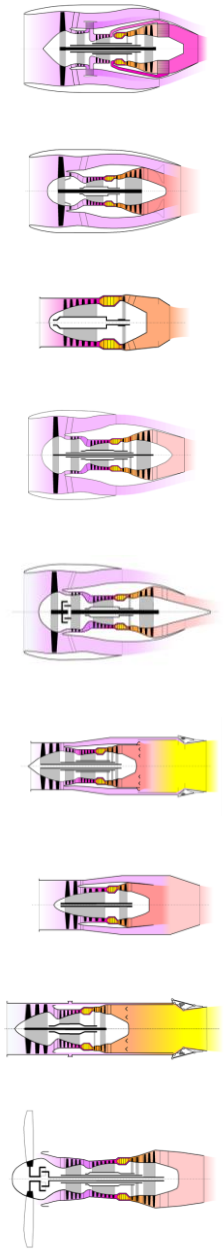












The Throttle Lever







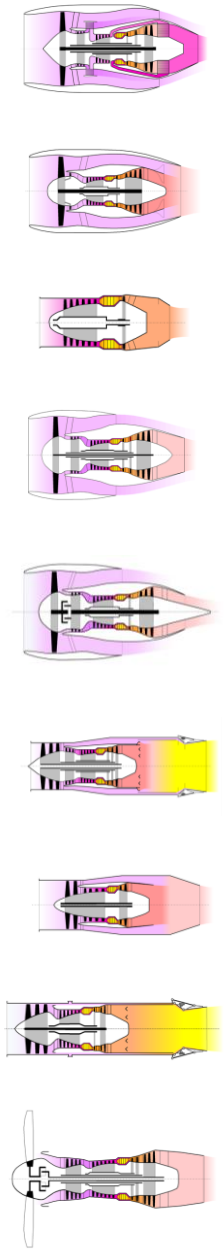
Maximum Take-off Thrust

The highest thrust level available from an engine

- This rating is a certified level, and is time-limited to a maximum of 5 minutes
- May be extended to 10 minutes for one-engine inoperative take-off

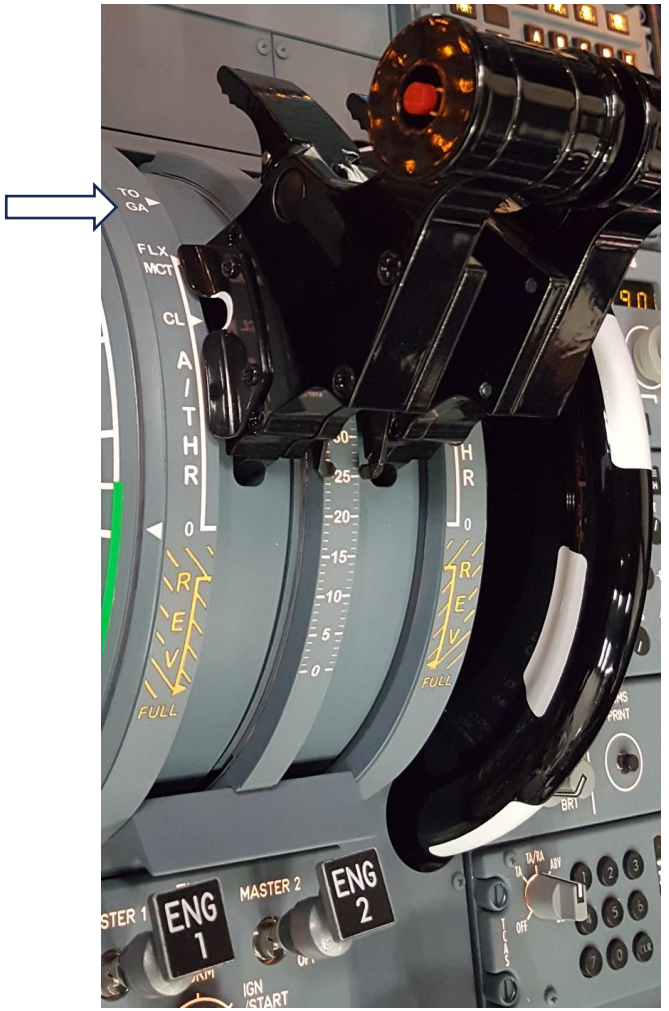
- This rating is used for take-off only and is specified in the Airplane Flight Manual.

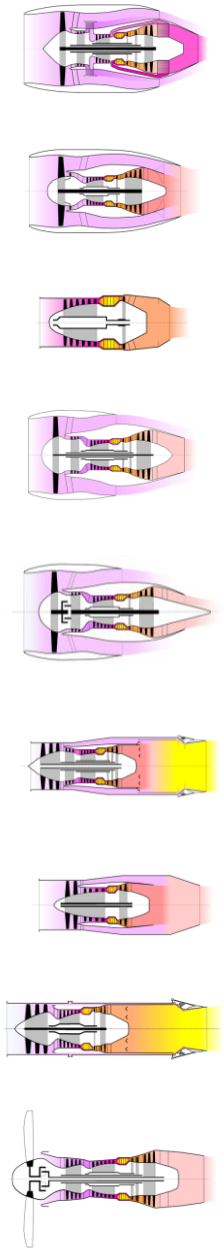
- As such, compliance with this limit is therefore mandatory



Go-Around Thrust

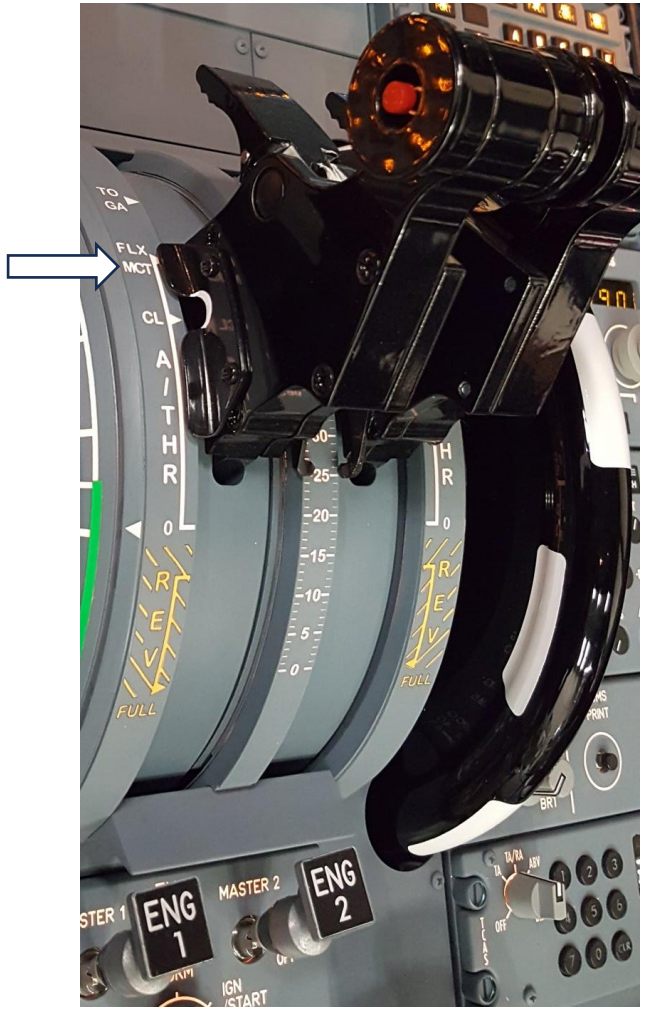
- Also known as ‘inflight take-off thrust’
- The amount of this thrust is the same as the take-off rating, but EPR’s (N_1’s) are different because of the effect of higher flight velocity
- Time limited to 5 minutes
- Intended for missed approach, when maximum power may be required for safety
- This is a ‘certified’ rating, compliance with this limit is mandatory

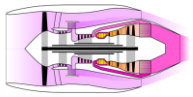
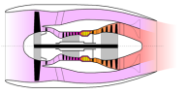
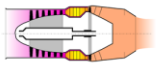
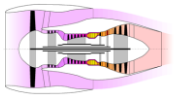
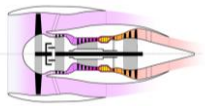
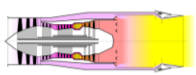
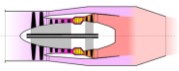
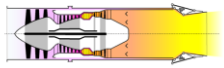
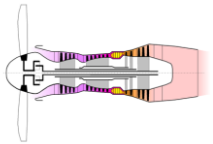




Maximum Continuous Thrust

- This is a special thrust rating, sometimes referred to as MCT. It is intended to only be used in an emergency, but has no time limitation
- This is a ‘certified’ rating, compliance with this limit is mandatory (just like take-off and go-around)
- In addition to the pressure and temperature limits, we now have to consider the airplane’s speed. As such, the presentation of the data is different from take-off and go-around



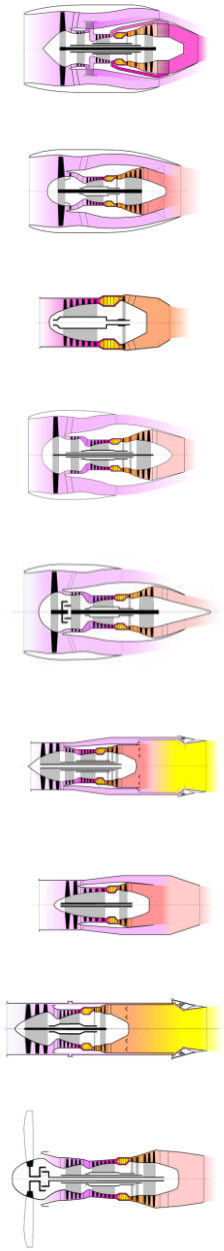
Maximum Climb Rating
Maximum Cruise Rating

Maximum Climb has no time limit.

- Max Climb is intended for use during normal enroute climb
- Max Cruise is intended for use during normal cruise operations.

For some engines, maximum continuous and maximum climb thrust are equivalent

Maximum climb thrust and maximum cruise thrust are not ‘certified’ ratings



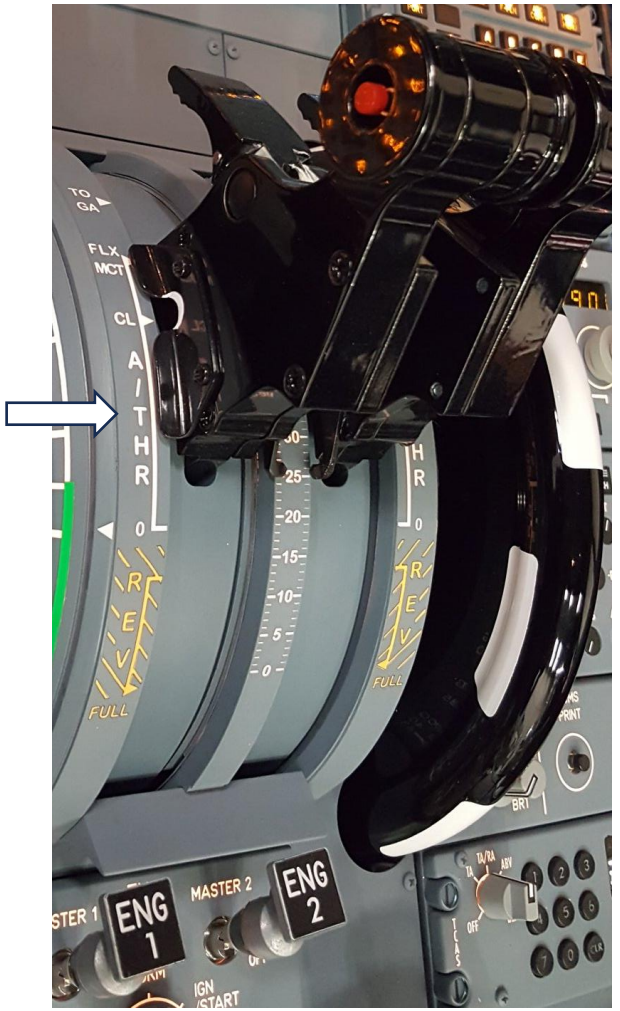
Auto Throttle A/THR

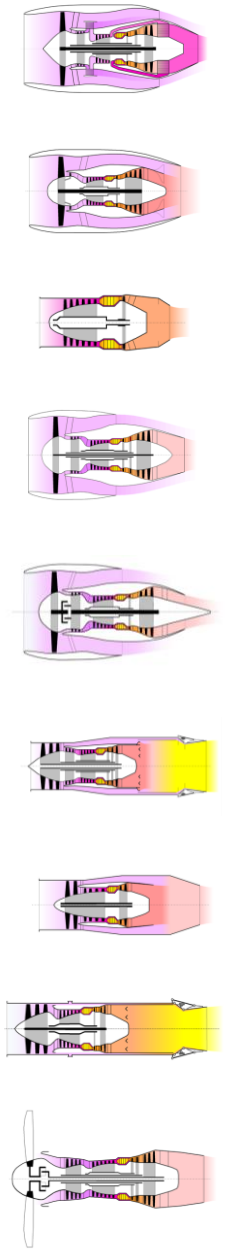
The A/THR activates when the throttle levers are set to the climb detent after take-off.

There are two parameters that an A/THR can try to attain:

- In **speed mode** the throttle is positioned to attain a set target aircraft speed

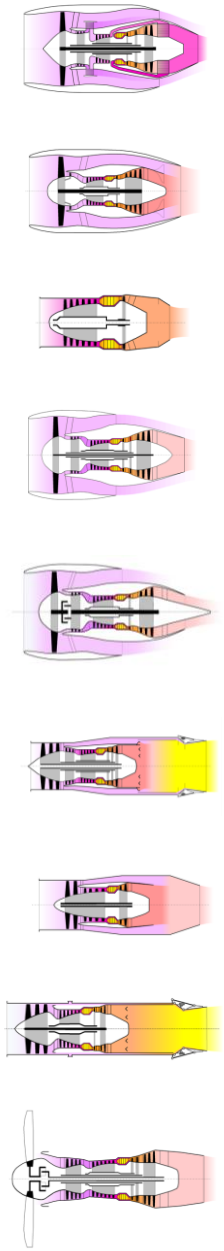
- In **thrust mode** the engine is maintained at a fixed power setting according to the different flight phases.
  - During climb, the A/THR maintains constant climb power
  - In descent, the A/THR reduces the setting to the idle position.
  - Speed is controlled by the aircraft control column.



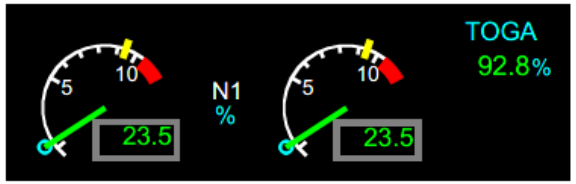
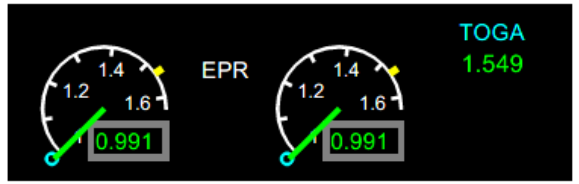
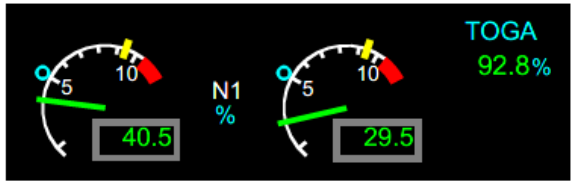
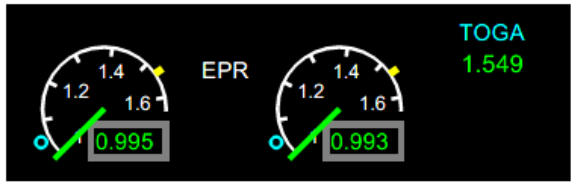
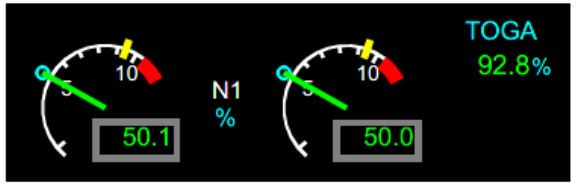
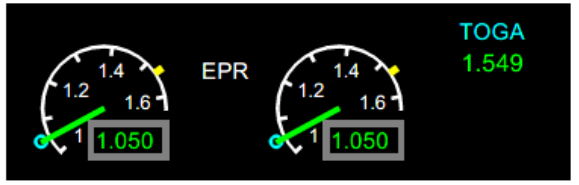
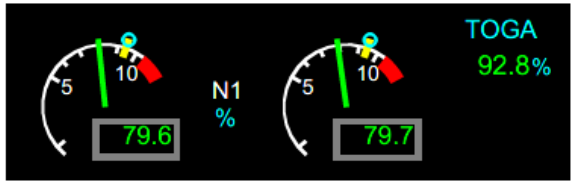
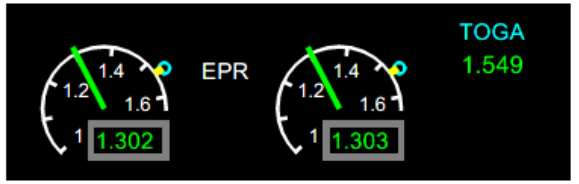
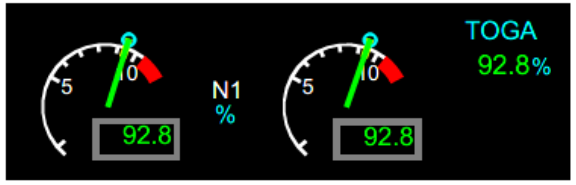
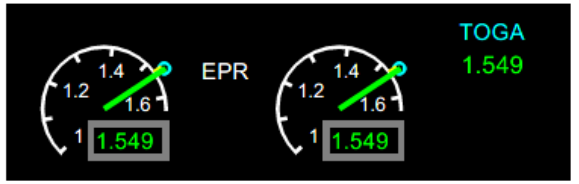


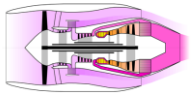
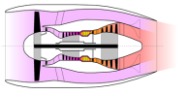
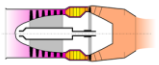
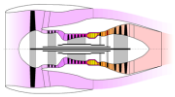
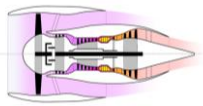
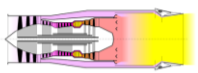
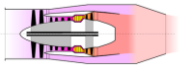
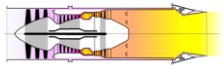
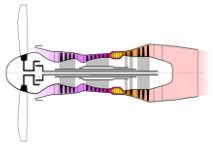
What the Pilot Sees

A350 Engines at Idle



A320 Standard Thrust Setting Procedure at Take-off

	A320 CFM or PW	A320 IAE
Idle Thrust		
Thrust levers set to stabilization step: 50%N1 / 1.05EPR		
Both engines Stabilized at Stabilization value		
Thrust levers moved to takeoff thrust (FLX or TOGA)		
Both engines Stabilized at takeoff thrust before 80kt		

Outline

Constant thrust, independent from engine-to-engine variations and deterioration

Wing-mounted Engines

Thrust

- Thrust Setting Parameters
- Engine Pressure Ratio
- Spool Speed

Ratings

- Flat Rating
- Generating Schedules
- Derating
- Idle

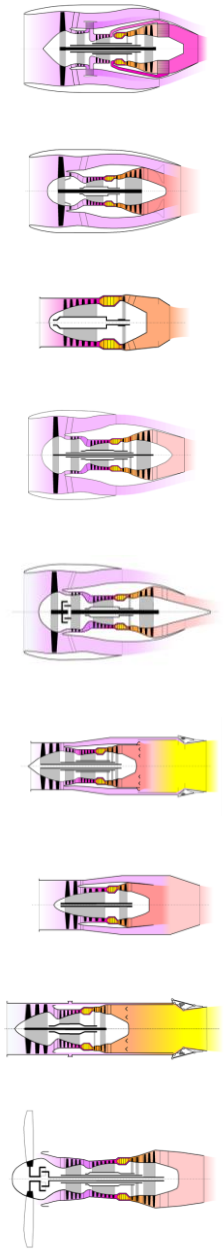
Exhaust Gas Temperature

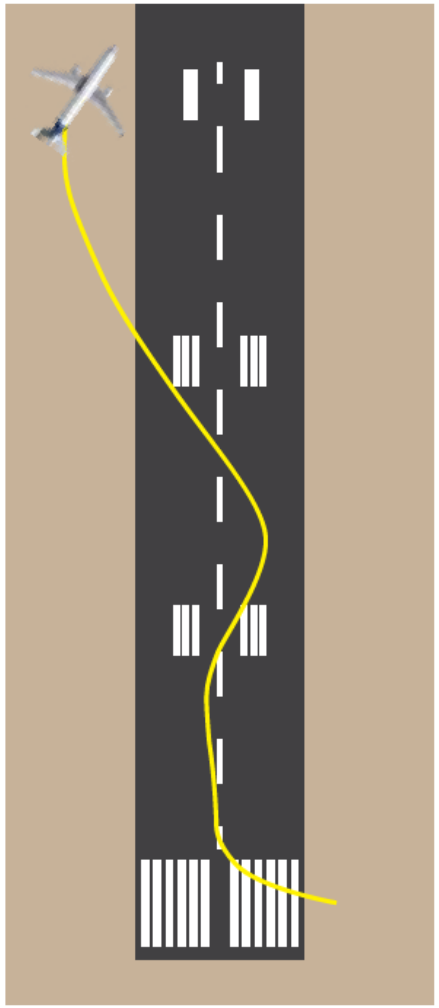
- Deterioration
- EGT Margin

The Cockpit

- A320
- A350

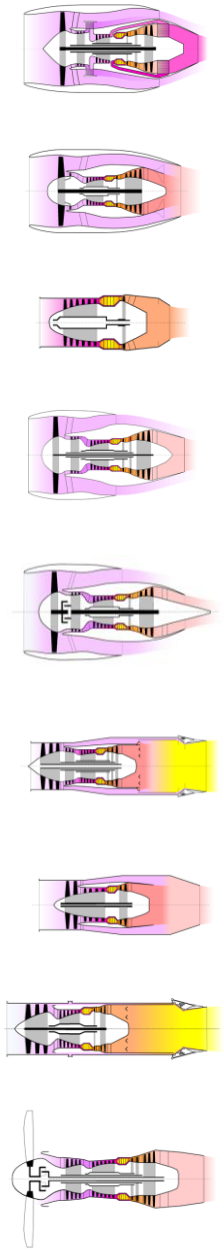
Transient





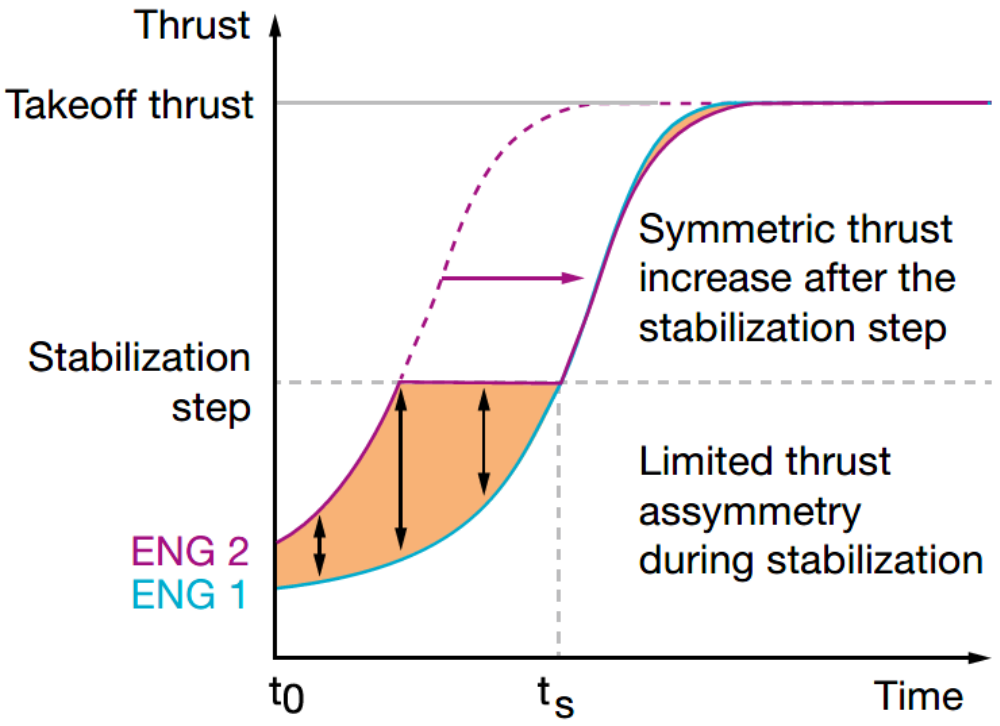
The Problem

- When two or more engines are operated at the same time, there can be a difference in the acceleration rate of each individual engine.
- This difference in acceleration is due to the wear and aging of the engines.
- When two engines accelerate at different rates, it can create a thrust asymmetry, which can be quite dangerous at low speeds, where control difficulties might cause the aircraft to run off the runway.



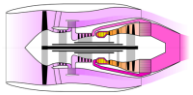
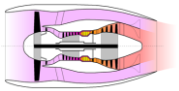
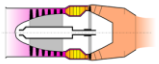
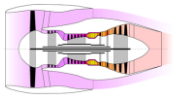
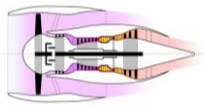
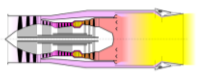
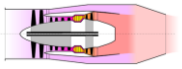
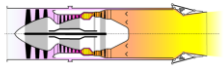
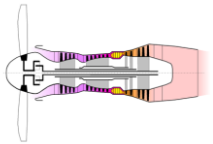
Pilots Set Thrust in 2 Steps For Take-Off

Intermediate Stabilization

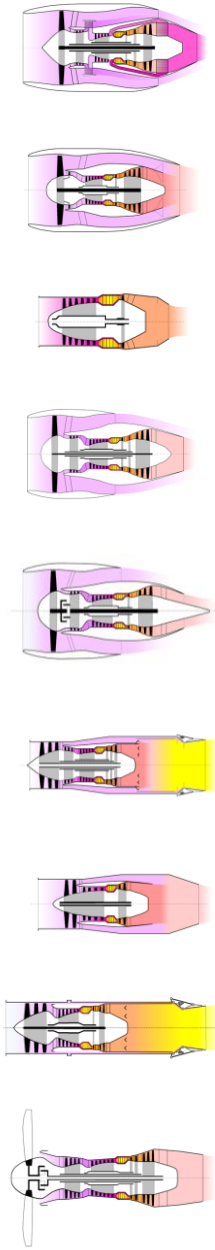


- To ensure that an aircraft's engines accelerate simultaneously during the early stages of the take-off roll, the flight crews must wait for all engines to reach the stabilization step before advancing the thrust levers to command take-off thrust.
- The stabilization step ensures that all engines reach a N_1 value where the increase of engine thrust will be almost identical to each other.
- The N_1/EPR/THR stabilization value is defined during flight test campaign for every engine type with collaboration from engine manufacturers.

Source: Airbus Safety first, #27, 2018

Alternative Facts



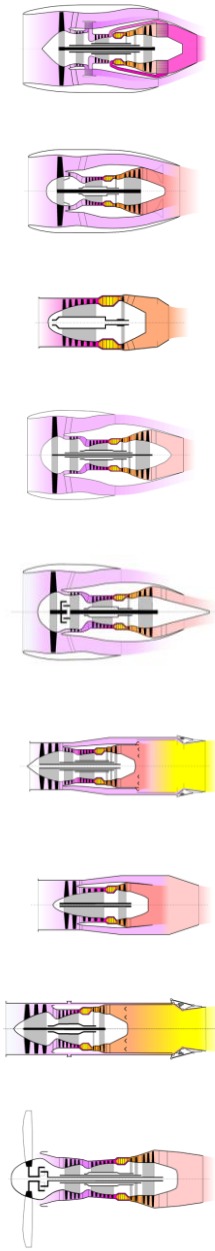
Outline

Maximum performance from each engine

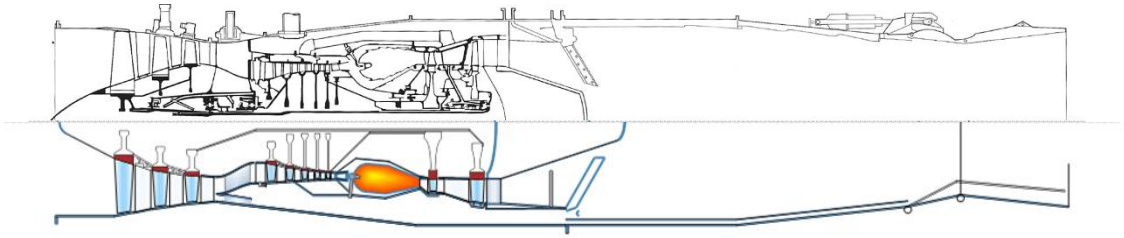
Embedded Engines

Ratings

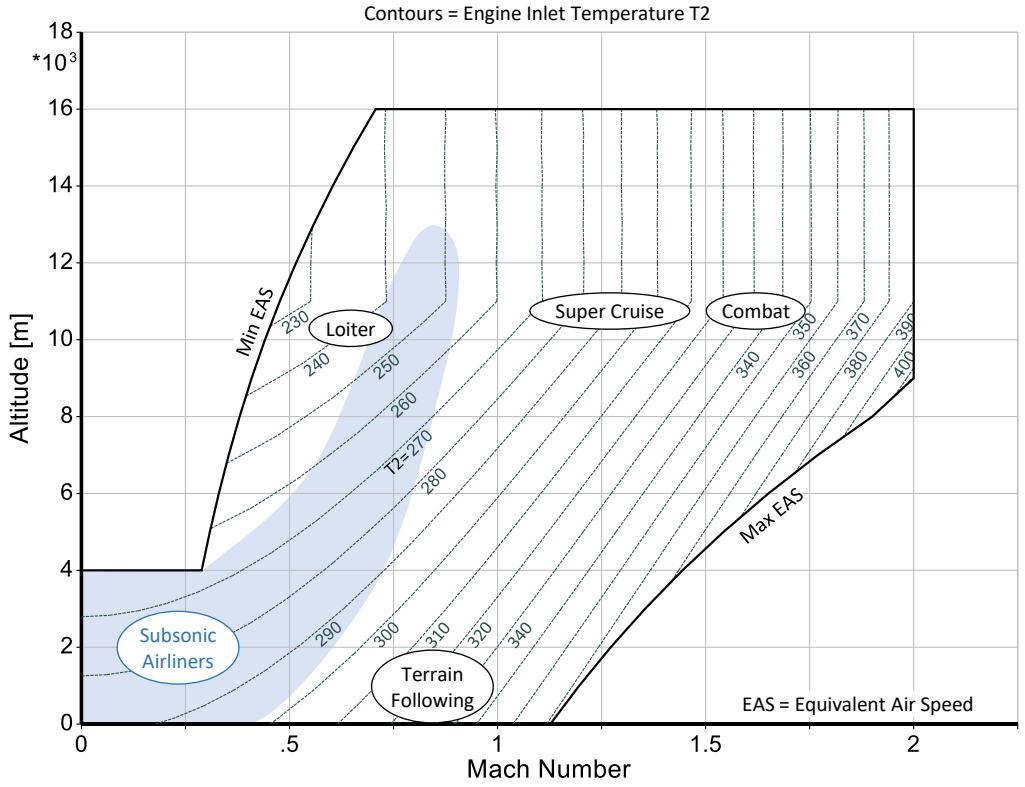
- Limiters
- Deterioration
- Thrust Rating

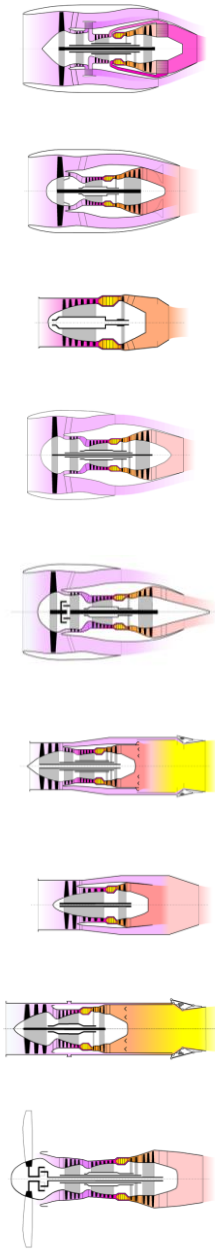


Flight Envelope of a Fighter Aircraft



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





Fighter Engine Thrust Control

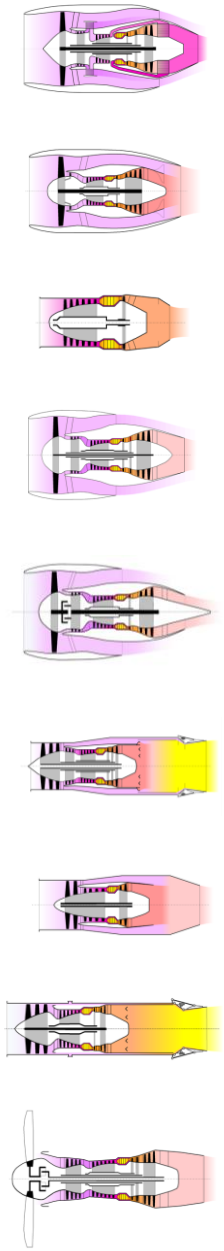
The aim: get the maximum thrust from the given hardware

- Run the engine to its limits

Limits are

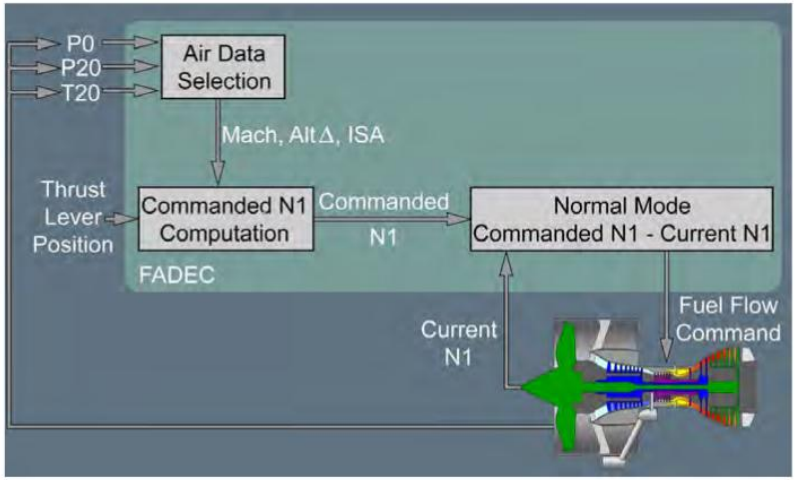
- Spool speeds N_1 and N_2
- Corrected spool speeds $N_1/\sqrt{\Theta}$ and $N_2/\sqrt{\Theta}$
- Hot end temperatures
  - Turbine blade temperature TBT (pyrometer required)
  - Exhaust gas temperature T_{45} or T_5
- HP compressor exit temperature T_3
- Burner pressure P_3
- Nozzle actuator load

"Lowest wins" logic is employed

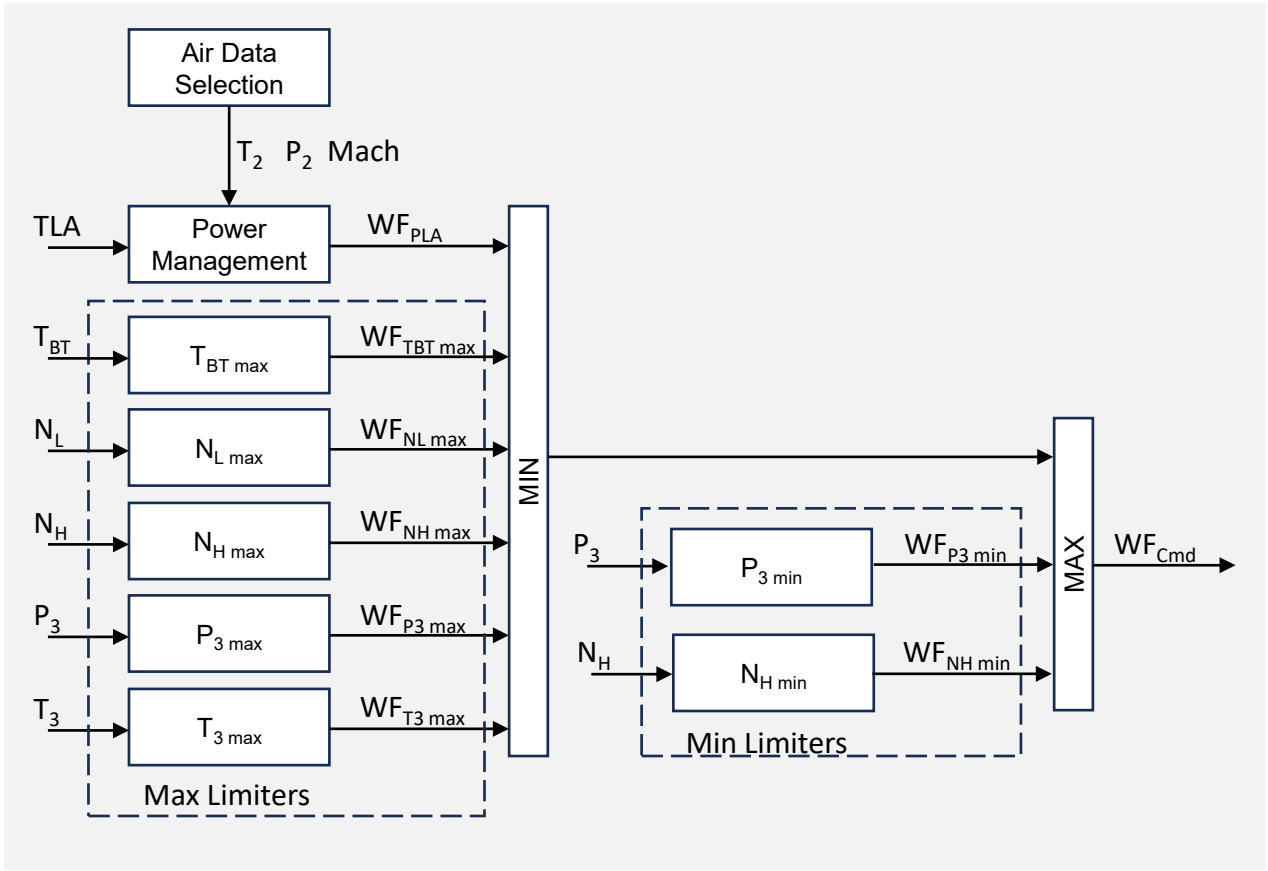


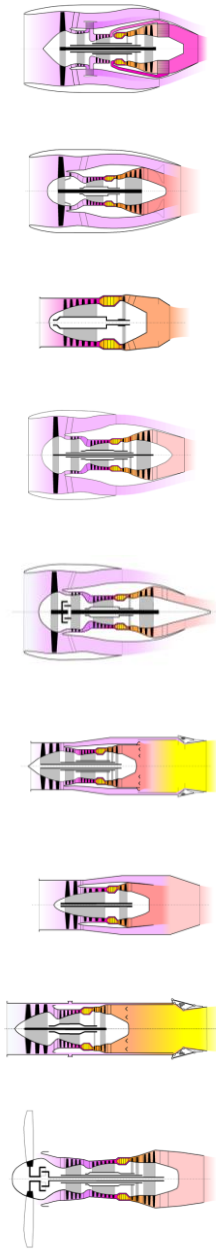
Control Logic Difference

Thrust Rating



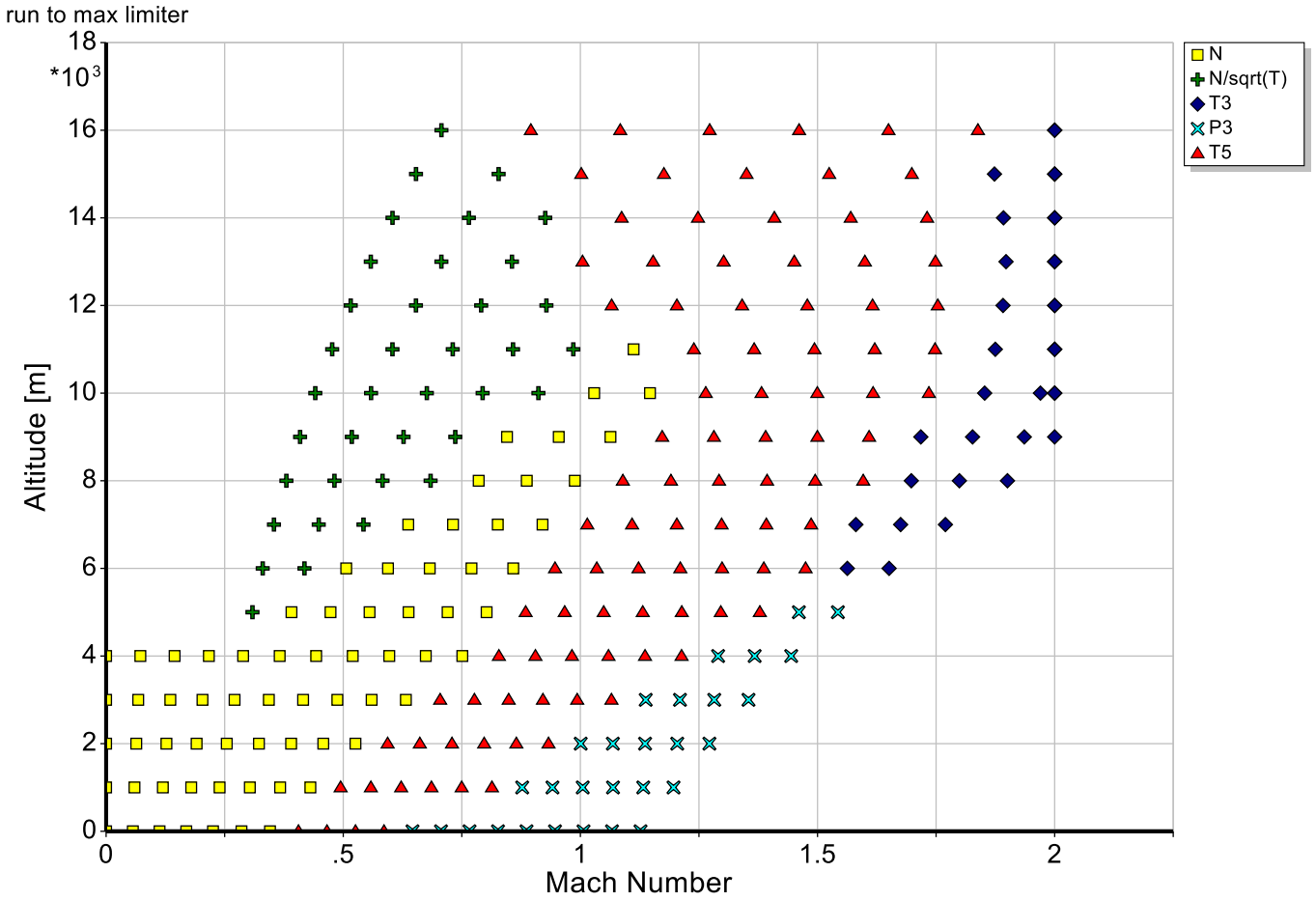
Power Rating

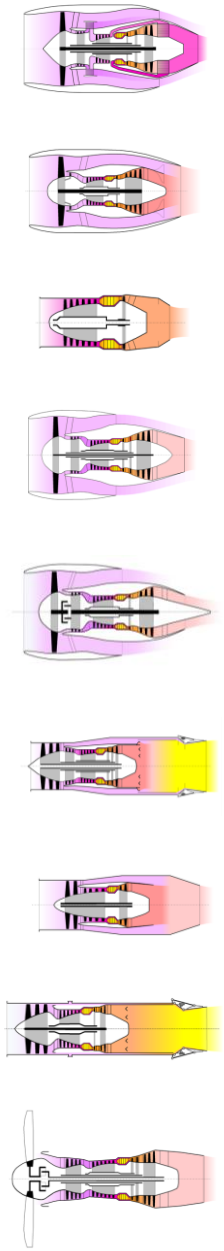




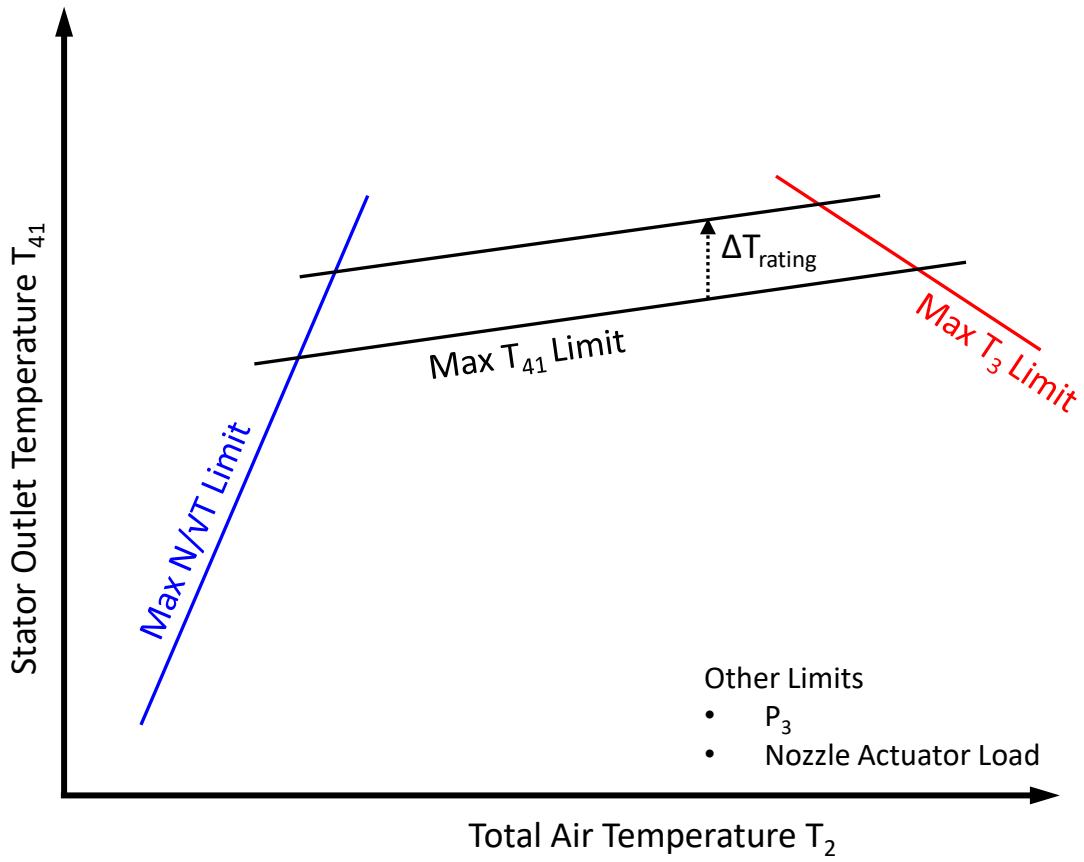
Turbojet Active Limiters

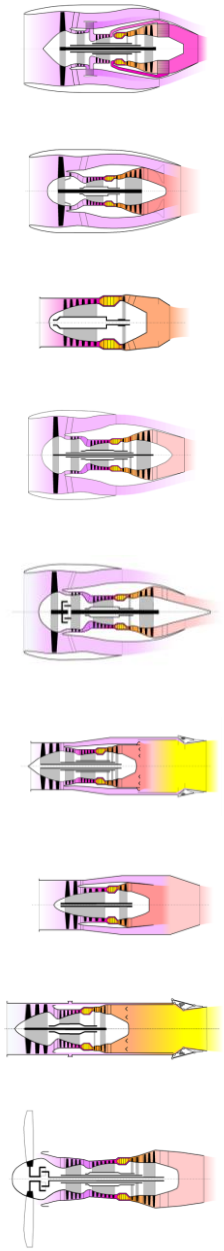
GasTurb Demo Example





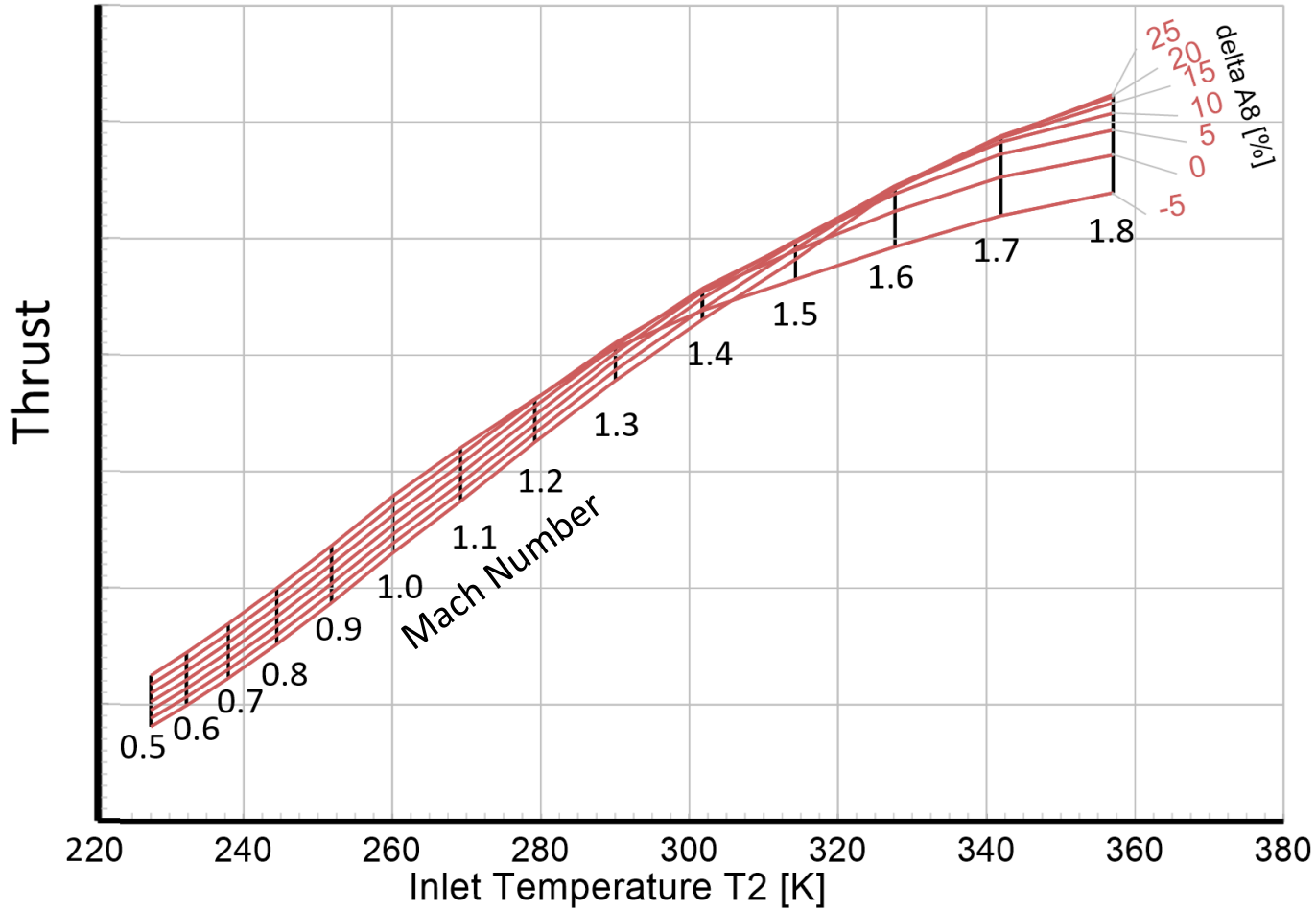
Basic Control Schedules

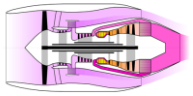
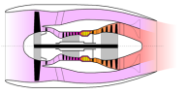
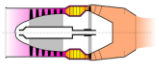
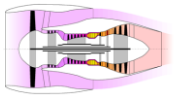
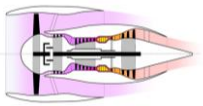
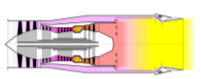
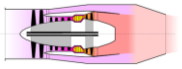
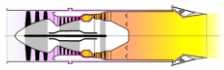
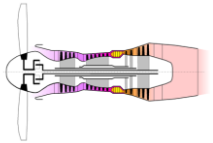




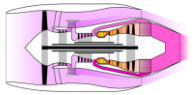
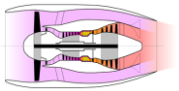
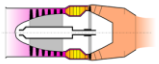
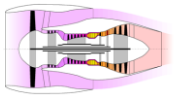
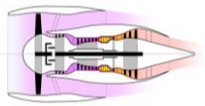
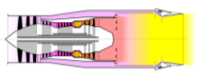
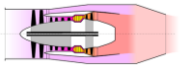
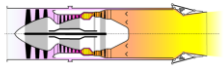
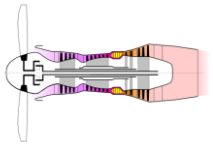
Additional Control Variables

Nozzle Area Trim 36000ft Max Reheat



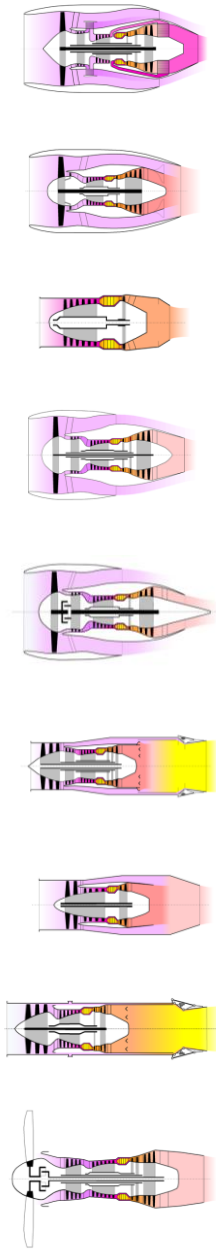
Afterburner Control

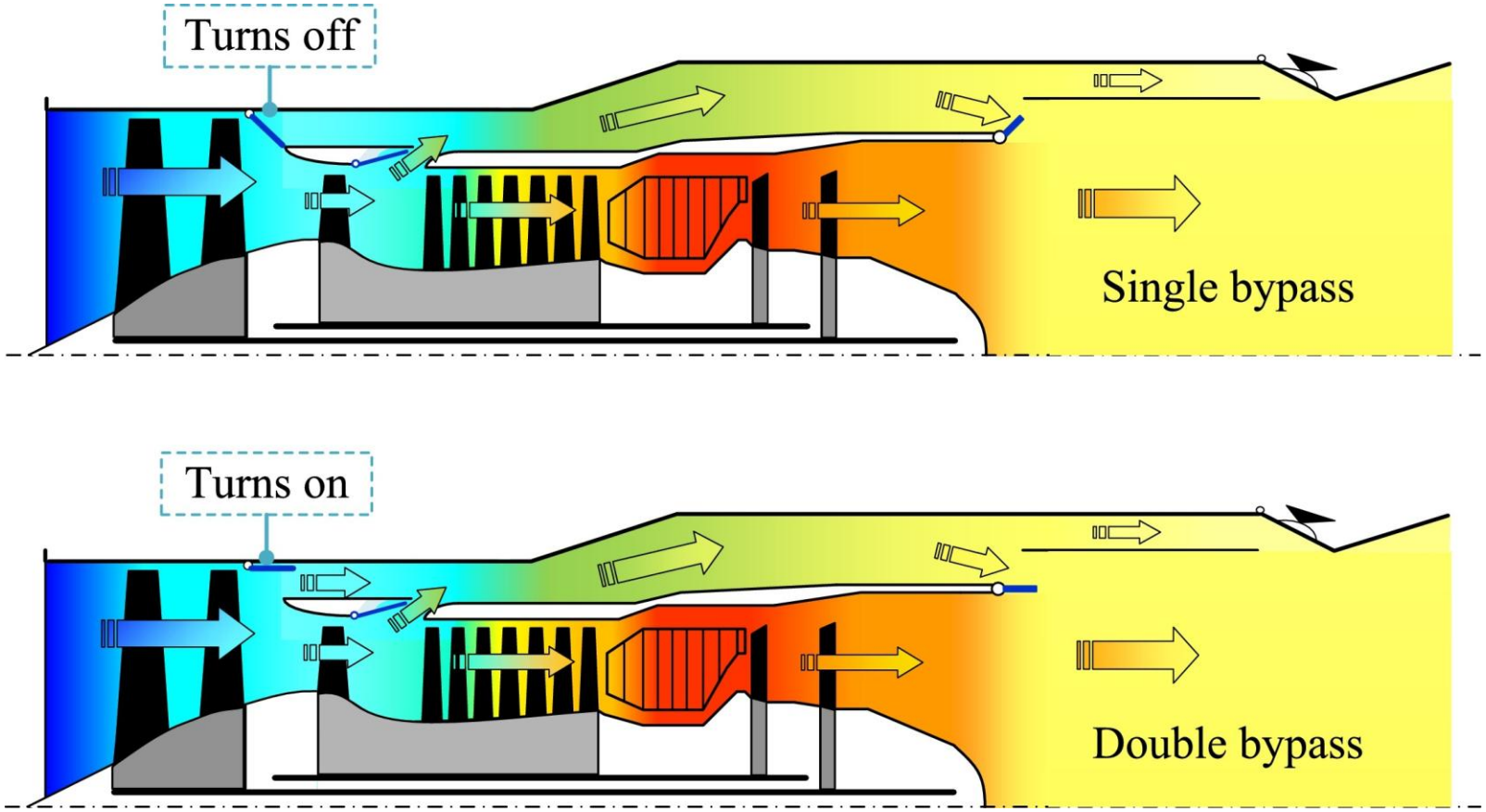
Additional Control Variables

Thrust Vectoring

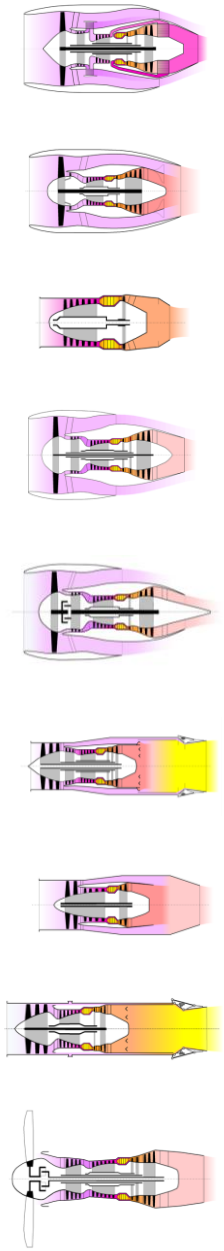
https://warwingsdaily.com/how-the-3d-thrust-vectoring-system-works-on-the-su-30sm-and-su-35/



Variable Cycle Engine

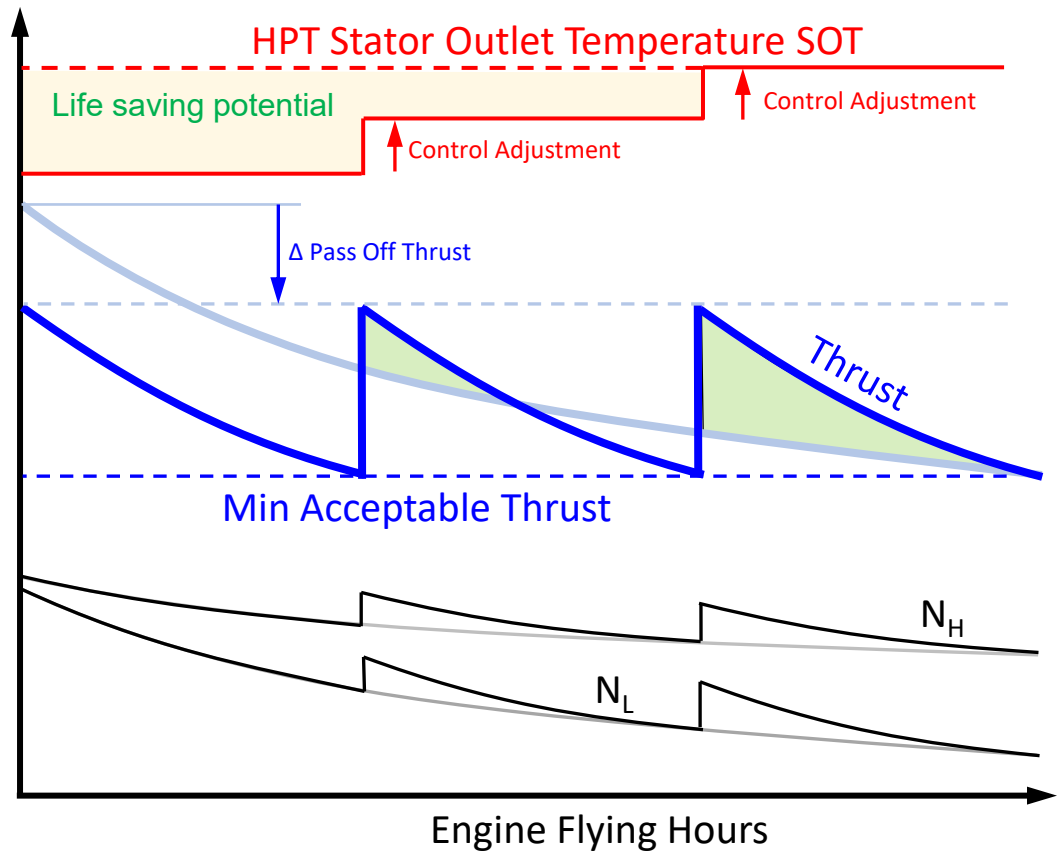


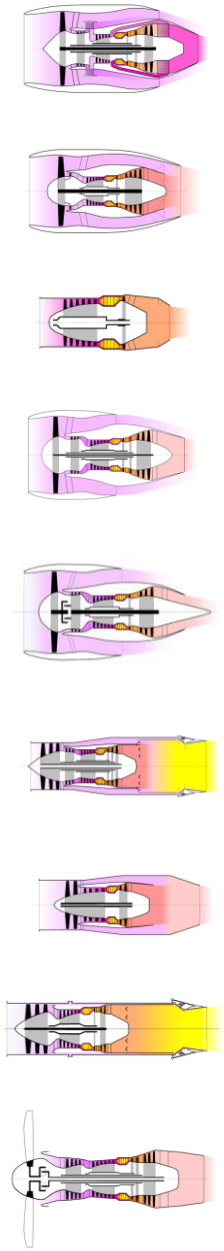
https://doi.org/10.1016/j.ast.2022.108078



Military Engine Thrust Rating

- All engines experience varying levels of performance above the minimum acceptable level
- Thrust rating is the limiting of engine performance to a specified baseline value in order to obtain an increase in engine life
- Manual adjustment of the SOT limit is done in periodic intervals during ground maintenance
- Automatic adjustment of the SOT limit requires a reliable assessment of thrust by an on-board computer system





Eurofighter Typhoon. Image Created by Ideogram.

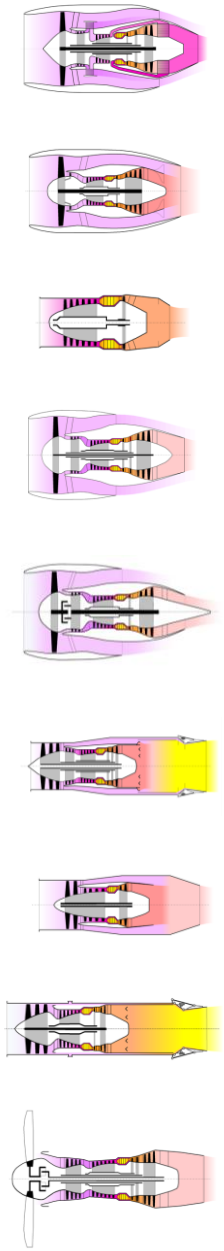
The End

Wing-mounted Engines

- Thrust
  - Thrust Setting Parameters
  - Engine Pressure Ratio
  - Spool Speed
- Ratings
  - Flat Rating
  - Generating Schedules
  - Derating
  - Idle
- Exhaust Gas Temperature
  - Deterioration
  - EGT Margin
- The Cockpit
  - A320
  - A350
- Transient

Embedded Engines

- Ratings
  - Limiters
  - Deterioration
  - Thrust Rating



www.kurzke-consulting.de

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

SPRINGER NATURE

Springer

Joachim Kurzke, Ian Halliwell, Robert Hill

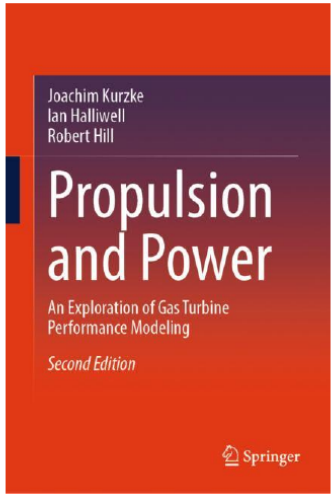
Propulsion and Power

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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