FLIGHT
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Propulsion (1): Jet Engine Basics

Propulsion (1): Jet Engine Basics

- Jet Engine Fundamentals (Videos)
- Types of Jet Engines
- Propulsive Efficiency and the Thrust Equation
- More Engine Terminology

Pratt & Whitney Videos on Jet Engine Fundamentals

1 - “The concepts of thrust”
2 - “Typical Turbo Jet Engines”
3 - “Variations in Jet Engine Design”
4 - “Types of Gas Turbine Engines”

What is a Jet Engine?

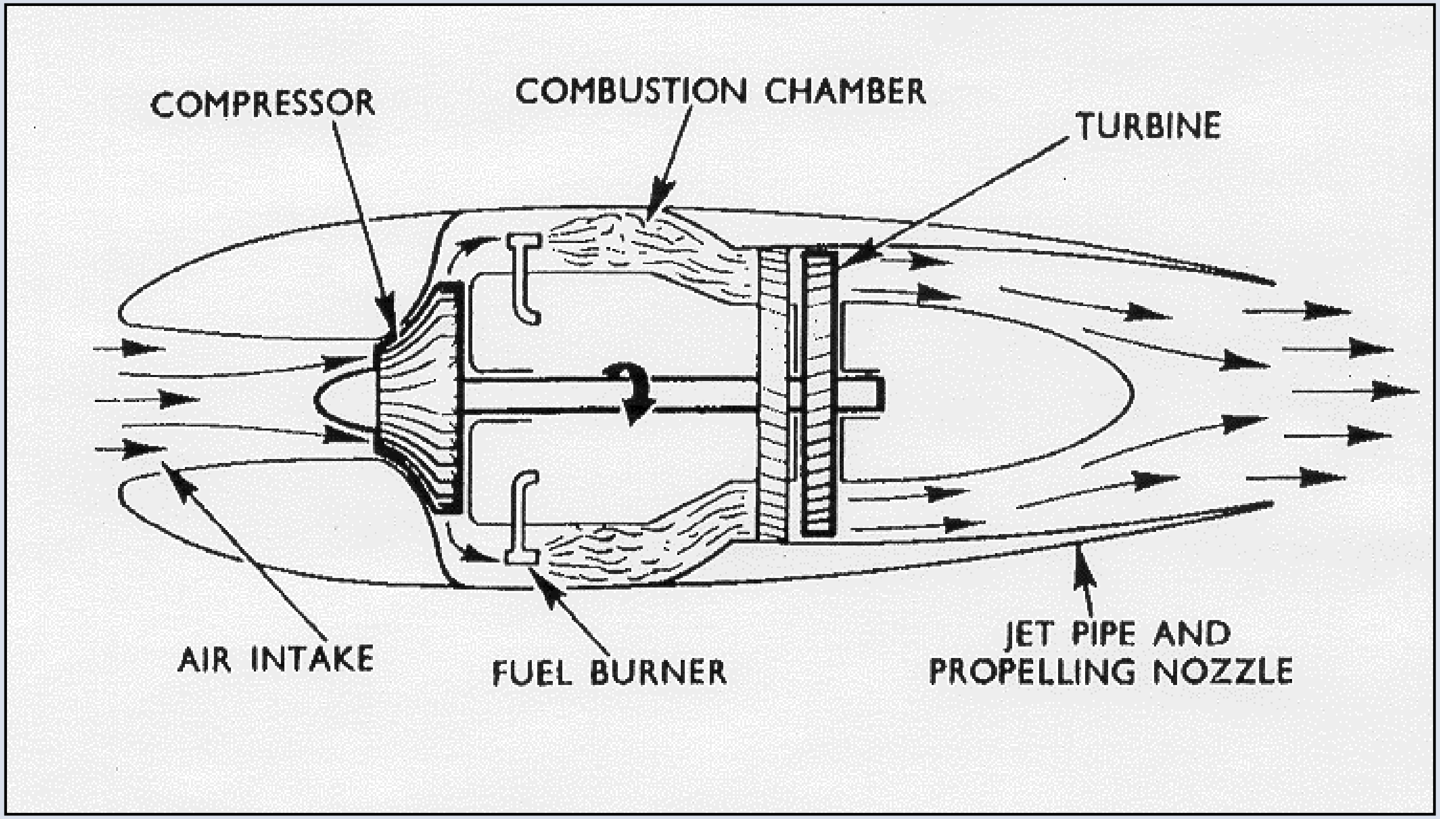
- A jet engine is a machine designed for the purpose of creating large volumes of high-velocity exhaust gasses. (This sounds simplistic, but it is essentially correct.)
- This is done in order to produce the thrust needed to overcome the aerodynamic drag of an airplane.
- In the process of producing high-velocity exhaust, the jet engine also produces:
  - Electrical power
  - Hydraulic power
  - Pneumatic power for A/C and pressurization
  - Hot air for anti-icing protection

Basic Operation of a Jet Engine

- The basic operation of a jet engine is:
  - Air enters and is compressed in a compressor.
  - Fuel is then added and ignited.
  - The resulting gas spins a turbine,
  - The turbine powers the compressor.
  - The gas then exits the engine at the tailpipe.
- The way a jet engine operates is similar to the way an automobile engine operates: Intake, compression, ignition, exhaust.

Structure of the Jet Engine

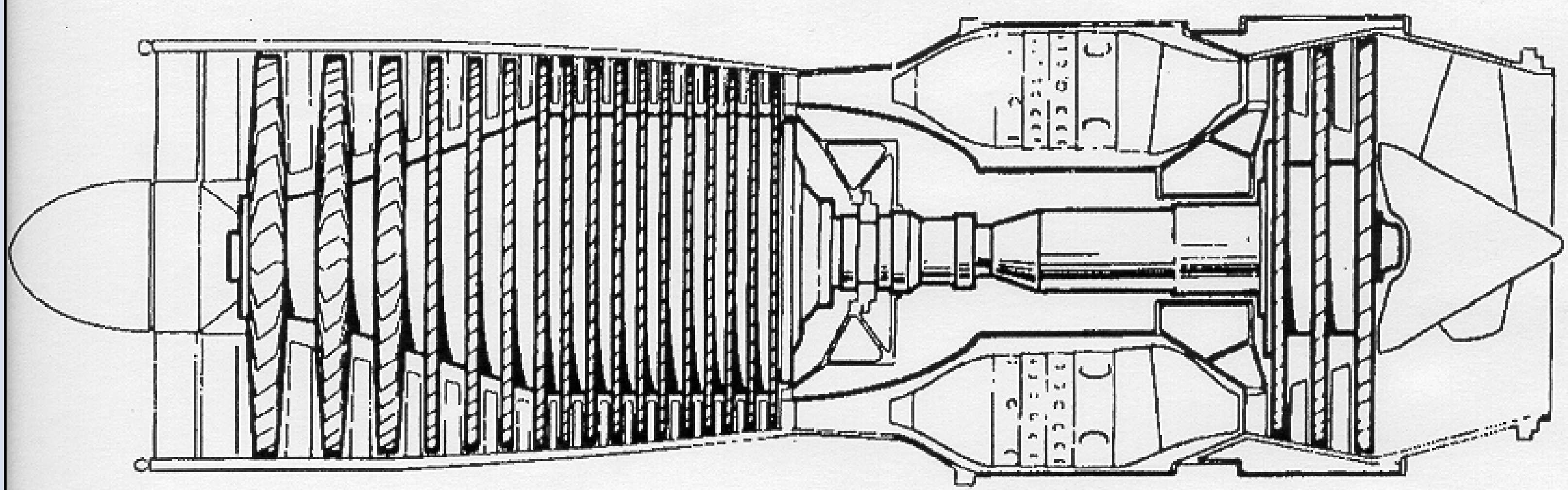
- The engine shown here is known as a "Whittle" type engine, since it follows the original design features developed by Sir Frank Whittle in the 1930's. The first flight of a jet engine of his design was in 1941.



- All engines in use on today's commercial jet airplanes have been developed based on this original design.

Types of Jet Engines

- The earliest commercial (paying passenger-carrying) jet airplanes used a single-spool turbojet engine, like that shown below.
- The term "single spool" refers to the fact that there is only one shaft. This shaft connects one turbine section to one compressor section.

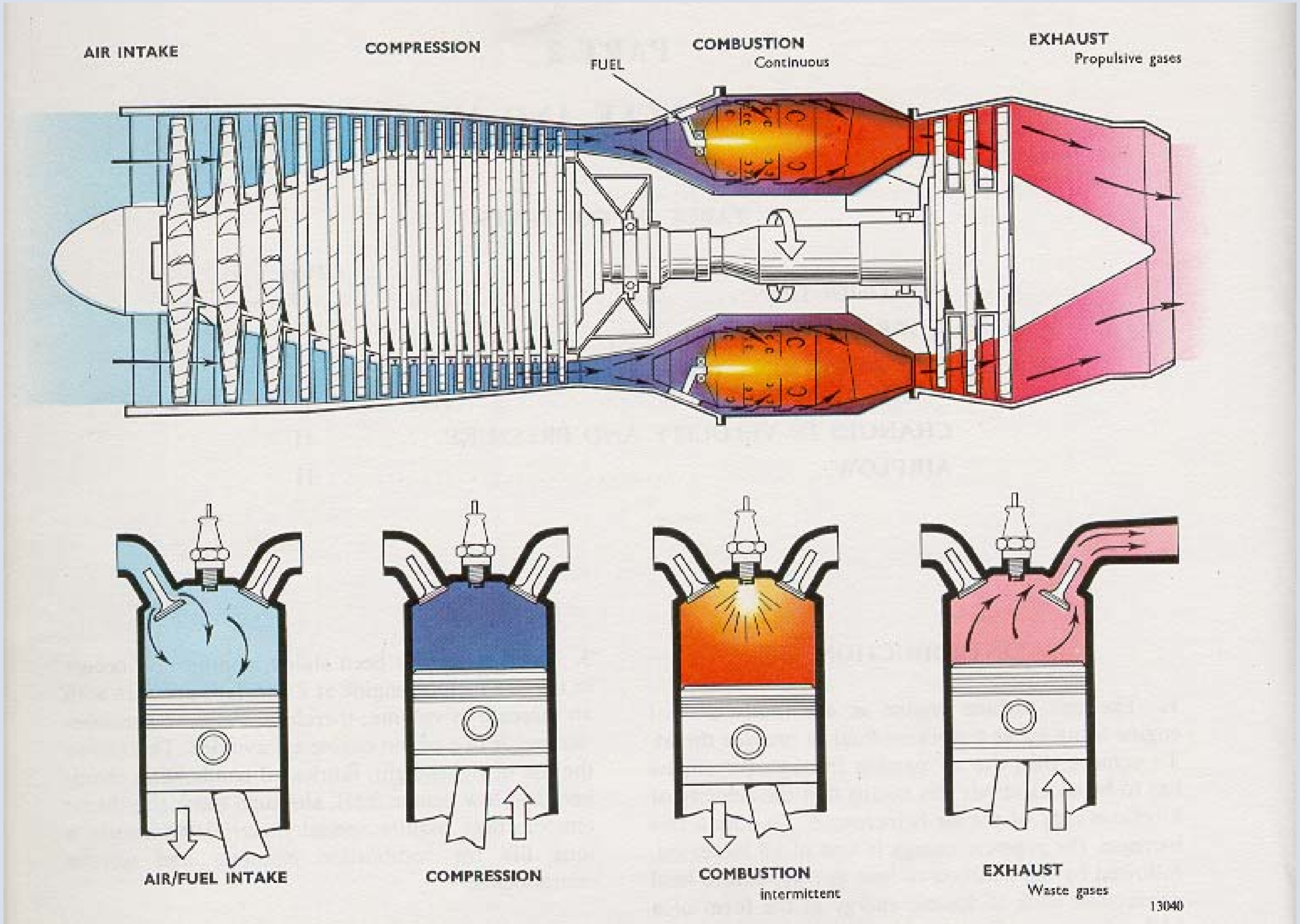


SINGLE-SPOOL AXIAL FLOW TURBO-JET

Types of Jet Engines

- All jet engines in current use are *axial flow* engines, meaning that the compression phase is done axially (parallel to the axis of the engine) as the air flows through the compressor.
- Axial flow engines are different from early jet engines which compressed air in a centrifugal compressor.

Thermodynamic Cycles Through a Jet Engine—Similar to a Four-Stroke Engine



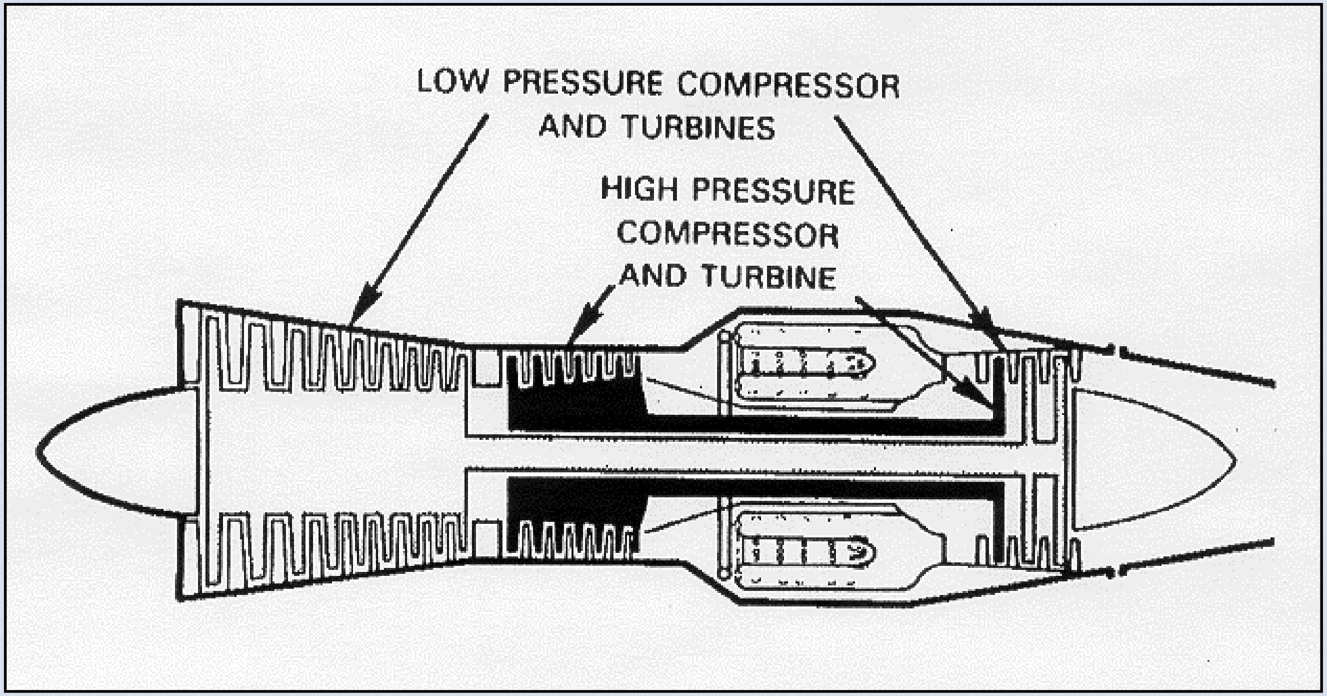
(suck) (squeeze) (bang) (whoosh!)

Twin-Spool Turbojet Engine

- The first significant development after the introduction of the early axial-flow, single-spool turbojets was the introduction of a second shaft.
- This second shaft allowed the engine to have two independent stages of compression powered by two independent turbines.
- The compressors and turbines could now be more accurately matched to the characteristics of the airflow through the engine, creating an improvement in efficiency.

Twin-Spool Turbojet Engine

- The first stage of compression is the low-speed rotor, and the second stage is the high-speed rotor. These terms refer to the fact that the first stage of the turbine, which rotates the second stage compressor, turns at a faster rate than the second stage turbine/first stage compressor.
- These are often referred to as the N1 rotor (low-speed) and the N2 rotor (high-speed).

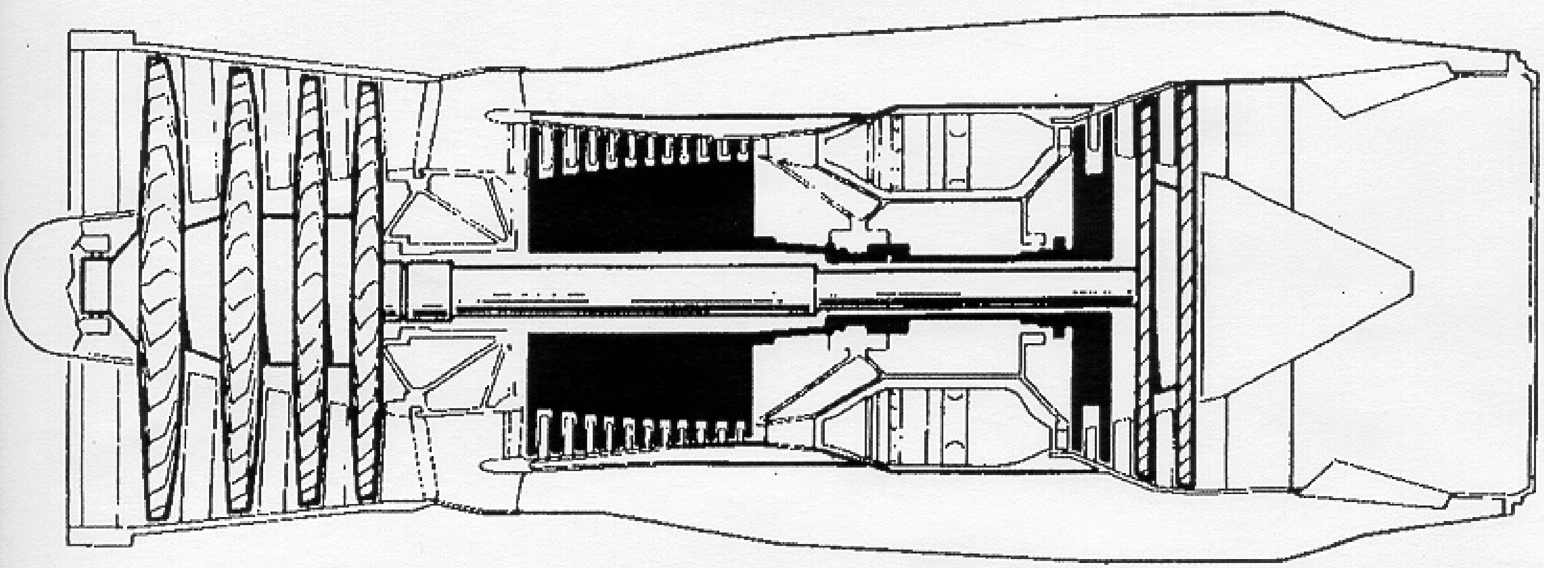


Turbofan Engine

- The next significant development was the introduction of the turbofan engine. In a turbofan engine, a portion of the thrust is developed by the “fan” – which is, in effect, a multi-bladed propeller, rotated by the N1 turbine.
- A large portion of the air which is accelerated by the fan stage does not progress through the rest of the engine. The fan accelerates a large amount of air mass by a relatively small amount. This is more efficient then accelerating a smaller volume of air by a larger amount.

Turbofan Engine

- The bypass ratio is the ratio of the air which exits the engine without going through the rest of the engine core compared to the amount of air which goes through the engine core (the primary flow). Each of these produces thrust.
- Turbofan engines produce lower noise levels than earlier engines, and have considerably improved fuel economy.



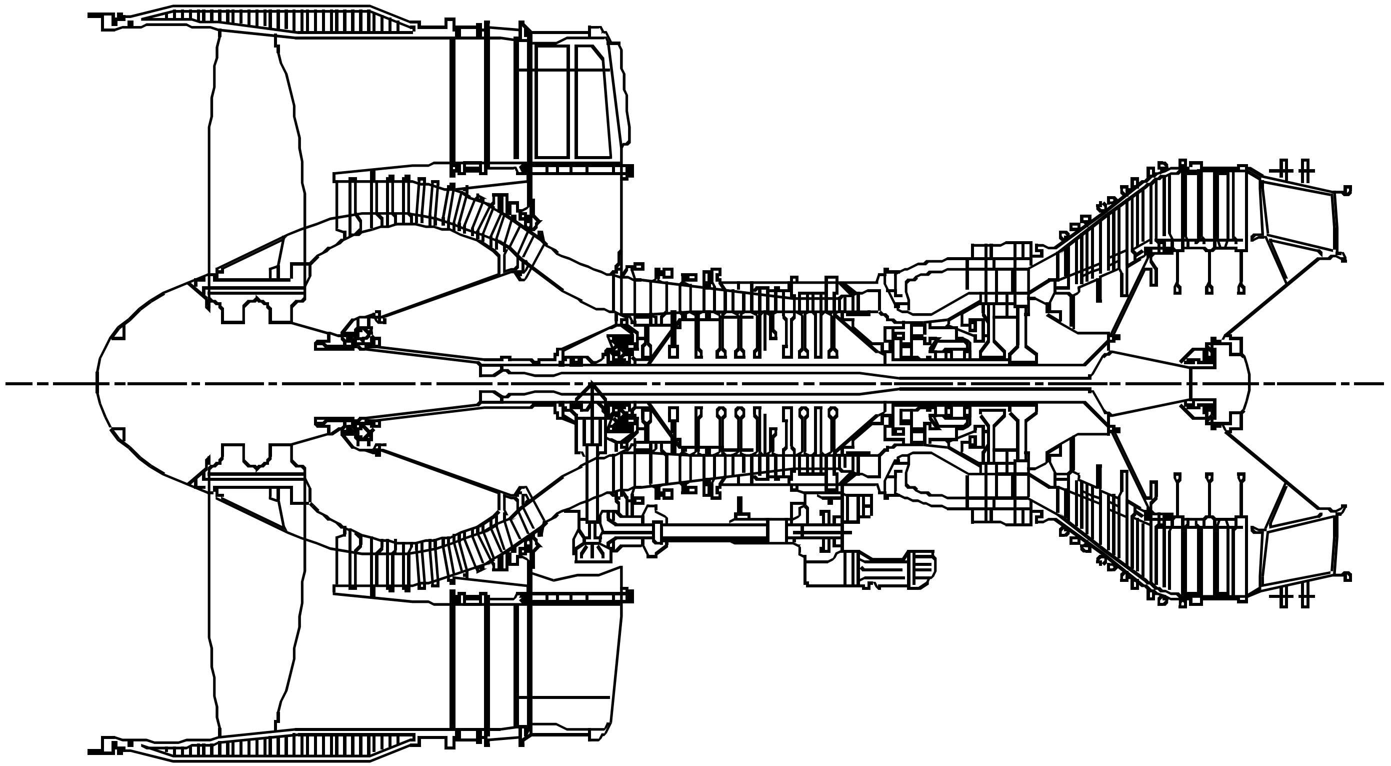
Twin-spool By-pass Turbo-jet (low by-pass ratio)

High Bypass Ratio Turbo Fan Engine

- Early turbofan engines were “low-bypass ratio” engines. Approximately ½ of the thrust was produced by the fan stage, and the other half by the primary flow.
- Engines currently in production for most commercial airplanes are all high-bypass ratio turbofans. The difference is that these engines have a much higher ratio of bypass (fan stage) air compared to the primary air.
- Current bypass ratios are around 5:1 and higher. For these engines, the fan stage provides about 75 to 80 percent of the total thrust produced by the engine.

High Bypass Ratio Turbo Fan Engine

High bypass ratio engines take in a large amount of air and accelerate it only a small amount (relative to low bypass ratio engines).



High Bypass Ratio Turbofan Engine

High Bypass Ratio Turbo Fan Engines

PW4084 engine:
6.8 bypass ratio

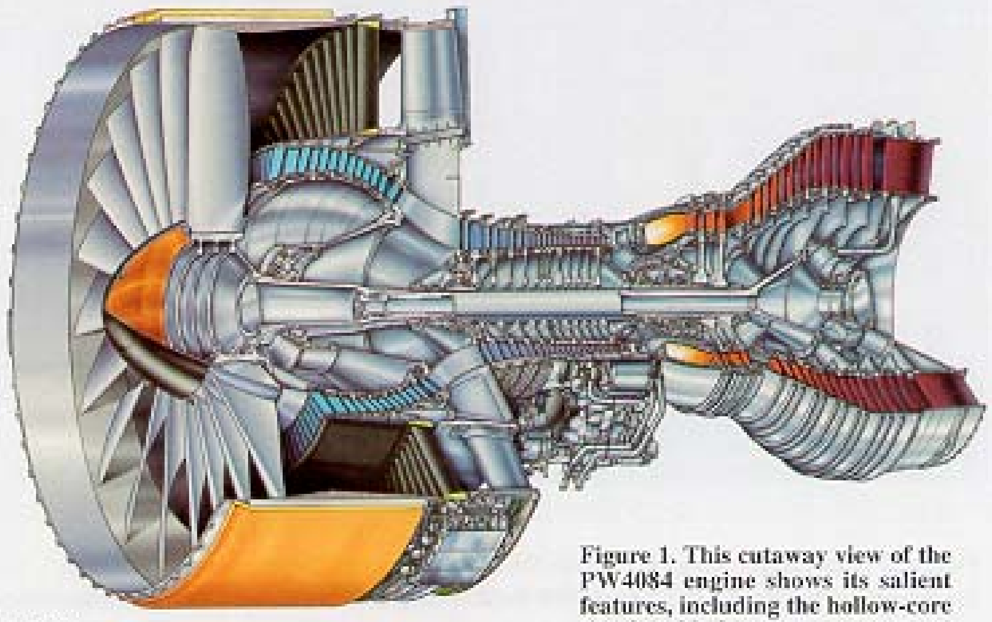


Figure 1. This cutaway view of the PW4084 engine shows its salient features, including the hollow-core titanium blades.

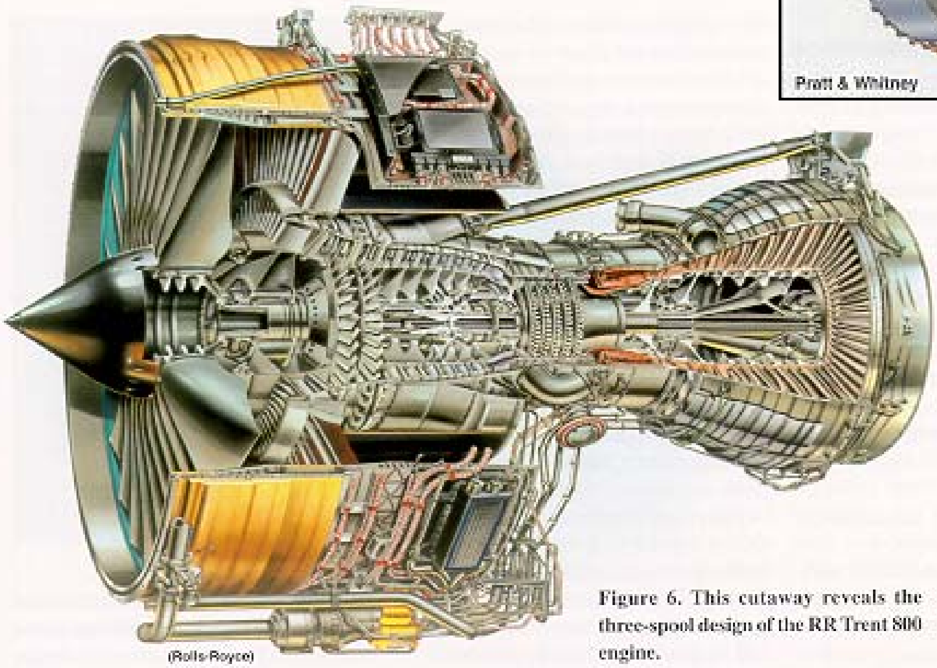
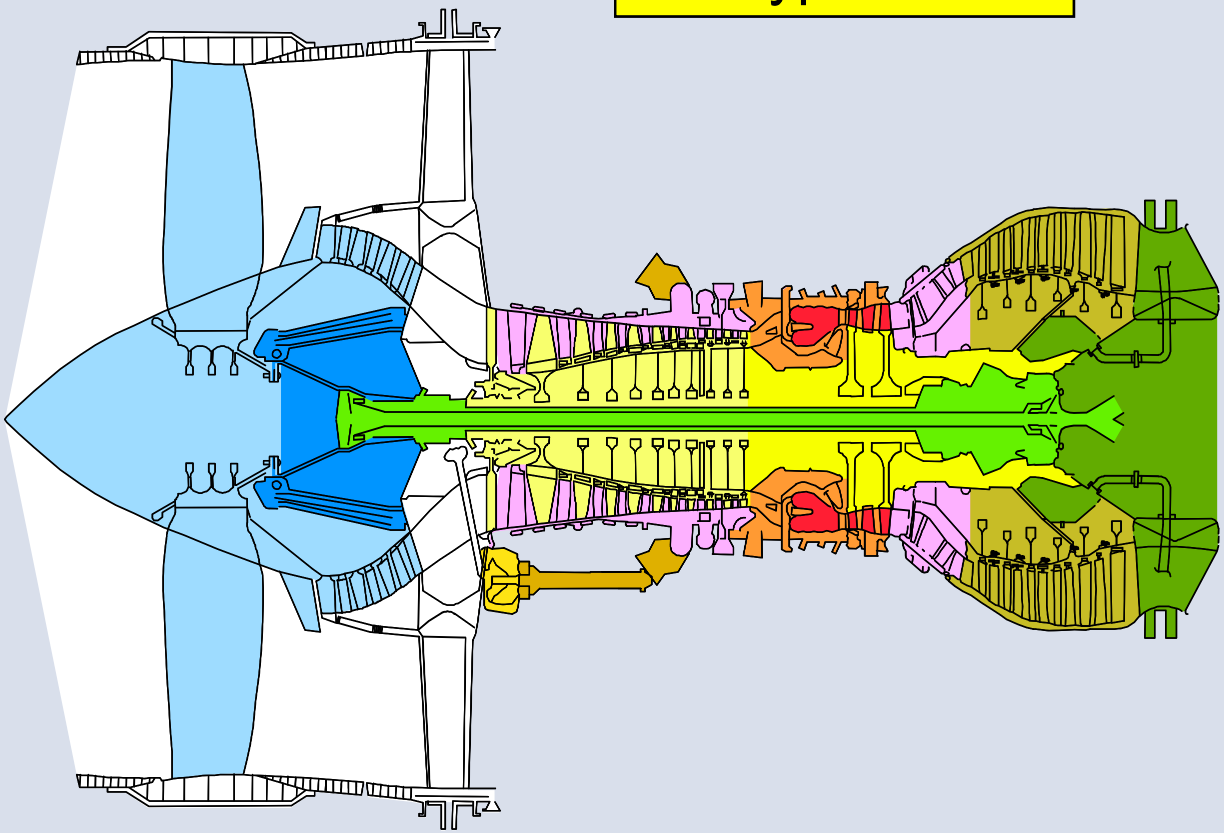


Figure 6. This cutaway reveals the three-spool design of the RR Trent 800 engine.

RR Trent 800 engine:
6.5 bypass ratio

High Bypass Ratio Turbo Fan Engines

GE-90B engine:
9:1 bypass ratio



High Bypass Ratio Turbo Fan Engines

Engine used on 777s sets thrust record

The newest derivative of the GE90 jet engine, which is used on several 777 family airplanes, recently set a world record for thrust, reaching 127,900 pounds during final engine certification testing.

High Bypass Ratio Turbo Fan Engines


POWER STRUGGLE

General Electric's flight test team had to learn new techniques to knock the rough edges off the the world's most powerful jet engine, the GE90-115B.

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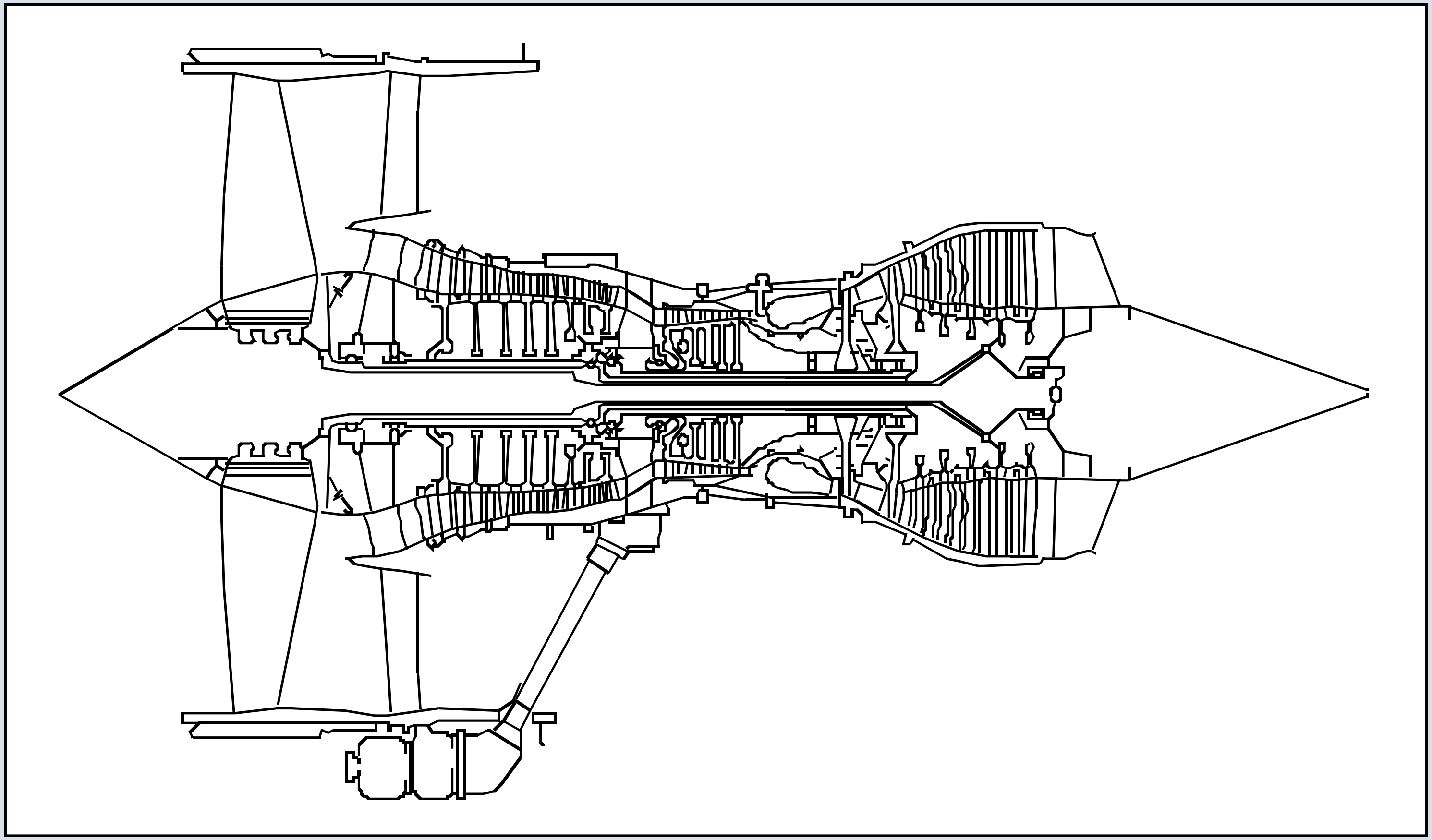
Triple Spool Turbofan Engines

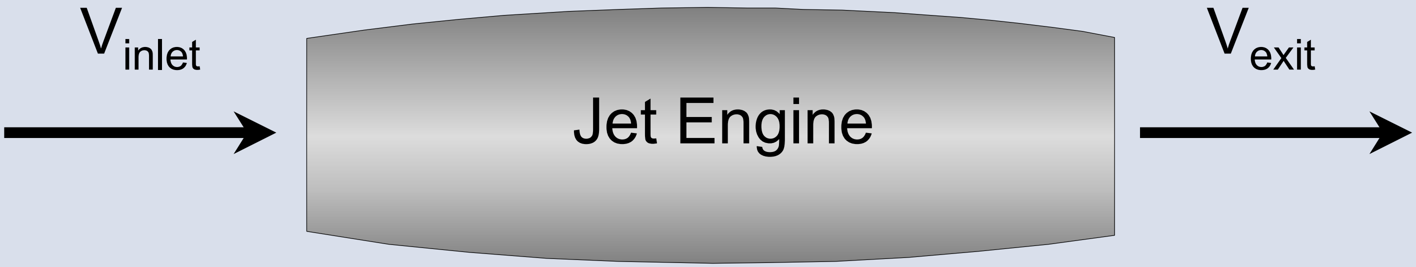
- RR engines now in production use a triple-spool design, incorporating three independent rotors.
- Designed to achieve better fuel economy due to the ability of the triple-spool design to better match the design of the compressors and turbines to the airflow.



Propulsive Efficiency

The propulsive efficiency of an engine can be expressed in terms of the inlet velocity of the air and the exhaust velocity.

$$\eta_p = \frac{2 * V_{inlet}}{(V_{inlet} + V_{exit})}$$



Propulsive Efficiency

- An efficiency of 100% would be attained if the exhaust velocity was equal to the inlet velocity. However, for this to occur, the mass flow through the engine would need to be infinite.
- Infinite mass flow is obviously not achievable in the real world, but this does indicate that greater efficiency is obtained when a large mass of air is accelerated by a small amount rather than a small mass of air being accelerated by a large amount.
- The high-bypass ratio engine is a way to achieve the acceleration of a large mass of air by a small amount, thus helping the engine to achieve greater efficiency than a low-bypass ratio engine can achieve.

The Thrust Equation

- Recall from Newton's third law:
  - For every action there is an equal and opposite reaction
- The jet engine's *action* is accelerating a mass of gas and sending it out tailpipe.
- The equal and opposite *reaction* is thrust.

The Thrust Equation

- Recall from Newton's second law:

$$F = d(mv)/dt \quad (= ma \text{ for a constant mass})$$

- In jet engine terms, we can re-write this as:

$$F = \frac{\dot{w}}{g} * (V_2 - V_1)$$

- Where:

F	is force in pounds
$\dot{w}$	is the gas flow in pounds per second
g	is the gravitational constant
V_1	is the initial velocity of the gas, in ft/sec
V_2	is the final velocity of the gas, in ft/sec

The Thrust Equation

- Note that instead of using F = ma, we are re-writing the equation as force equals *mass flow* per unit time multiplied by *velocity change*.
- This difference is subtle but essential: Acceleration is not the same as velocity change. Thus force is *not* equal to mass times velocity change; acceleration is velocity change per unit of time.
- Using F = mass flow per unit time multiplied by velocity change is dimensionally correct.

The Thrust Equation

We can re-write the thrust equation to make it more meaningful in the context of a jet engine:

$$F_{net} = \left(\frac{\dot{w}_{air} + \dot{w}_{fuel}}{g} * V_{jetexhaust} \right) - \left(\frac{\dot{w}_{air}}{g} * V_{airplane} \right)$$

- F_{net}: thrust of engine
- $\frac{\dot{w}_{air} + \dot{w}_{fuel}}{g}$: total mass flow out tailpipe
- $V_{jetexhaust}$: exhaust velocity
- $\frac{\dot{w}_{air}}{g}$: incoming mass flow of air
- $V_{airplane}$: velocity of incoming mass flow

The Thrust Equation

- This is called the "net" thrust, because it accounts for the momentum of the incoming air; "Gross" thrust is given by the first term in the equation – which is the force created at the exhaust of the engine.
- To compute usable thrust, the gross thrust has to be reduced by the amount of the second term, which is the momentum already existing because of the airplane's speed.
- From the equation, you can see that net thrust is a function of the mass flow rate of the air and fuel passing through the engine, and of the exhaust velocity minus the incoming velocity.

Additional Thrust Due to Internal Pressure

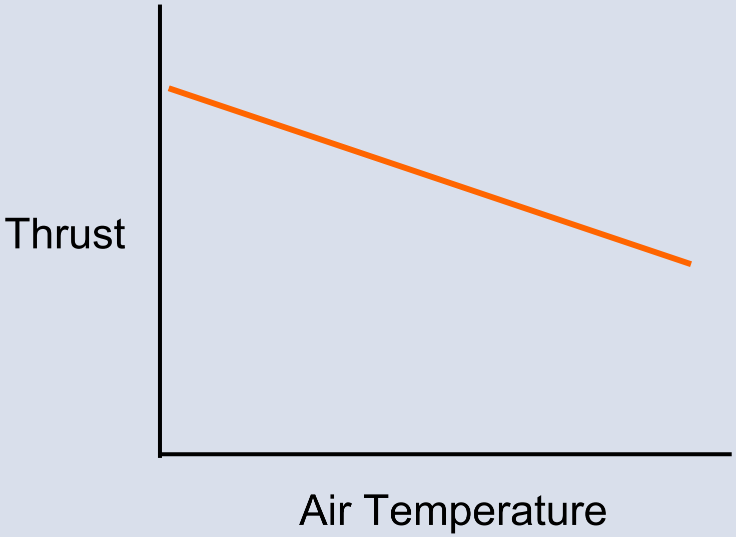
- The thrust equation as written is somewhat simplified in that it ignores one more possible component of thrust. That component is *thrust due to internal pressure*.
- Most of the internal pressure within the engine is converted to velocity of the exhaust gasses, which in turn produces thrust.
- At the exhaust, if the total pressure of the gasses is greater than the total pressure at the intake, this surplus of pressure will produce some additional thrust.

$$F = A_{exhaust} * \left(p_{exhaust} - p_{ambient}\right)$$

- This component of thrust is small compared to the thrust due to exhaust velocity, but should not be ignored.

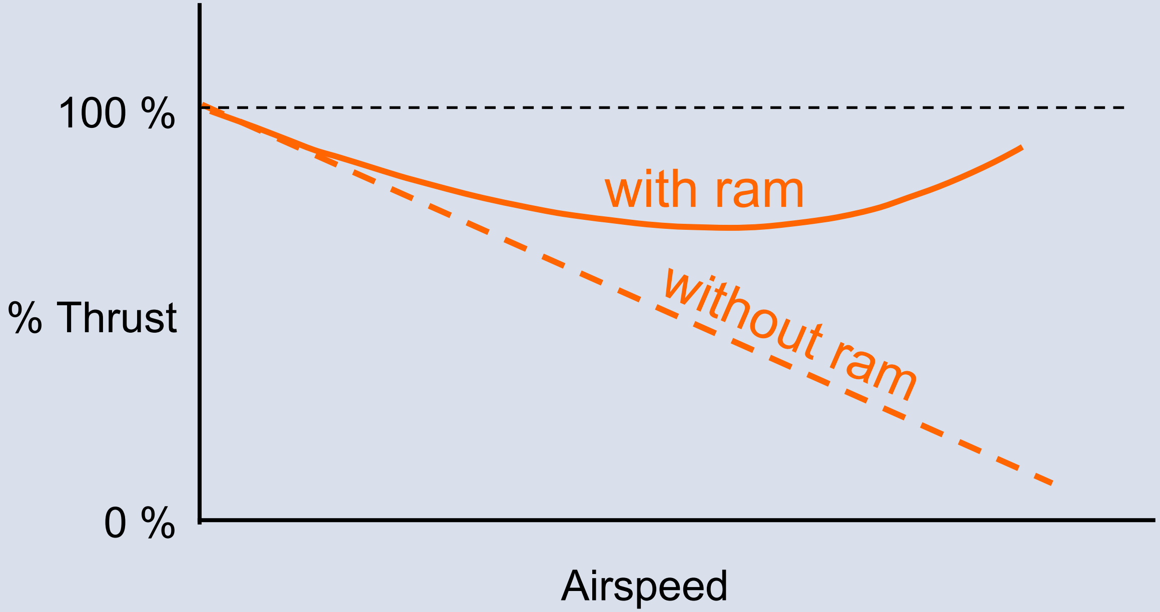
Factors Affecting Thrust

Air density, a function of temperature and pressure altitude, is a very significant component affecting thrust.



Factors Affecting Thrust

- *Velocity* affects both the momentum and the pressure of the air entering the engine intake.
- Increasing aircraft speed increases the momentum of the incoming air, lowering thrust, while at the same time compressing the air at the intake (ram effect) increasing thrust by increasing density. The combined effect is show below.



Other Factors Affecting Thrust

- Bleed air extraction affect thrust (bleeds will be discussed later)
- Power extraction for hydraulic pumps, electric generators, fuel pumps, etc., affects thrust.
- Humidity has a negligible effect on thrust.

Installed Thrust

- The performance of an engine on the manufacturer's test stand is not the same as the performance of that same engine when installed on an airplane. The installed engine is different in several aspects:
  - The test stand engine uses an ideal "bell-mouth" air inlet. This has different airflow characteristics from the production inlet on an installed engine.
  - The test stand engine is not providing electric, hydraulic or pneumatic energy for use anywhere. An installed engine must provide energy for use elsewhere in the airplane.
- Installed thrust is less than test stand thrust because of these differences.

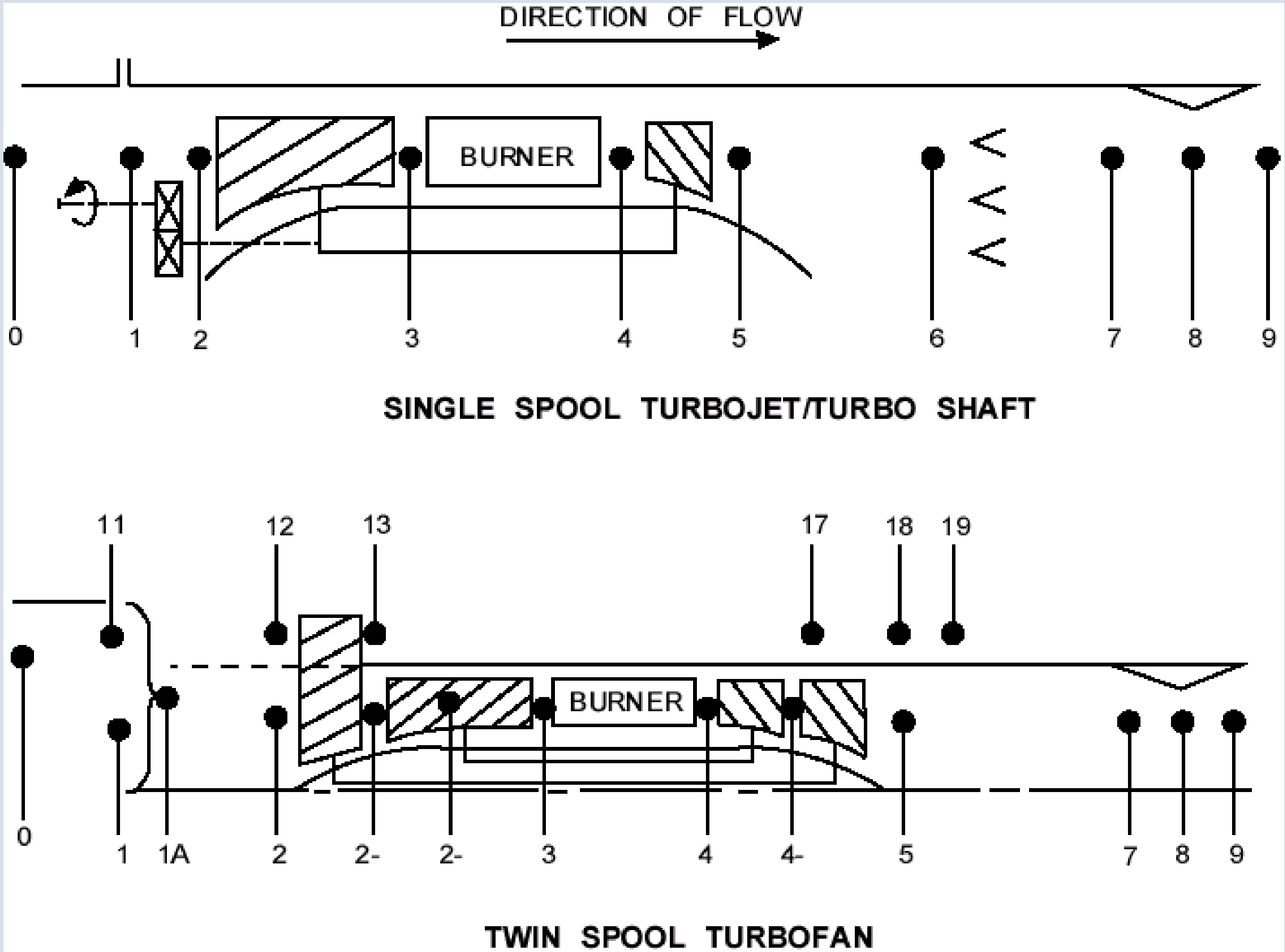
"Average Engine" Thrust and "Minimum Engine" Thrust

- There are minor variations between engines of the same type due to manufacturing tolerances. Therefore, for a given power setting, thrust produced is not the same for every engine.
- The lowest level of thrust, the minimum of the range of thrust variation, is called *"minimum engine" thrust*. Minimum thrust is used in performance calculations where performance is critical, such as takeoff performance, as it conservatively represents the output of all engines of a given type.
- *"Average engine" thrust* represents the thrust of an average engine – that is, an engine having thrust in the middle of the thrust variation range. Average thrust is used in performance calculations where performance is not critical – for example, cruise.

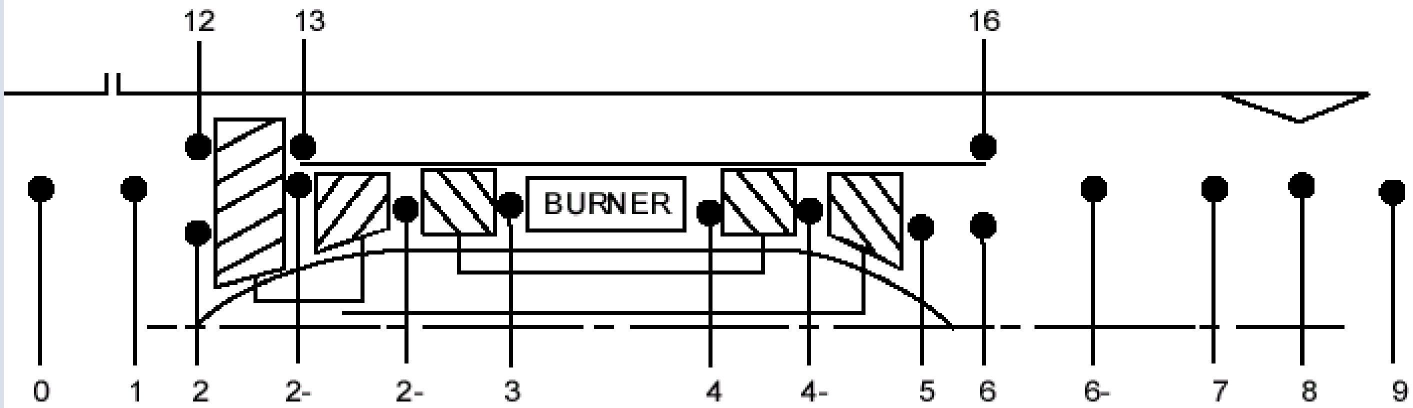
Engine Station Designations

- For reference, and for convenience, different locations within an engine have designations called “stations.” These stations are used as a means of identifying specific locations in an engine.
- Station 2, for example, is usually located at the front of the fan/compressor section. Station 7 is generally at entrance of the nozzle.
- Typical station numbering is illustrated on the following pages.

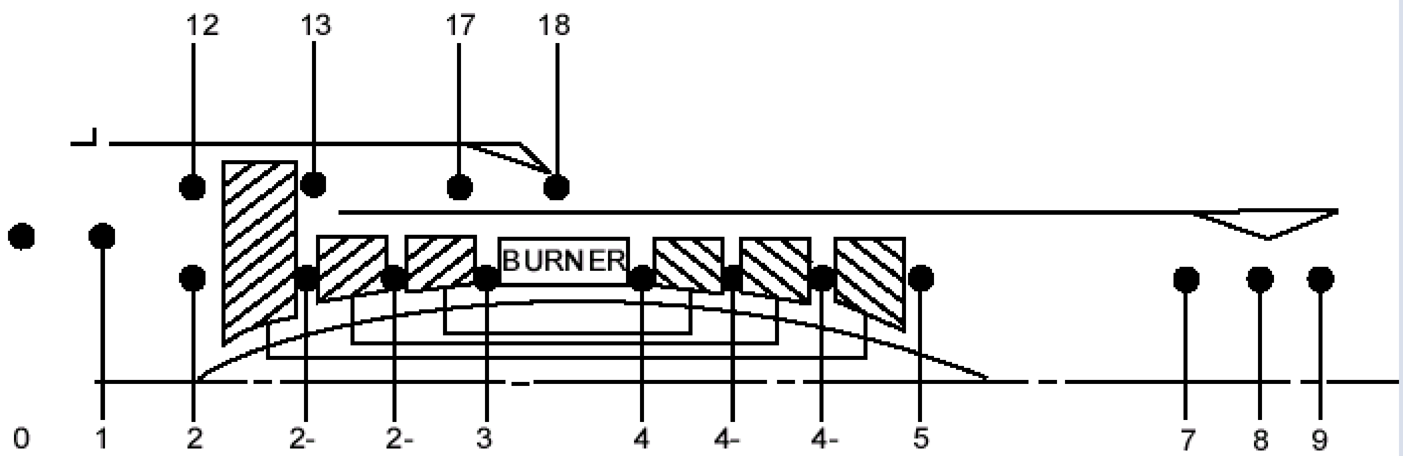
Typical Engine Station Designations



Typical Engine Station Designations



MIXED TWIN SPOOL TURBOFAN



TRIPLE SPOOL TURBOFAN

Other Commonly Encountered Jet Engine Terms

- *EPR* - Engine Pressure Ratio:
  - Ratio of total pressure at the exhaust (P_{T_7}) to total pressure at the front of the fan/compressor (P_{T_2})
  - This is commonly used as a measure of engine thrust, and is the primary thrust setting parameter on Pratt and Whitney and Rolls Royce engines.
- N1 or %N1:
  - N1 is the rotation rate, in RPM, of the low-speed rotor of a two or three-spool engine.
  - N1 is usually expressed as %N1, a percentage of some nominal value.
  - General Electric and CFMI engines use %N1 as the primary thrust setting parameter.

Other Commonly Encountered Jet Engine Terms

- *Corrected N1 (or, Referred N1):*
  - N1, or %N1, divided by the total temperature ratio raised to some power.

$$\%RN1 = \frac{\%N1}{(\theta_T)^x} \qquad (\text{'x' is } \textit{usually} = .5)$$

  - The exact relationship between gauge N1 – i.e., cockpit N1 and corrected N1 depends on the engine type.
- *N2 and N3:*
  - The rotation rate of the medium-speed and high-speed rotors of a three-spool engine such as many Rolls Royce engines.
  - On a two-spool engine, N3 is not used, and N2 denotes the rotation rate of the high-speed rotor.

Other Commonly Encountered Jet Engine Terms

- *Engine Stall (compressor stall):*
  - A condition characterized by stalled airflow over the compressor blades.
- *Surge:*
  - Refers to a condition of unsteady airflow through an engine as the result of abnormal flow conditions.
  - Surge can result from strong crosswinds at low airspeeds (e.g., during takeoff) or other conditions such as very rapid acceleration or deceleration of the engine.
- *Flameout:*
  - A condition in which the combustion chambers lose their ignition. This could be the result of unsteady airflow (e.g., strong turbulence) or other conditions.

Other Commonly Encountered Jet Engine Terms

- *Bleed:*
  - Extraction of compressed air from the engine.
  - Bleed air is used for air conditioning and pressurization, as well as for providing icing protection.
  - Engine bleeds are also used in some cases to prevent surging.
- *EGT – Exhaust Gas Temperature:*
  - This is the temperature at the engine exhaust

End of Propulsion (1):
Jet Engine Basics

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Propulsion (2): Jet Engine Thrust Ratings

Propulsion (2): Jet Engine Thrust Ratings

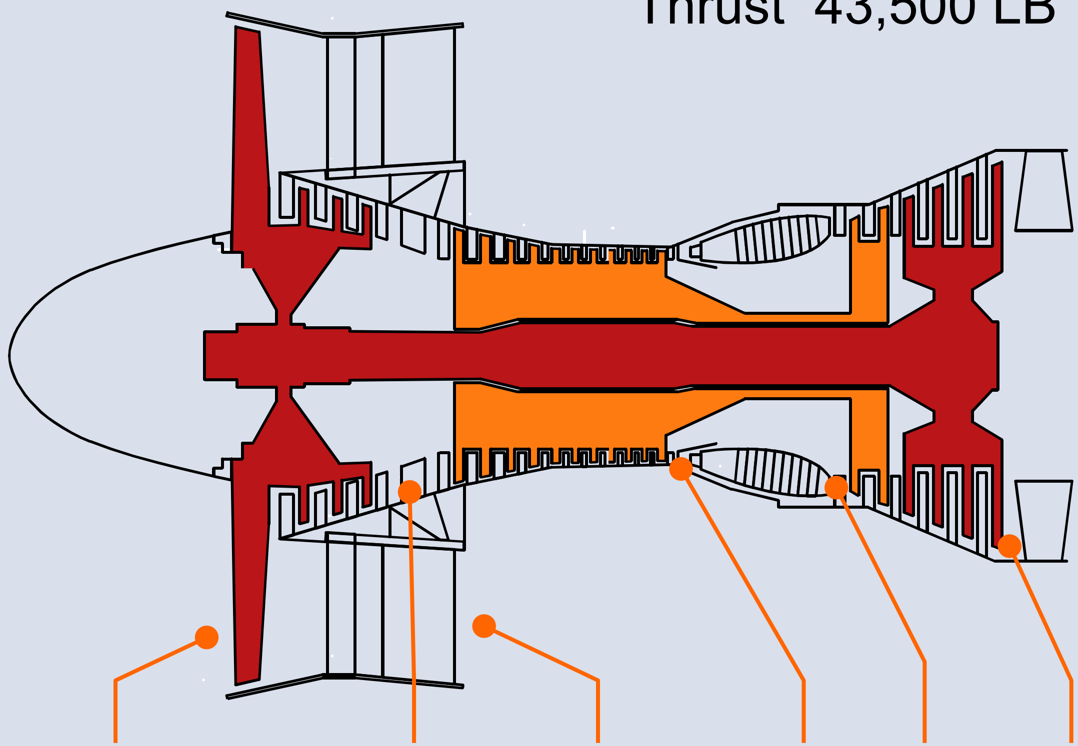
- Limitations on Maximum Thrust
- Thrust Setting Parameters
- Rated Thrust Levels
- Reduced Thrust
- EGT Limits

Engine Thrust Ratings

- When developing power from an engine it is necessary to observe certain restrictions to the thrust setting in order to avoid exceeding the engine's design limitations.
- The levels of thrust which meet the design limitations are referred to as *thrust ratings.*
- Different thrust ratings apply at different times during a flight. The ratings we will discuss are standard thrust ratings used by engines currently used in commercial service (as opposed to military).

Internal Temperatures and Pressures

JT9D Sea Level Static
Thrust 43,500 LB

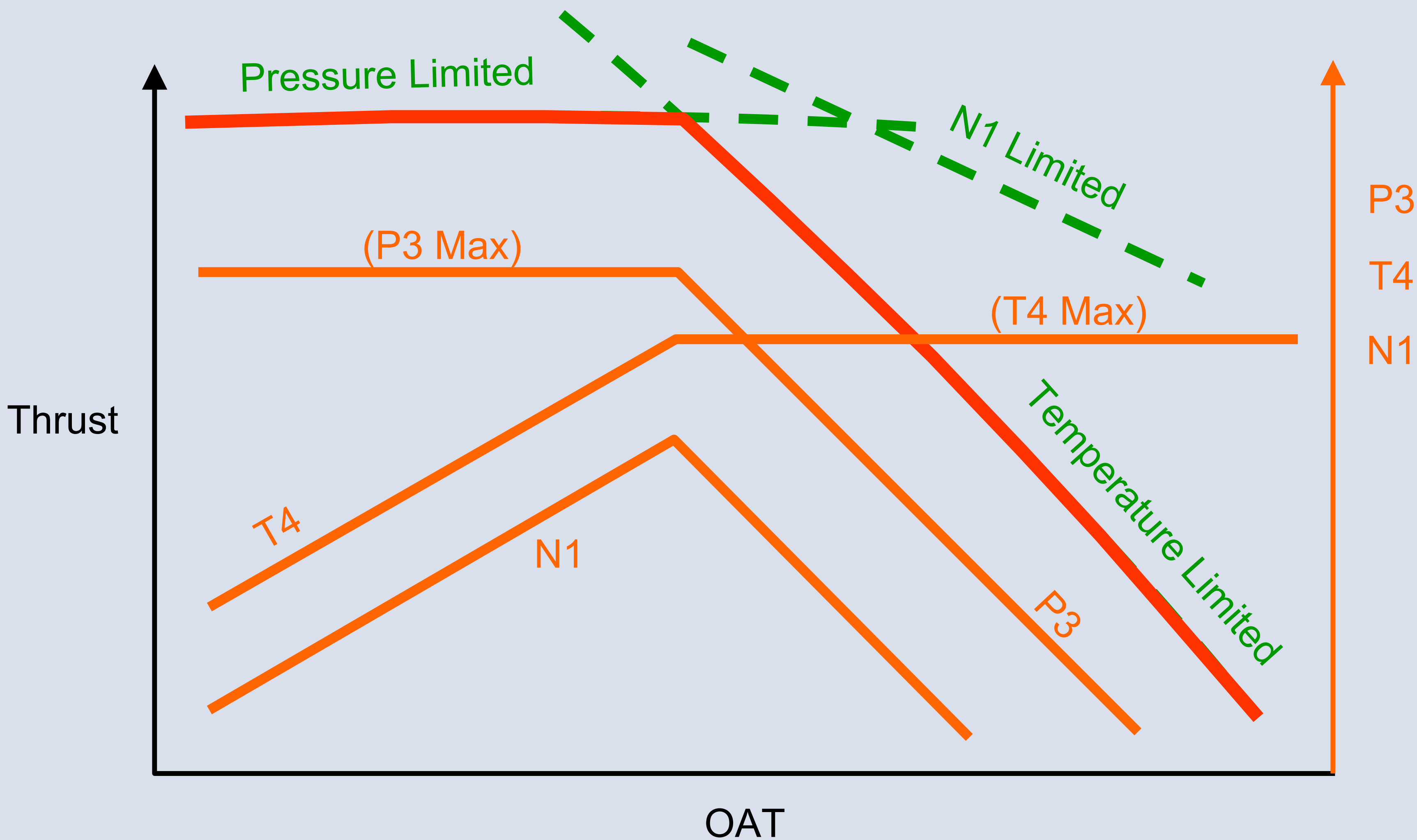


Station	2	2.5	14	3	4	5
P_t (PSIA)	14.7	32.1	22.4	316	302	20.9
T_t (°F)	59°	210°	130°	880°	1970°	850°

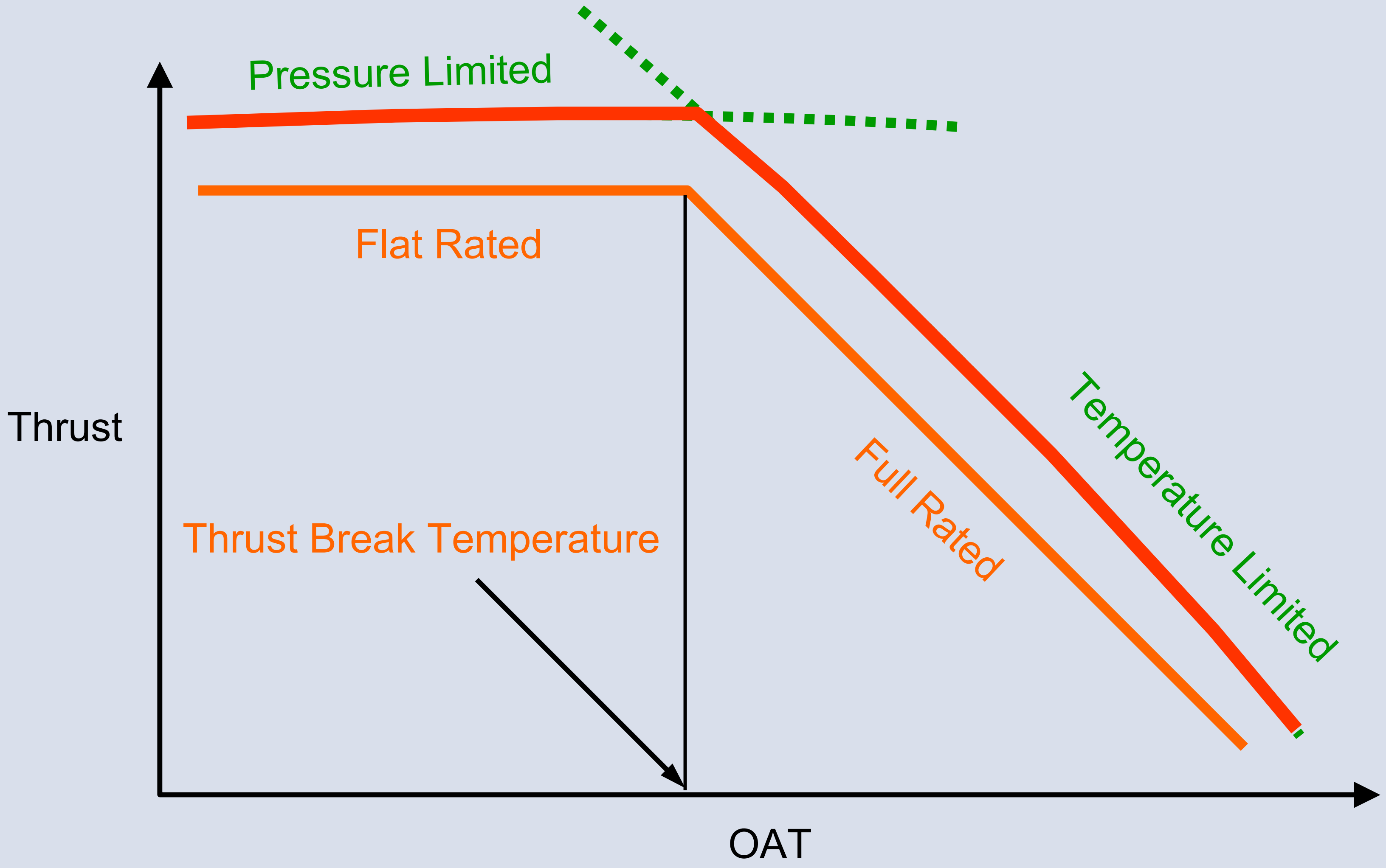
Limitations on Maximum Thrust Available

- Pressure differential across the engine case (at station P3):
  - Modern engines have compression ratios of as high as 40:1. Therefore, if the ambient air pressure outside the engine is 1000 mb, the pressure inside the engine can be as high as 40,000 mb; a differential pressure of as much as 39,000 mb.
- Turbine inlet temperature (station T4):
  - This limitation is required in order to avoid exceeding design maximum temperatures of the materials in the hottest section of the engine, just after the combustion chambers. Today's engines can experience temperatures up to 1500°C and higher at the entrance to the turbine. Exceeding the design temperatures can cause damage, or even failure of the turbine blades in this area.
- Fan speed (N1):
  - High centrifugal forces at the tips of the fan blades can also limit the maximum allowable thrust.

Design Thrust Limits



Rated Thrust

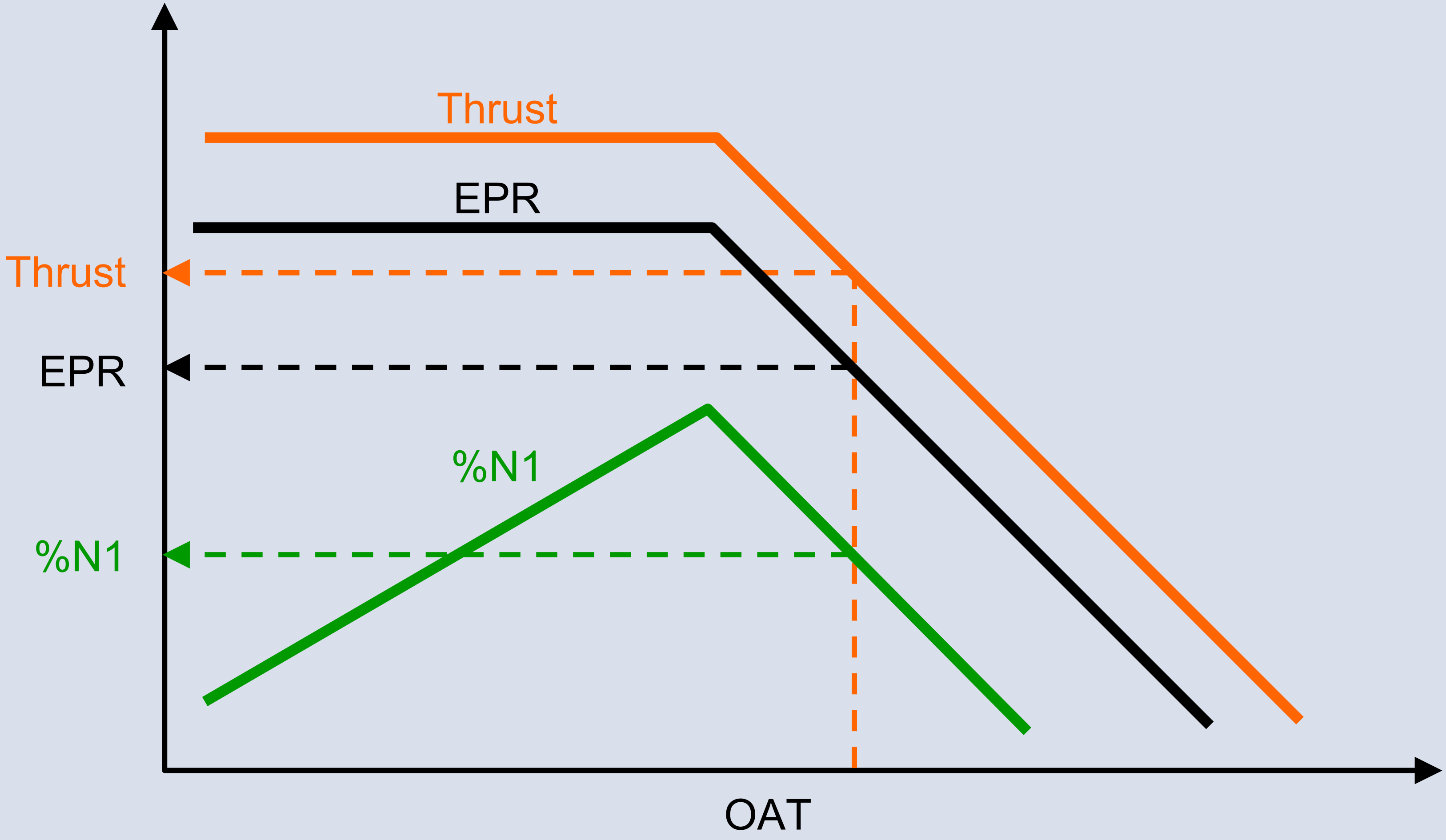


Thrust Setting Parameters

- Engine Pressure Ratio (EPR)
  - The ratio of the total pressure at the exhaust to the total pressure in front of the fan
  - Core EPR (PW) and Integrated EPR (RR)

- Percent of Fan Reference RPM (%N1)
  - The percentage of the reference rotation speed of the fan (GE and CFMI)

Thrust, EPR and %N1 Relationship



Rated Thrust Levels

- Ratings which are certified:
  - Maximum Takeoff Thrust
  - Go-Around Thrust
  - Maximum Continuous Thrust (MCT)

- Ratings which are not certified:
  - Maximum Climb Thrust (MCLT)
  - Maximum Cruise Thrust (MCRT)

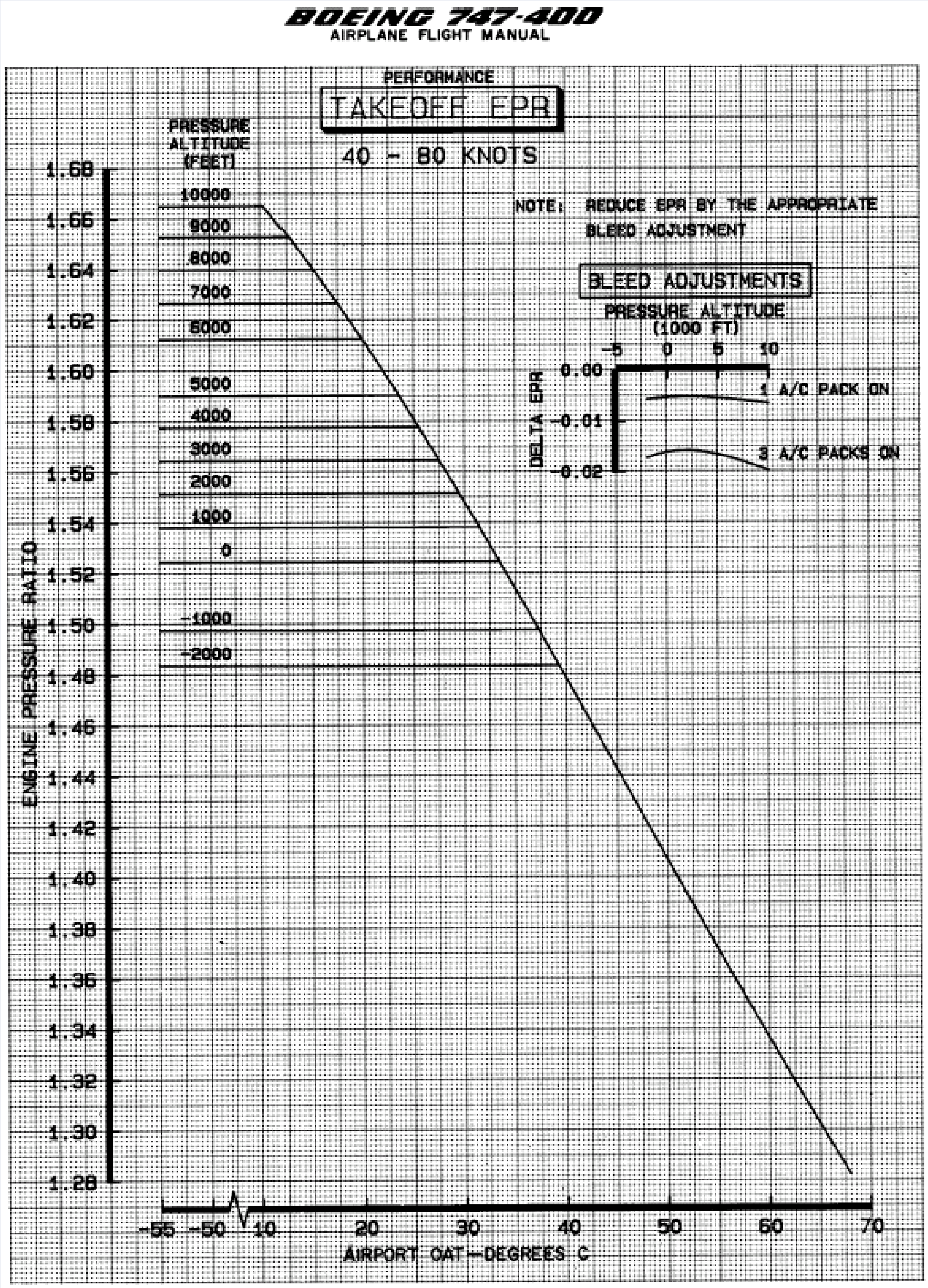
Maximum Takeoff Thrust

- 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 takeoff with the purchase of a special Flight Manual appendix).
- This rating is used for takeoff only, and is specified in the Airplane Flight Manual. As such, compliance with this limit is therefore mandatory.

Takeoff EPR

(Refer to the Chart on the Following Page)

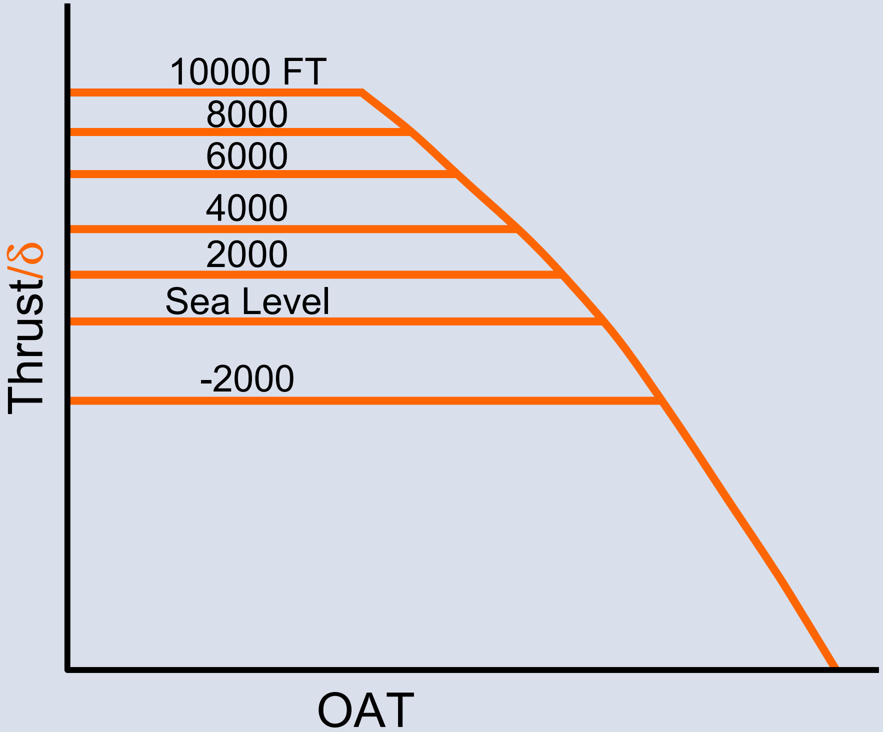
- The constant EPR lines are defined by the engine's pressure limits. When operating at the pressure limits, we refer to the thrust as being *flat-rated.* The EPR in this flat-rated region varies with ambient pressure, and hence with pressure altitude.
- The variable EPR line descending to the right is defined by the turbine temperature limit line. As the OAT increases, the EPR must decrease in order to maintain turbine temperatures within limits.
- Notice that the takeoff EPR chart is based on a specific bleed setting. Corrections for other bleeds are shown.
- Notice that this particular chart is valid at approximately 40 to 80 knots, matching the speed range at which takeoff power is to be set per the AFM instructions for this airplane/engine combination.



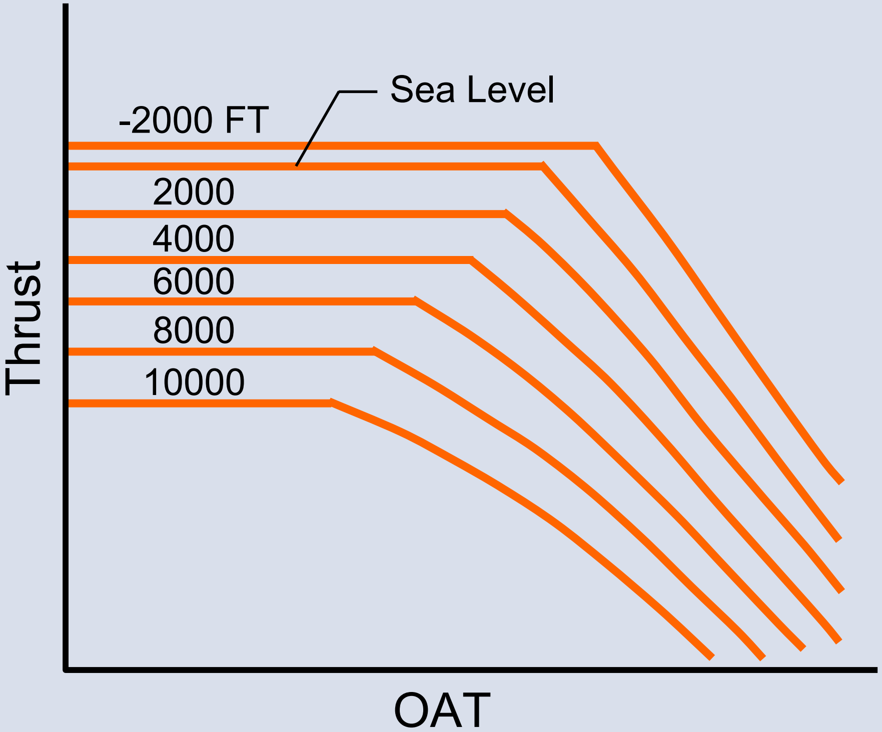
Example 747-400 AFM Takeoff EPR Chart (Pratt & Whitney Engines)

Takeoff Thrust Variation with Altitude

Takeoff Thrust/δ Increases with Increasing Altitude

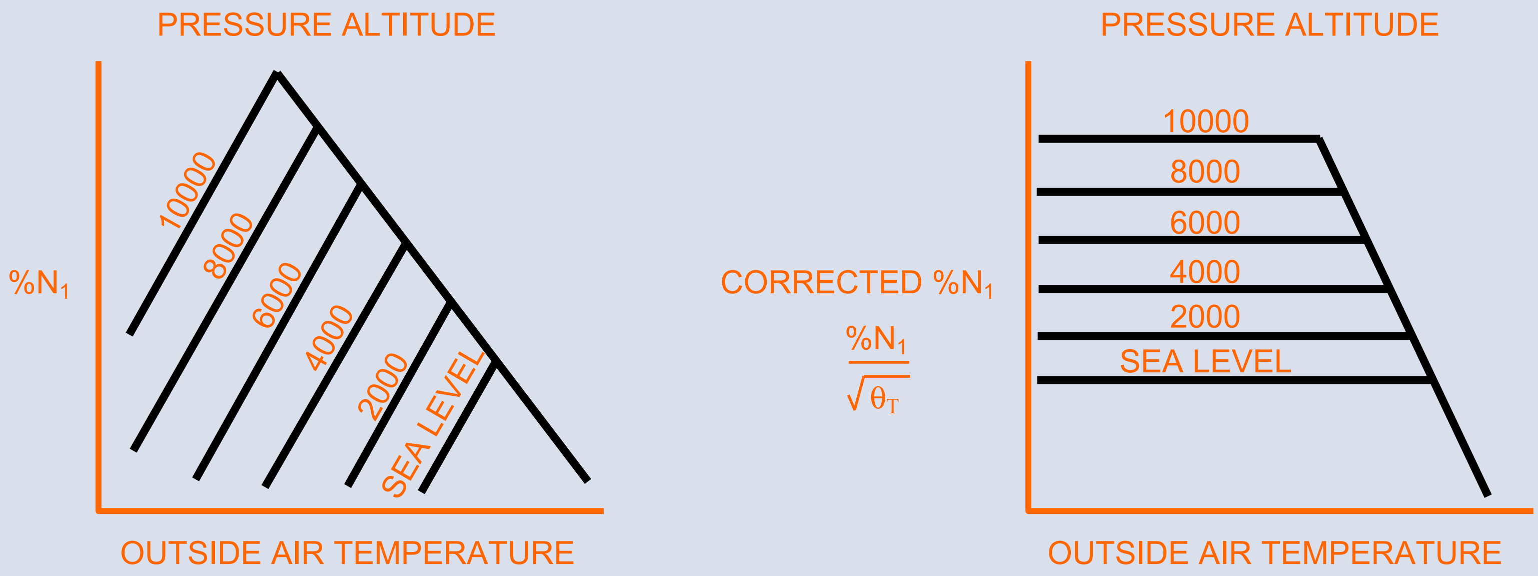


Takeoff Thrust Decreases with Increasing Altitude



Takeoff %N1

- Unlike EPR, %N1 is not constant in the flat-rated (pressure-limited) region. Instead, in the flat-rated region the corrected %N1 is constant.
- In the temperature-limited region the takeoff %N1 behaves similar to takeoff EPR.



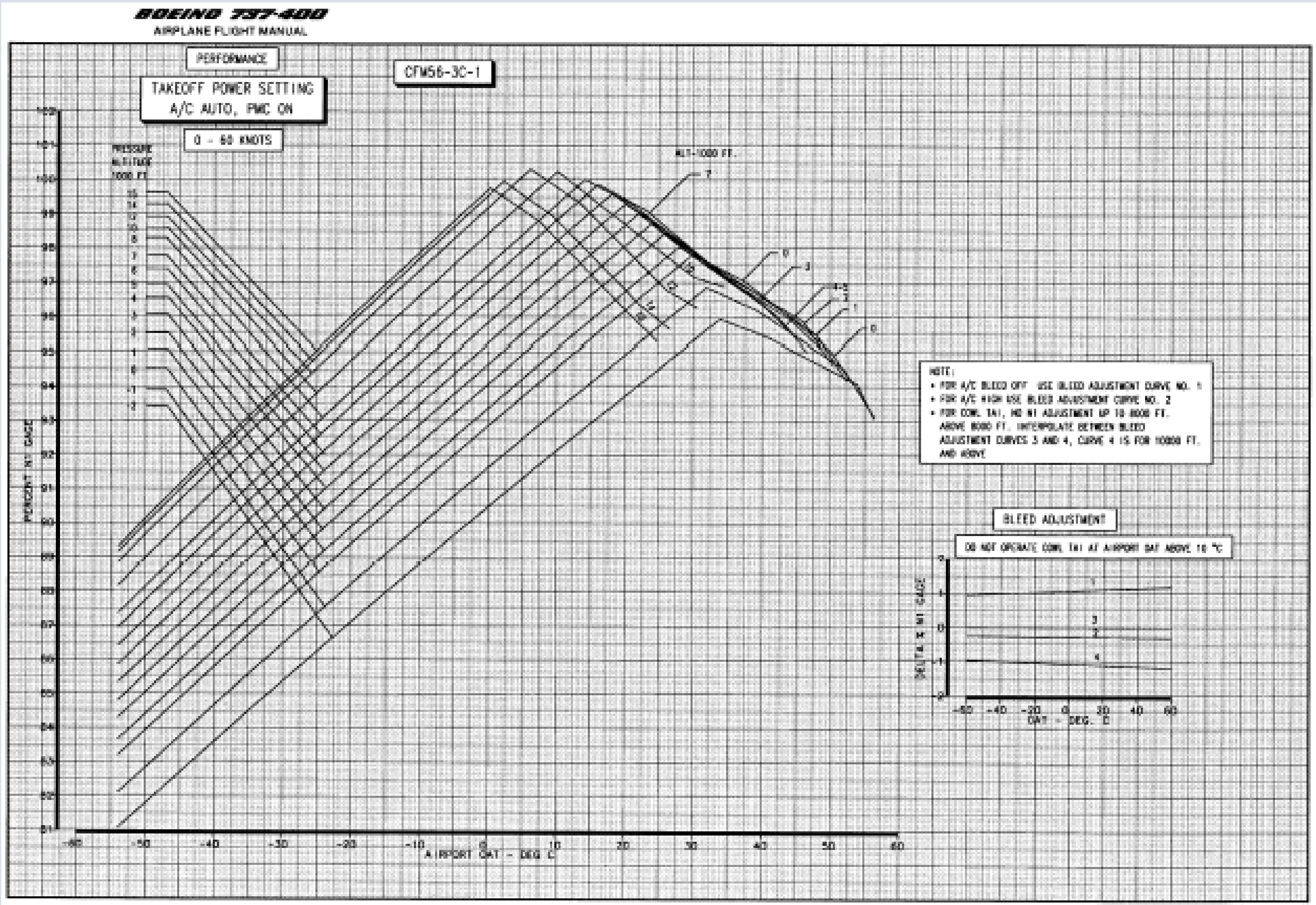
Takeoff %N1

(Refer to the Chart on the Following Page)

- The chart on the following page presents an example of a maximum takeoff %N1 chart from the AFM.
- %N1, as opposed to ‘corrected %N1’, is often referred to as “gage” %N1, meaning that it is the %N1 seen by the flight crew on the cockpit instruments.

Example 737-400 AFM Takeoff %N1 Chart

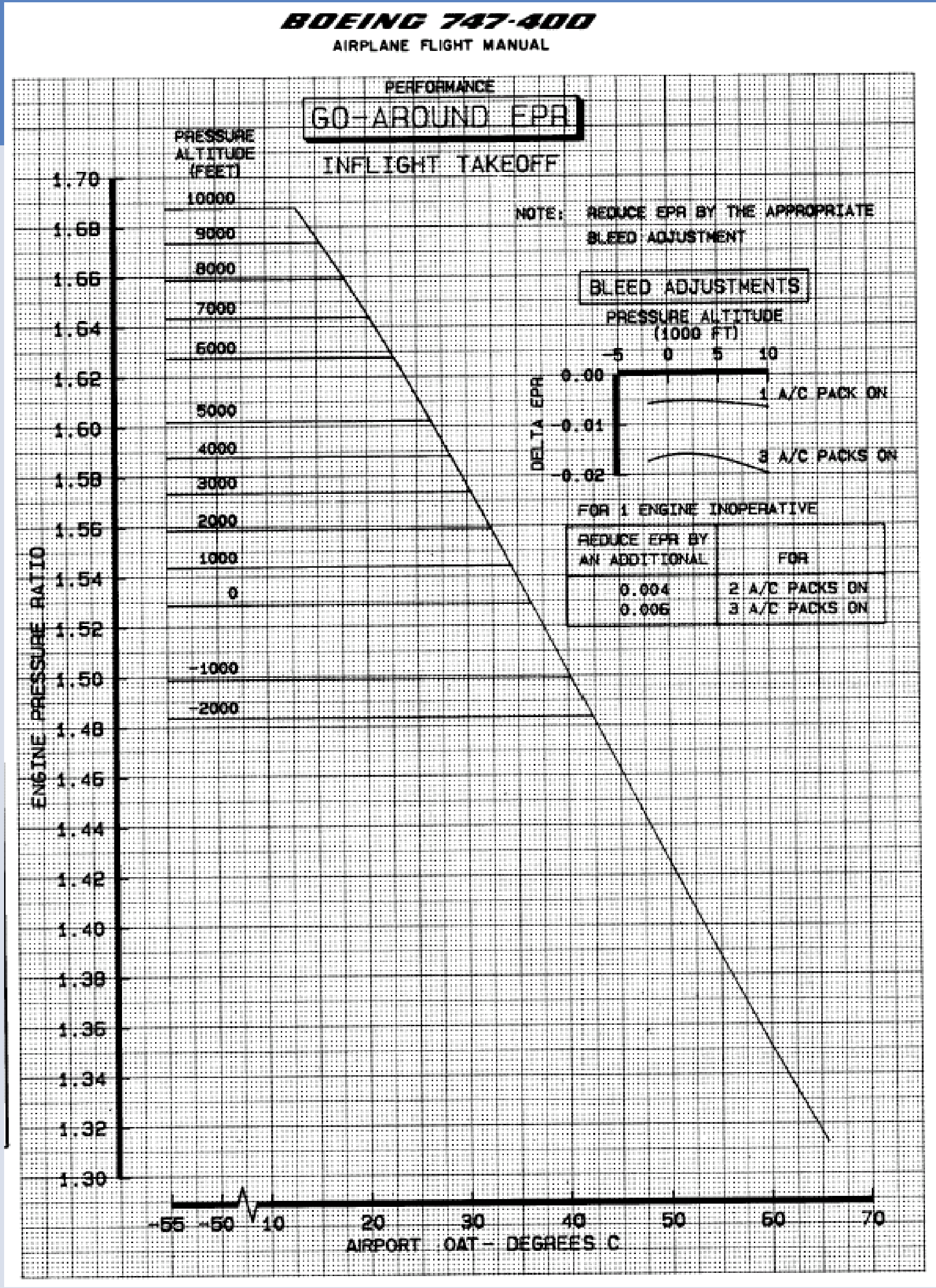
CFM Engines



Go-around Thrust

(Refer to the Chart on the Following Page)

- Also known as ‘inflight takeoff thrust’.
- The amount of thrust is same as the takeoff rating, but EPR's (N1's) are different because of the effect of higher velocity.
- Time-limited to 5 minutes.
- Intended for missed approach, when maximum power may be required for safety.
- This rating is also specified in the Airplane Flight Manual. As such, compliance with this limit is therefore mandatory.



Example 747-400 AFM Go-Around EPR Chart (Pratt & Whitney Engines)

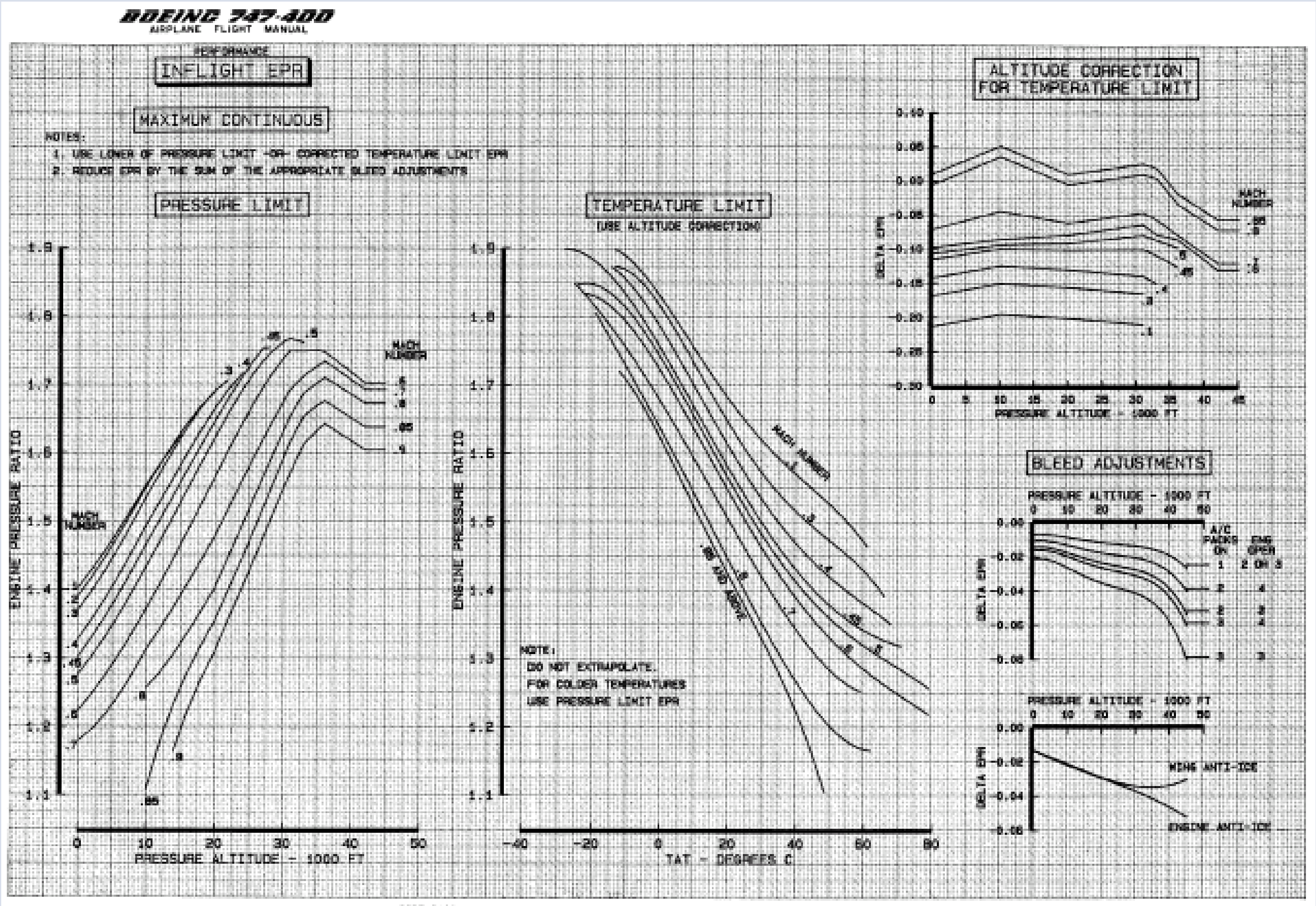
Maximum Continuous Thrust

(Refer to the Chart on the Following Page)

- This is a special thrust rating, sometimes referred to as MCT or CON. It is intended to only be used in an emergency, but has no time limitation.
- This rating is also specified in the Airplane Flight Manual. As such, compliance with this limit is therefore mandatory (just like takeoff 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 takeoff and go-around.

Example 747-400 AFM Max Continuous EPR Chart

Pratt & Whitney Engines



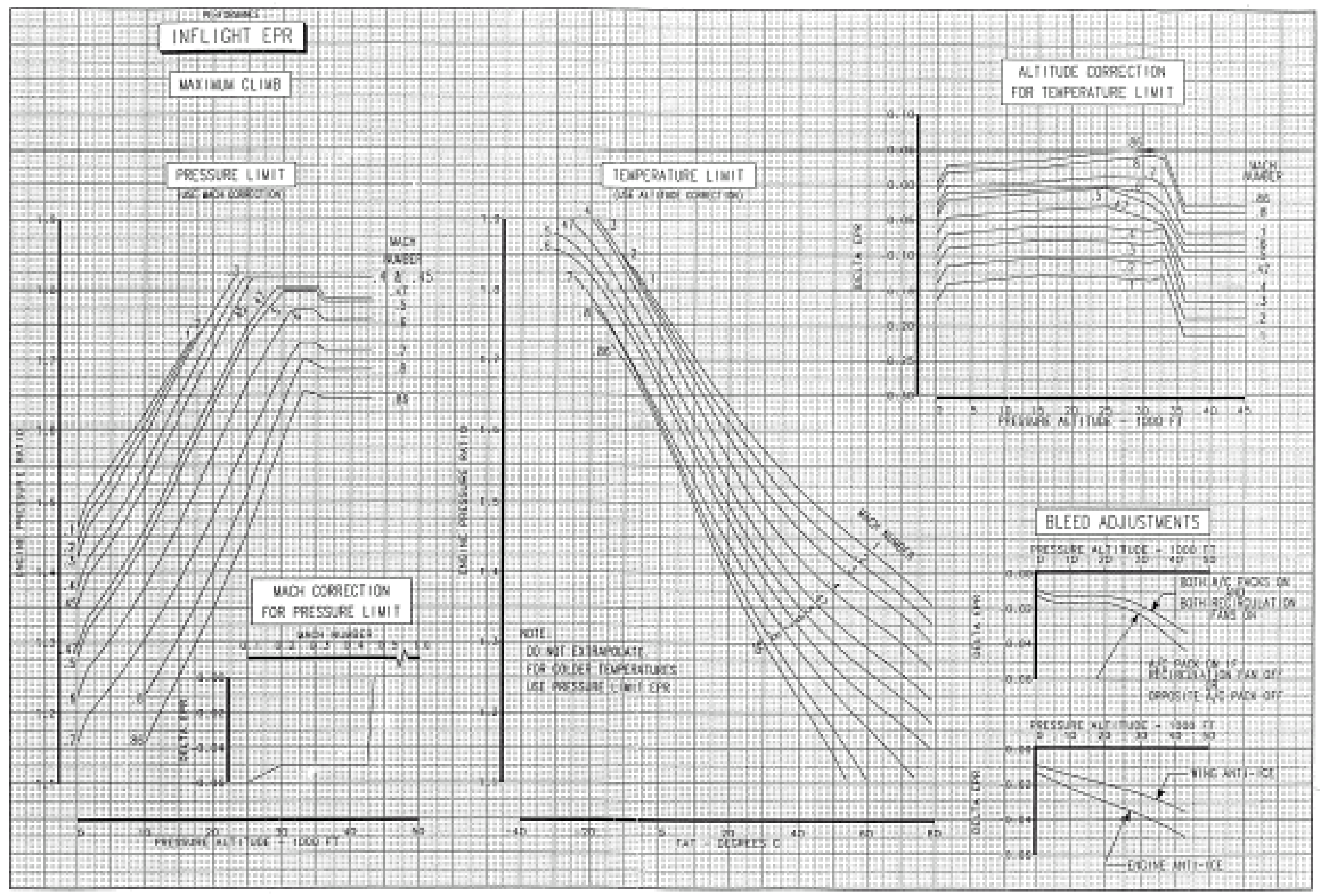
Maximum Climb Thrust

(Refer to the Chart on the Following Page)

- This thrust rating, sometimes called MCLT, has no time limit. It is intended for use during normal enroute climb only. For some engines, maximum continuous and maximum climb thrust are equivalent.
- Notice that this chart is not taken from the AFM. Instead, it is taken from the Performance Engineer's Manual. Maximum Climb thrust is not used in the calculation of any AFM performance levels, is not specified in the AFM, and is not a 'certified' rating.

Example 767-300 Max Climb EPR Chart

Pratt & Whitney Engines



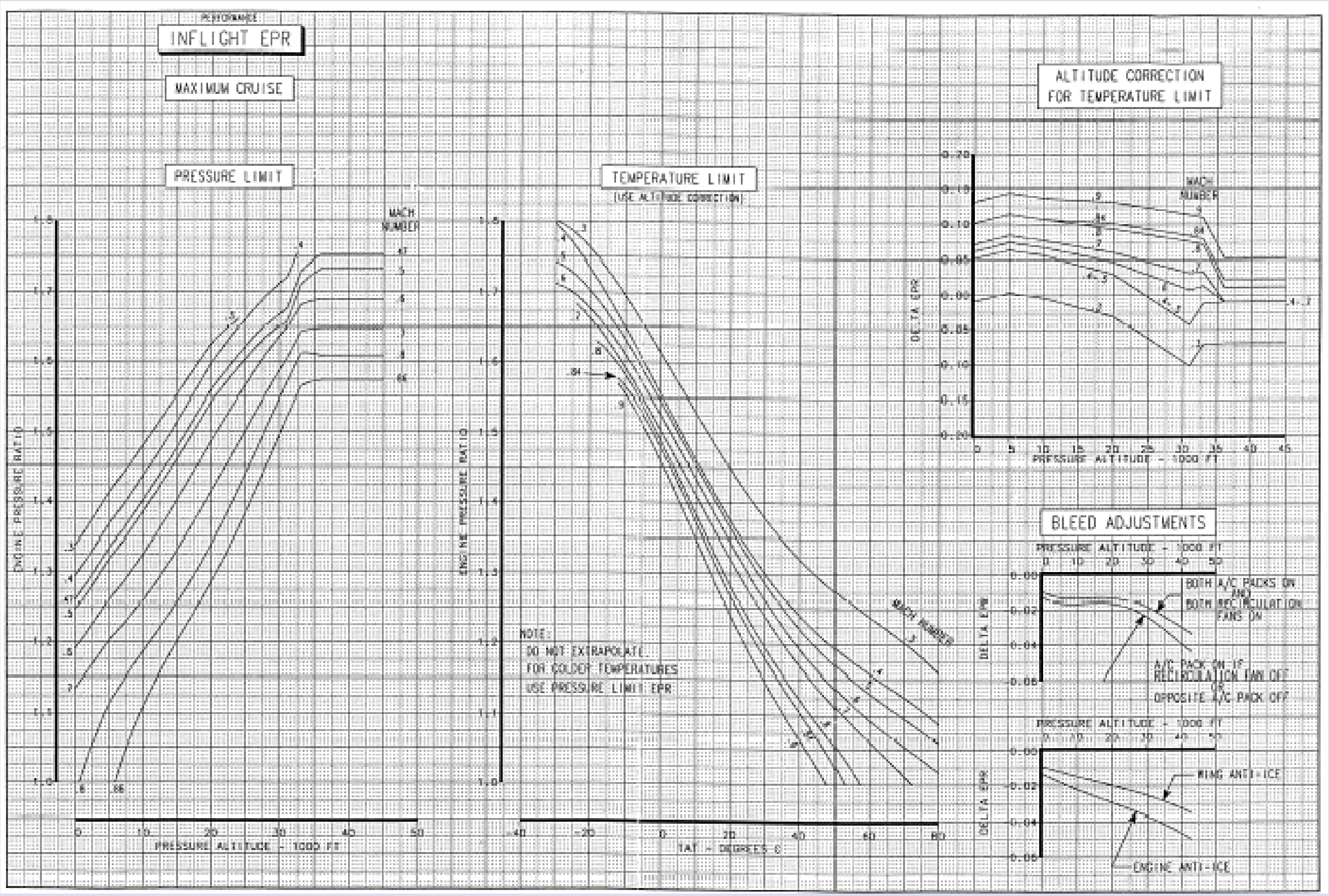
Maximum Cruise Thrust

(Refer to the Chart on the Following Page)

- This thrust rating, sometimes called MCRT, also has no time limit. It is intended for use during normal cruise operations.
- This rating also appears only in the Performance Engineer's Manual. It is not used in the calculation of any AFM performance levels, is not specified in the AFM, and is also not a 'certified' rating.

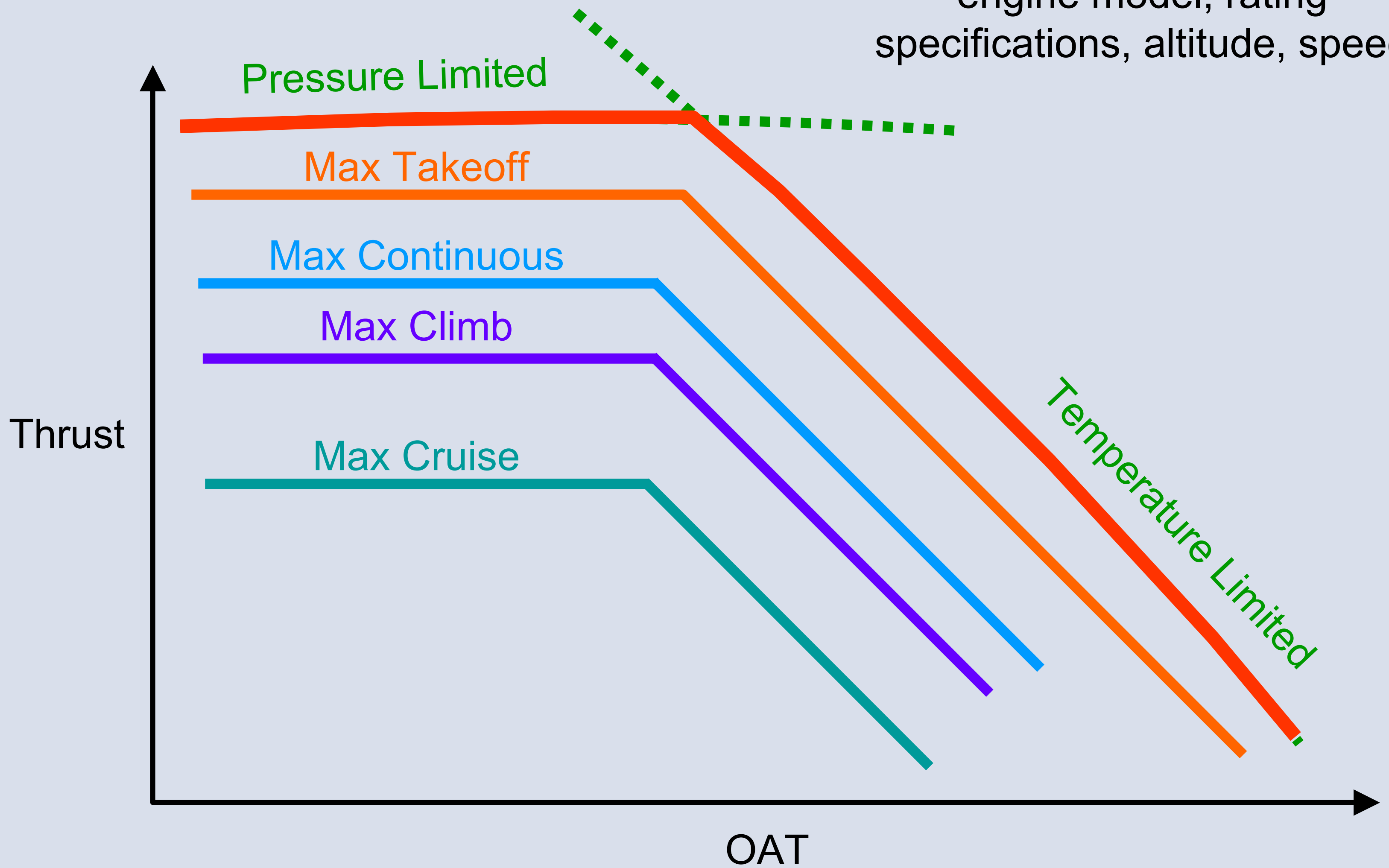
Example 767-300 Max Cruise EPR Chart

Pratt & Whitney Engines

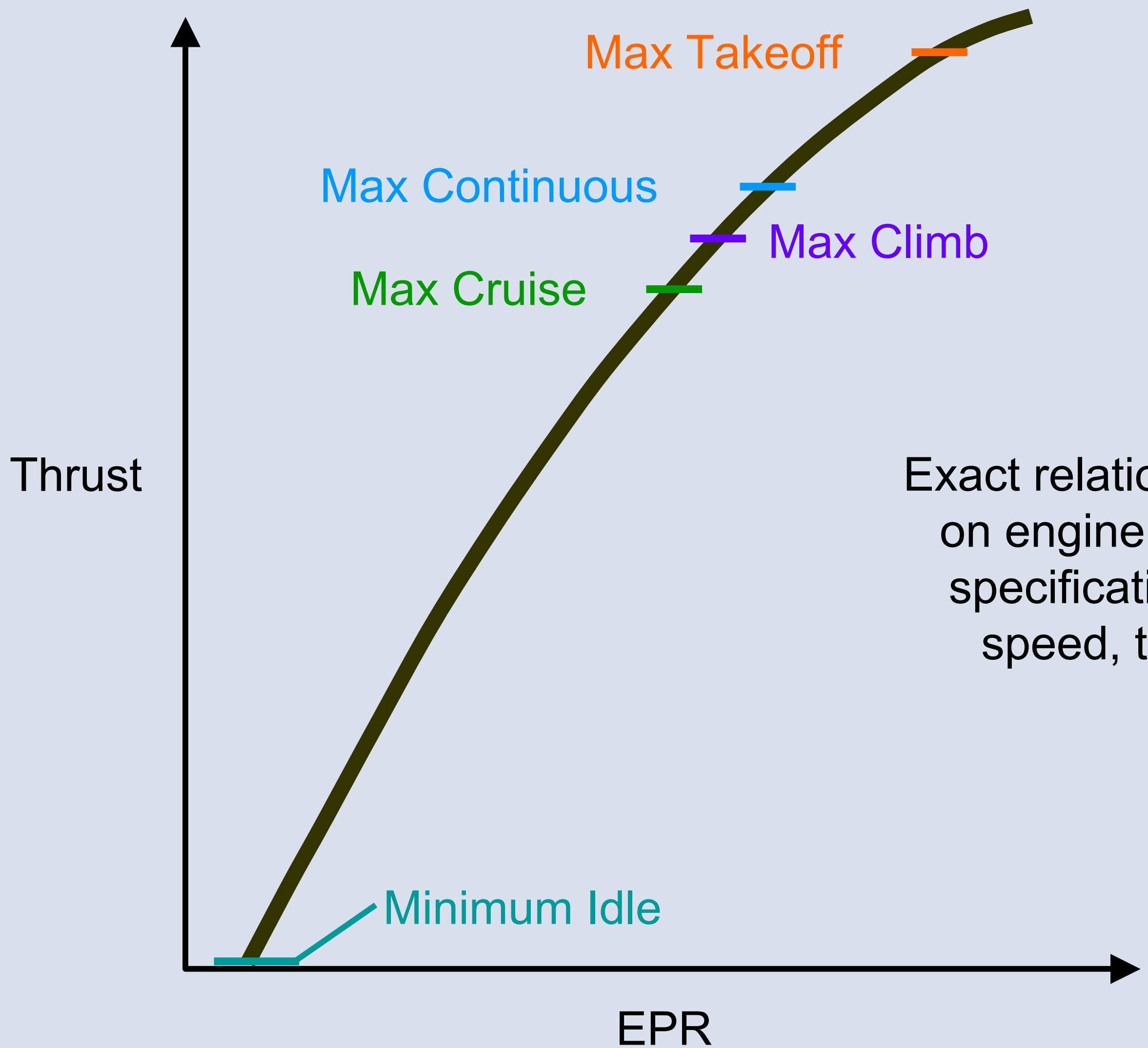


Thrust Rating Relationships

Exact relationship depends on engine model, rating specifications, altitude, speed

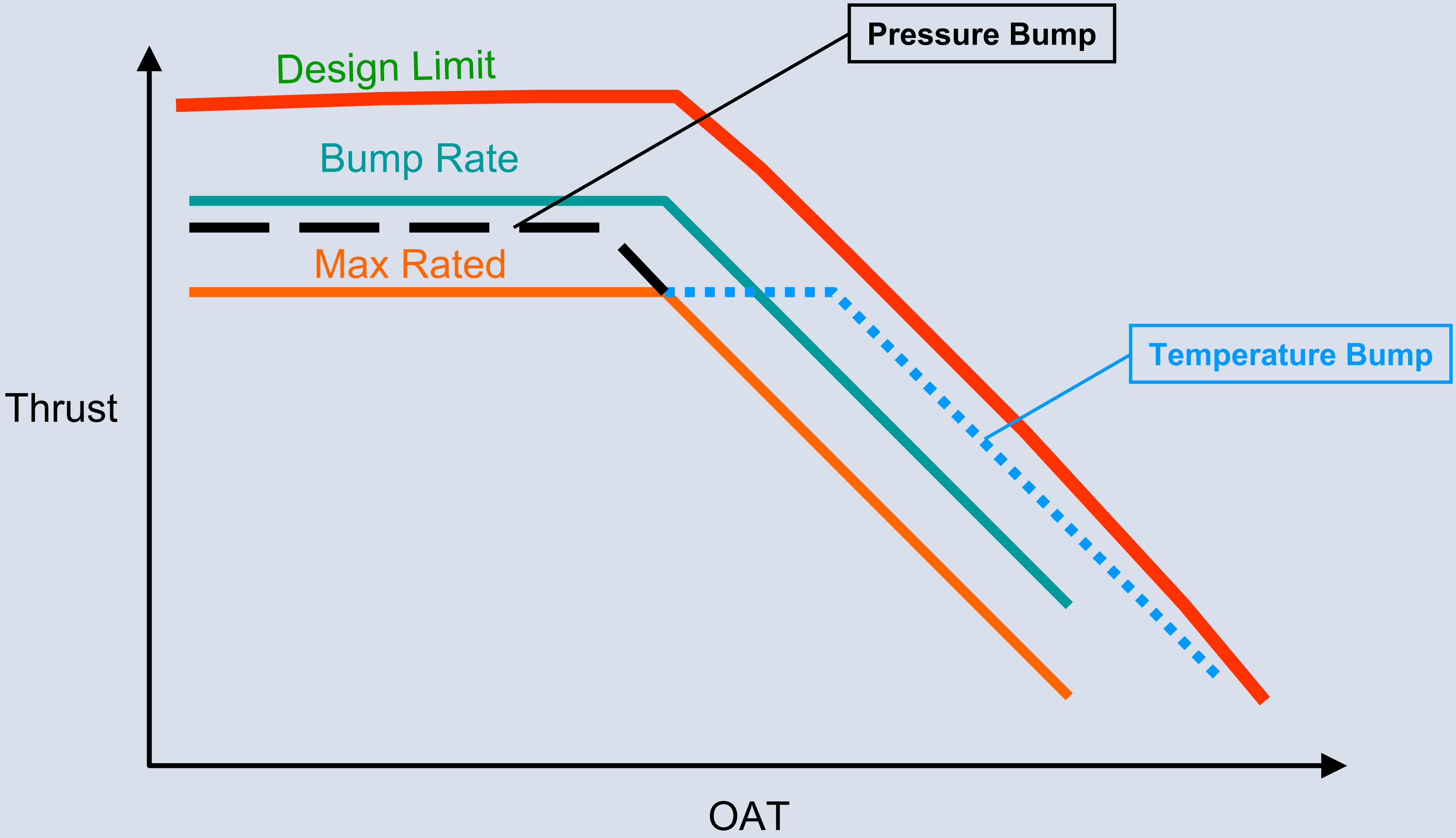


Thrust Rating Relationships



Exact relationship depends on engine model, rating specifications, altitude, speed, temperature

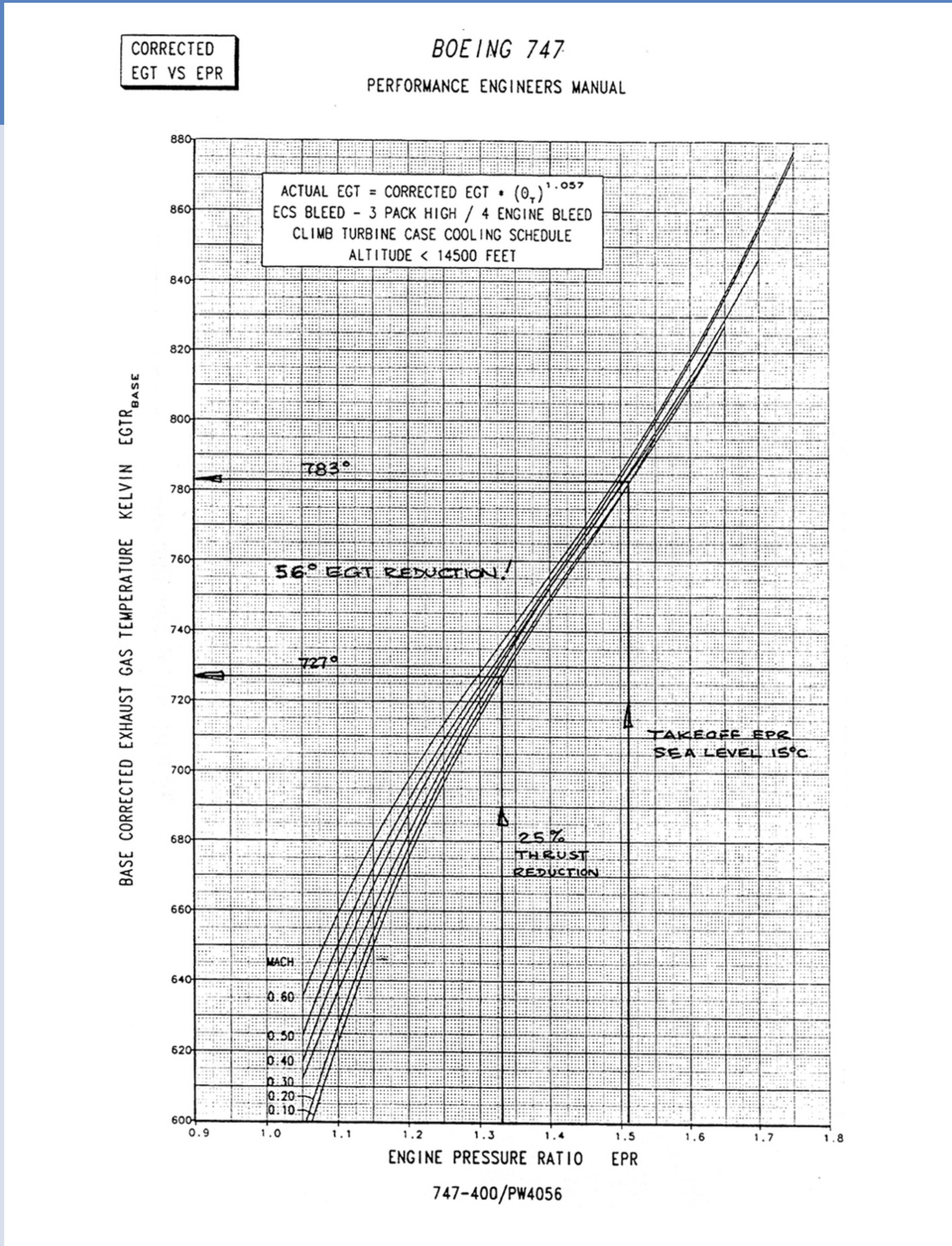
Takeoff Thrust Bump



Reduced Takeoff Thrust

- Using a thrust level for takeoff which is lower than the maximum allowable lowers the engine's internal operating pressures and temperatures.

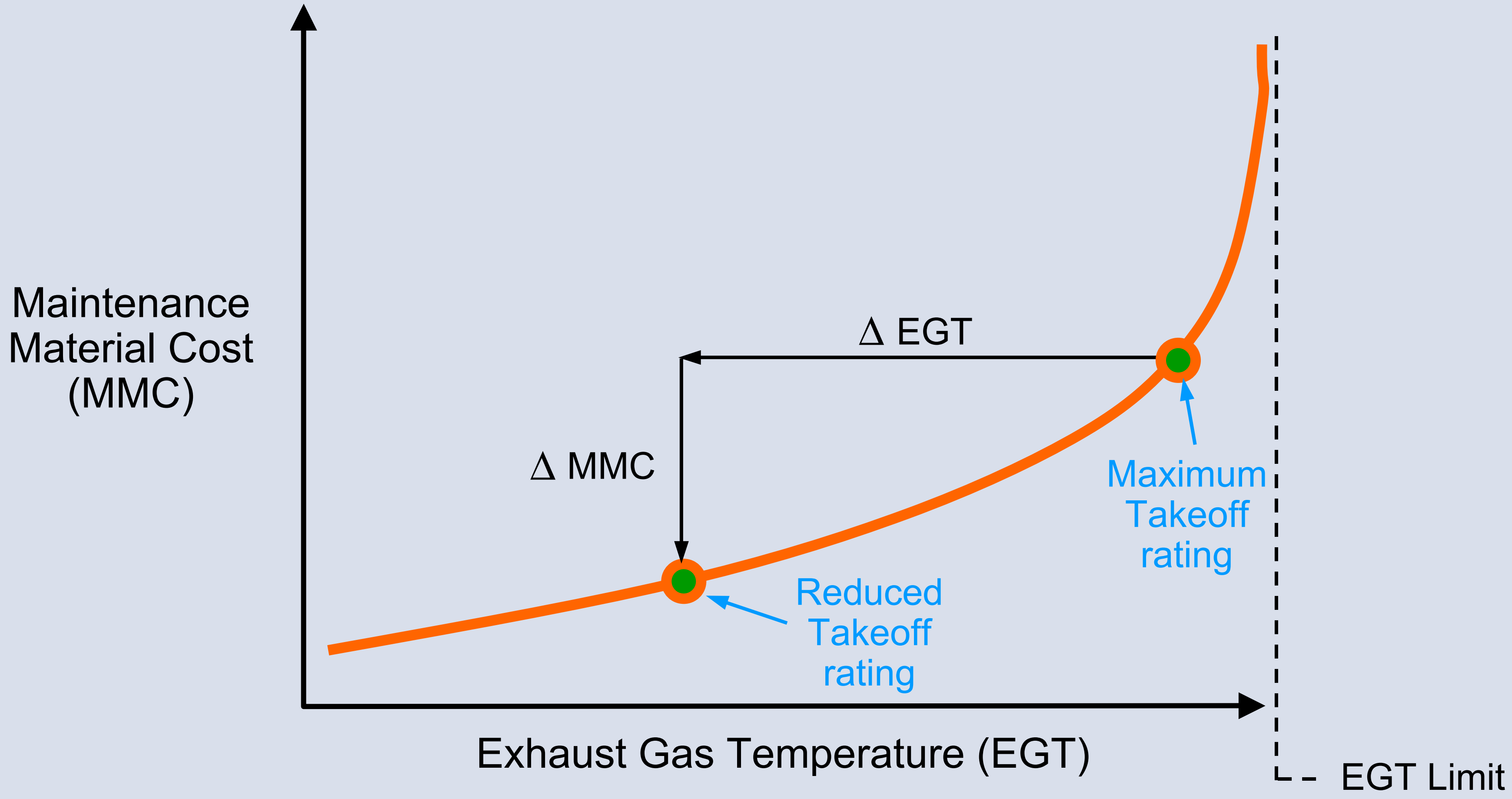
  This results in:
  - Reduced stress and wear on the engine
  - Reduced cost on parts and maintenance
  - Increased engine life
  - Increased reliability, thus improving operating safety and efficiency.



Reduced Takeoff Thrust lowers engine EGT's

Reduced Takeoff Thrust

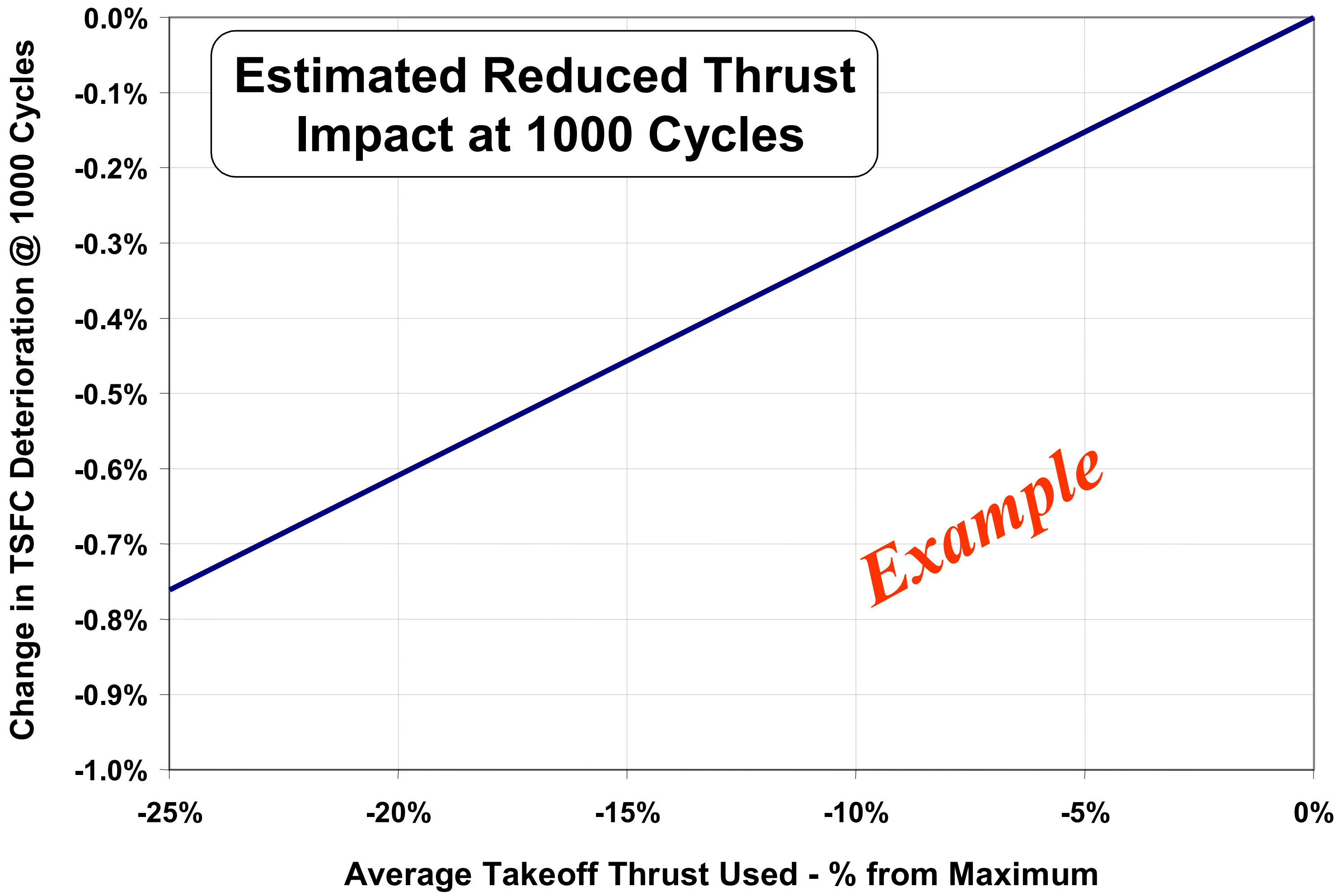
Maintenance Material Cost (MMC) Decreases With Lower EGT



Reduced Takeoff Thrust

Reduced Takeoff Thrust Improves Performance Retention

15% Average Thrust Reduction Can Improve TSFC at 1000 Cycles by over 0.4% !



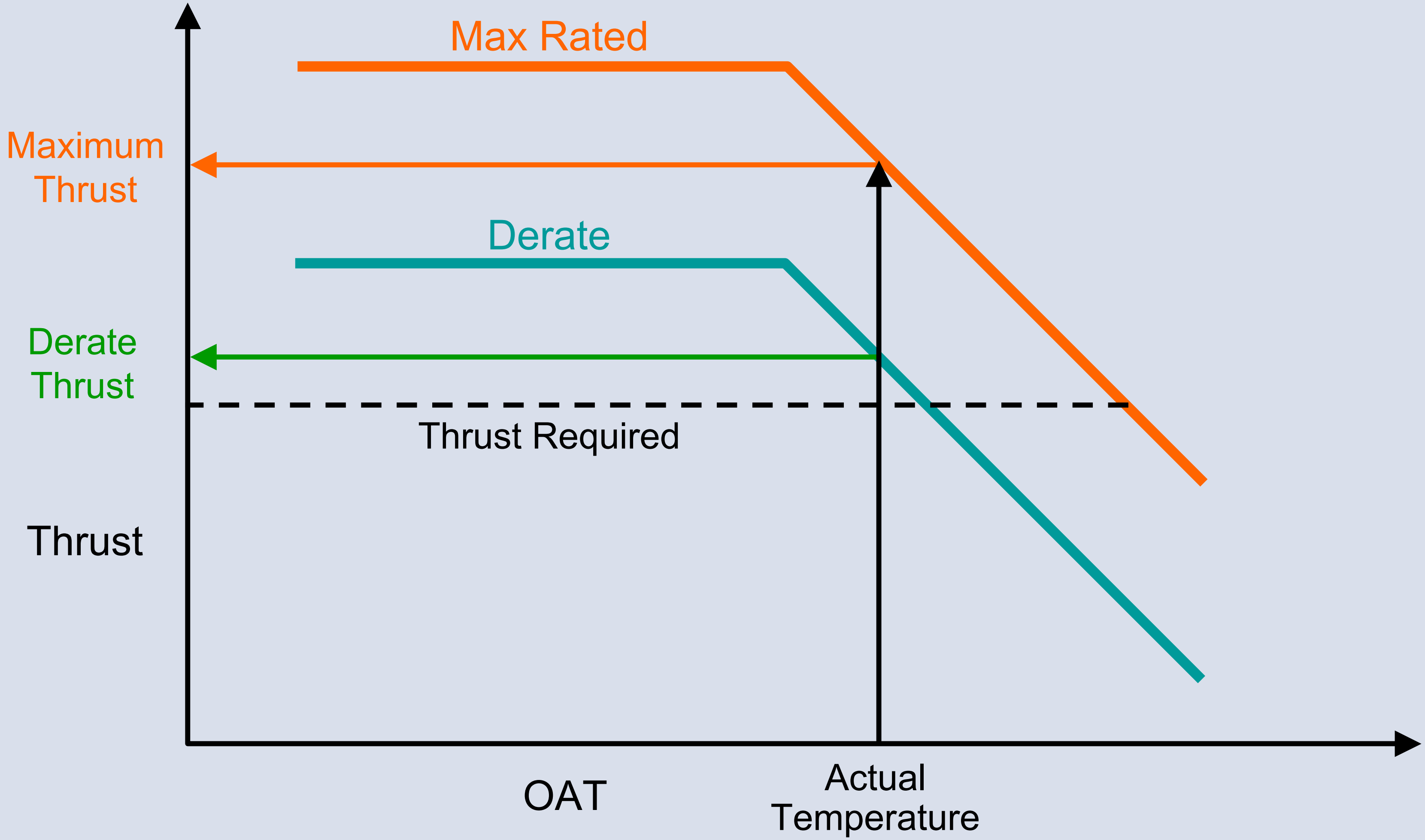
Methods for Reduced T/O Thrust

- Derate
  - The setting of takeoff thrust by selecting in the FMC (or TMC) an approved takeoff thrust rating that is lower than the max rated takeoff thrust
- Assumed Temperature (FLEX)
  - The setting of takeoff thrust by entering in the FMC (or TMC) a temperature higher than the actual Outside Air Temperature (OAT)

Derate Method

- 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 takeoff weight is low enough to permit the use of reduced thrust equal to or below the level of the derate.

Derate Method



Derate Method

T/O Performance Data Required for Each Derate

737-800 TAKEOFF PERFORMANCE KBFI RWY 13R LENGTH 10000 FT
CFM56-7B26 STANDARD CONFIGURATION BOEING FILED ELEV 17 FT
FLAPS 5 **MAX RATED THRUST (26K)** RWY COND WET

TEMP (C)	MAX
50	641*
48	652*
46	662*
44	673*
42	683*
40	694*
38	705*
36	716*
34	727*
32	738*
30	749*
25	753*
20	757*

ABOVE STD:
+KG/MB
BELOW STD:
-KG/MB

737-800 TAKEOFF PERFORMANCE KBFI RWY 13R LENGTH 10000 FT
CFM56-7B26 STANDARD CONFIGURATION BOEING FIELD ELEV 17 FT
FLAPS 5 **24K DERATE** RWY COND WET

TEMP (C)	MAX
50	586*
48	597*
46	607*
44	618*
42	628*
40	639*
38	650*
36	660*
34	671*
32	682*
30	694*
25	697*
20	700*

ABOVE STD:
+KG/MB
BELOW STD:
-KG/MB

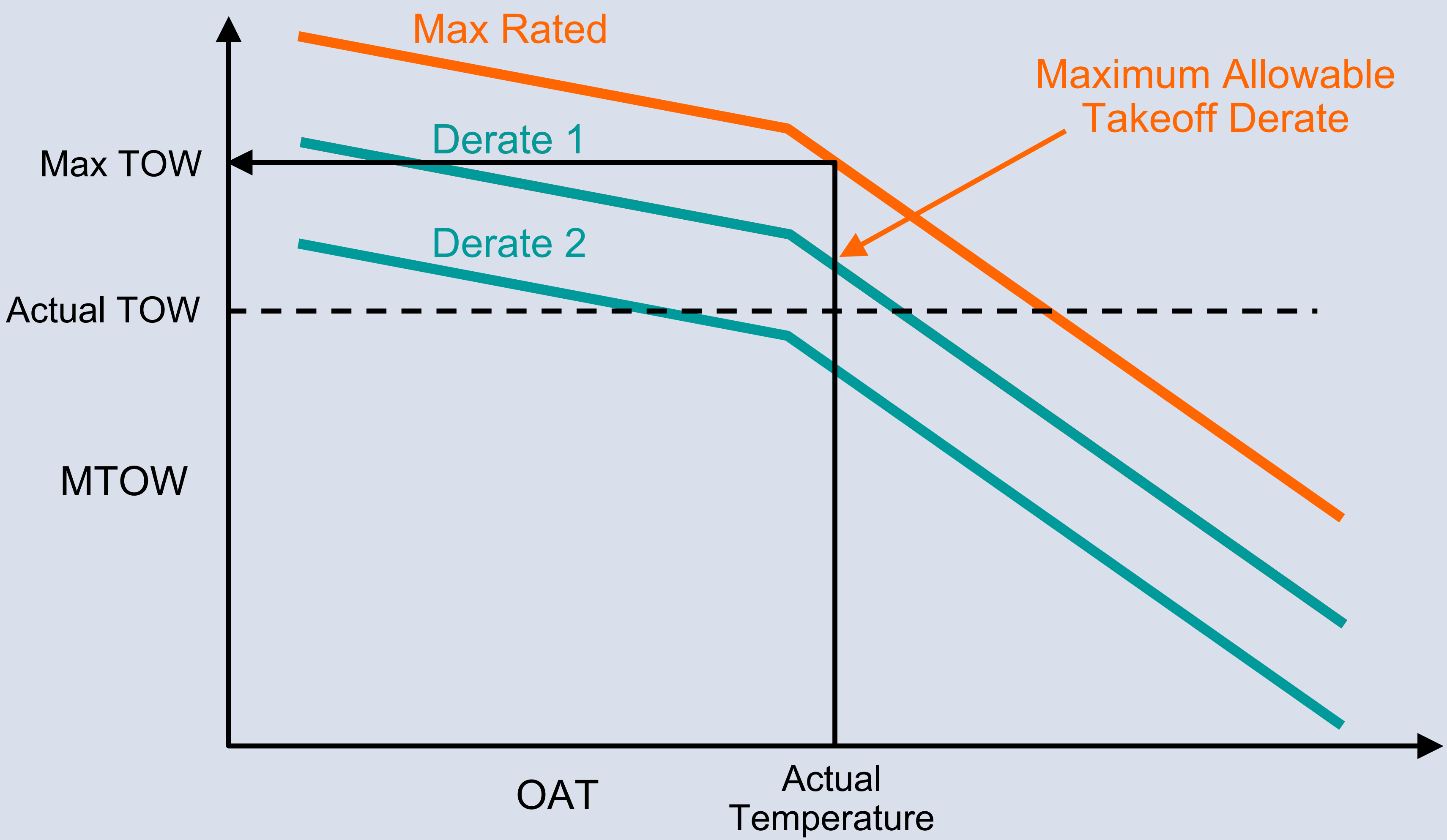
737-800 TAKEOFF PERFORMANCE KBFI RWY 13R LENGTH 10000 FT
CFM56-7B26 STANDARD CONFIGURATION BOEING FIELD ELEV 17 FT
FLAPS 5 **22K DERATE** RWY COND WET

MAXIMUM ALLOWABLE TAKEOFF WEIGHT (100 KG) / TAKEOFF SPEEDS

TEMP	WIND (KT)			
(C)	-10	0	5	10
50	551*/21-29-34	570*/26-32-36	574*/26-32-36	574C/27-32-36
48	561*/22-31-35	581*/27-33-37	585*/28-34-37	586C/28-34-38
46	572*/23-32-36	592*/28-34-38	596*/29-35-39	597C/29-35-39
44	582*/23-33-37	603*/29-35-40	606*/29-36-40	609C/30-36-40
42	592*/24-34-39	614*/30-37-41	617*/30-37-41	620*/31-37-42
40	602*/25-35-40	624*/31-38-42	628*/31-38-43	631*/32-39-43
38	613*/26-36-41	636*/32-39-44	640*/32-39-44	643*/33-40-44
36	624*/27-37-43	648*/33-40-45	651*/33-41-45	655*/34-41-46
34	635*/28-38-44	659*/34-41-46	663*/34-42-46	667*/35-42-47
32	646*/29-39-45	671*/34-42-47	675*/35-43-48	679*/36-43-48
30	657*/30-41-46	683*/35-43-49	687*/36-44-49	691*/37-44-49
25	660*/30-41-47	686*/36-44-49	690*/37-44-49	694*/37-45-50
20	663*/31-41-47	688*/36-44-49	692*/37-44-49	696*/38-45-50
ABOVE STD: +KG/MB	17	11	11	11
BELOW STD: -KG/MB	62	64	64	64

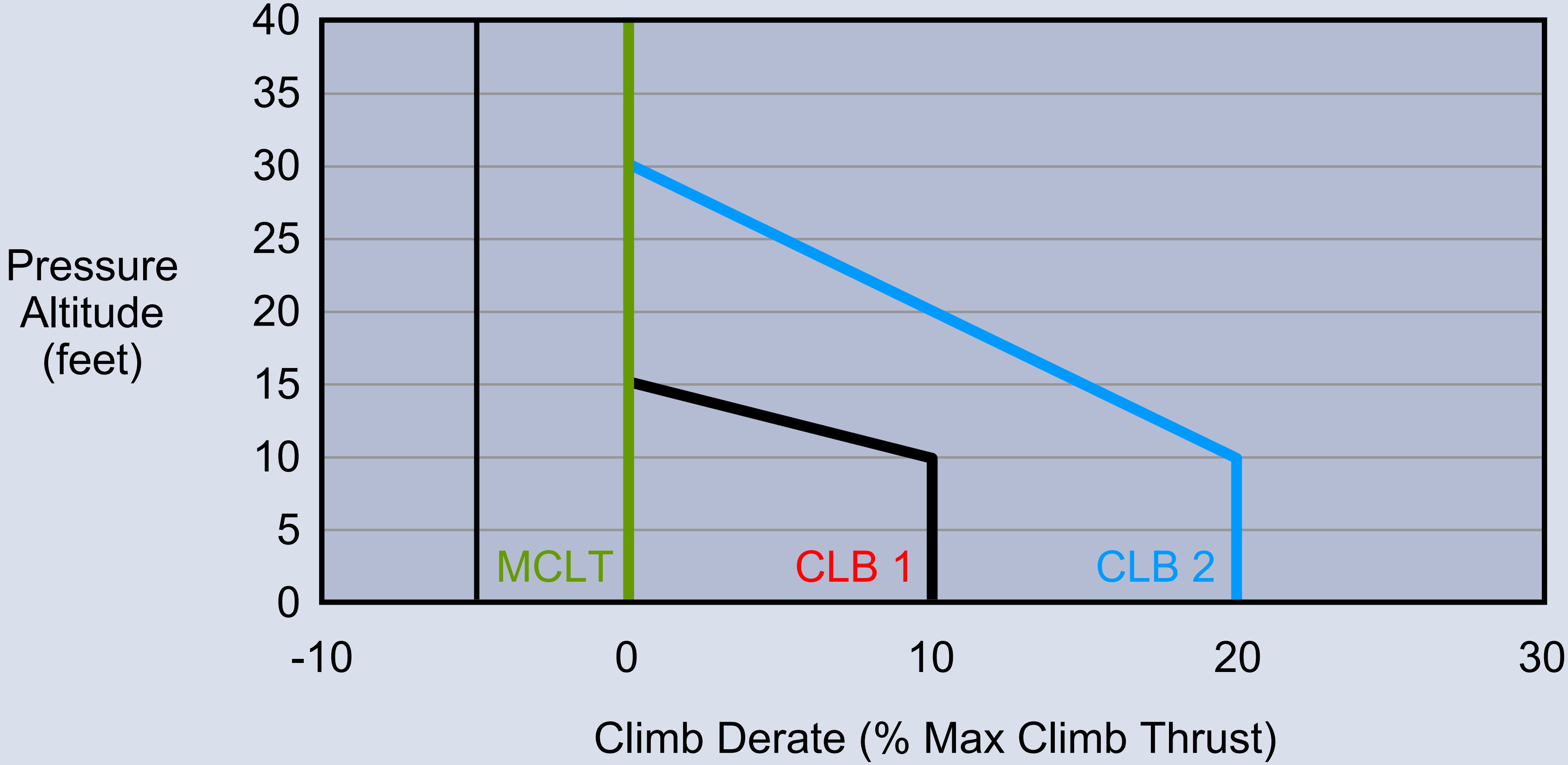
Derate Method

Selection of Allowable Derate



Climb Derate

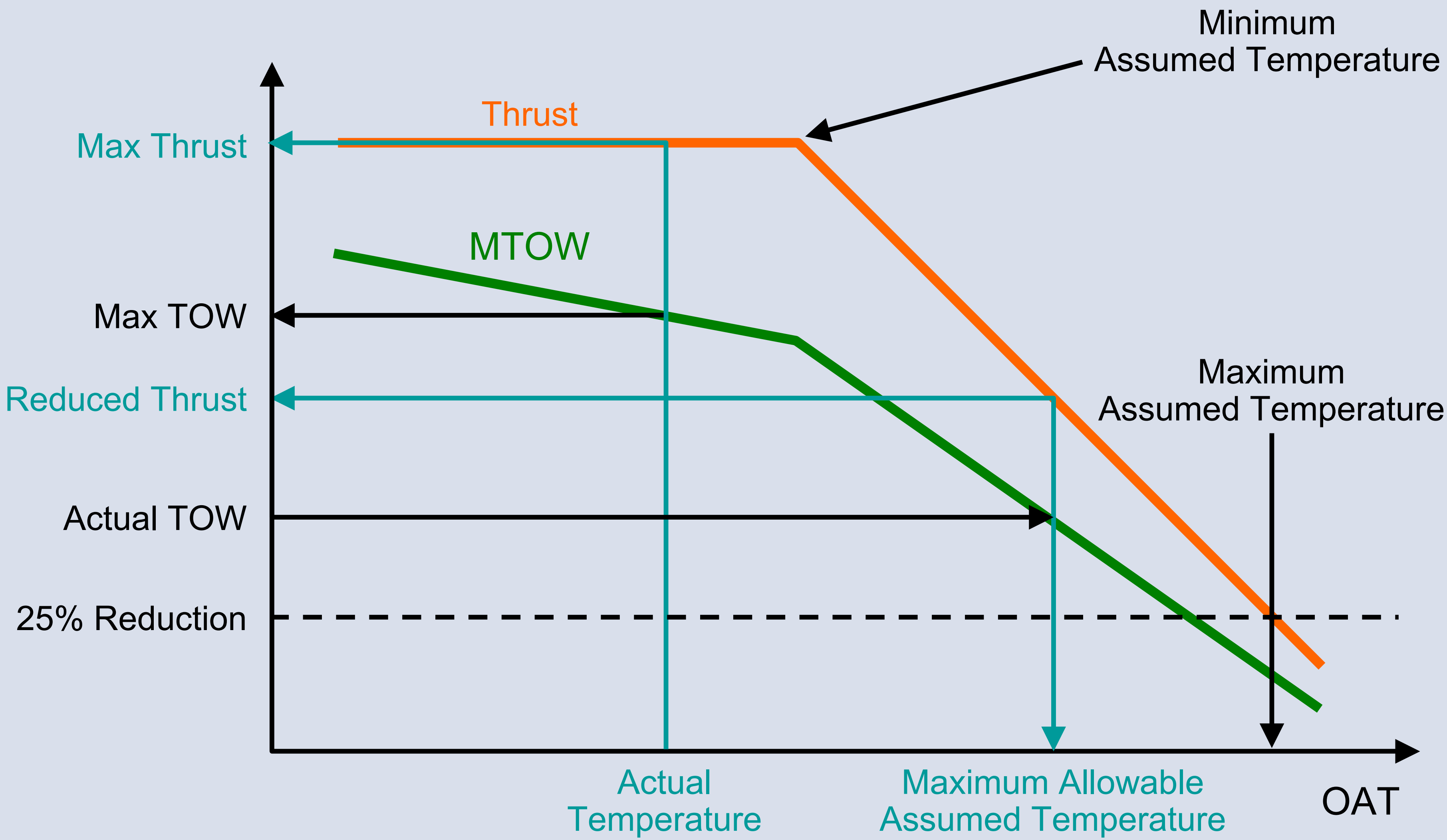
Example Climb Derate Schedule



Assumed Temperature Method

- The assumed temperature method uses a thrust setting based on a temperature that is greater than the actual temperature, thereby setting a thrust level lower than the maximum allowable for the actual temperature.
- The maximum temperature that meets all of the takeoff performance requirements at the actual takeoff weight for the planned takeoff conditions is the maximum allowable assumed temperature.
- Maximum of 25% thrust reduction from the max rated thrust, or from an approved derate.
- Requires only takeoff performance data for the max rated thrust, or an approved derate.

Assumed Temperature Method



Determination of Maximum Assumed Temperature

737-800	TAKEOFF PERFORMANCE	KBFI RWY 13R	LENGTH 10000 FT
CFM56-7B26	STANDARD CONFIGURATION	BOEING FIELD	ELEV 17 FT
FLAPS 5	MAX RATED THRUST (26K)	RWY COND	DRY

MAXIMUM ALLOWABLE TAKEOFF WEIGHT (100 KG) / TAKEOFF SPEEDS

TEMP (C)	WIND (KT) -10	0	5	10
50	647*/38-40-45	669*/41-42-47	673*/42-43-48	677*/42-43-48
48	658*/39-41-46	681*/42-43-48	685*/43-44-49	688*/43-44-49
46	669*/39-42-47	692*/43-44-50	696*/44-45-50	700*/44-45-50
44	680*/40-43-49	704*/44-45-51	707*/45-46-51	711*/45-46-51
42	691*/41-44-50	715*/45-46-52	[illegible]	[illegible]-53
40	702*/42-45-51	727*/46-47-53	[illegible]	[illegible]-54
38	713*/43-46-52	738*/47-48-54	[illegible]	[illegible]-55
36	724*/44-47-53	750*/47-49-55	[illegible]	[illegible]-56
34	735*/44-48-54	762*/48-50-56	766*/49-51-57	770*/49-51-57
32	746*/45-49-55	774*/49-52-58	779*/50-52-58	783*/50-52-58
30	757*/46-50-56	785*/50-53-59	790*/50-53-59	794*/51-53-59
25	761*/46-50-57	789*/50-53-59	794*/51-53-59	798*/51-54-60
20	764*/47-50-57	792*/50-53-59	797*/51-54-60	801*/52-54-60

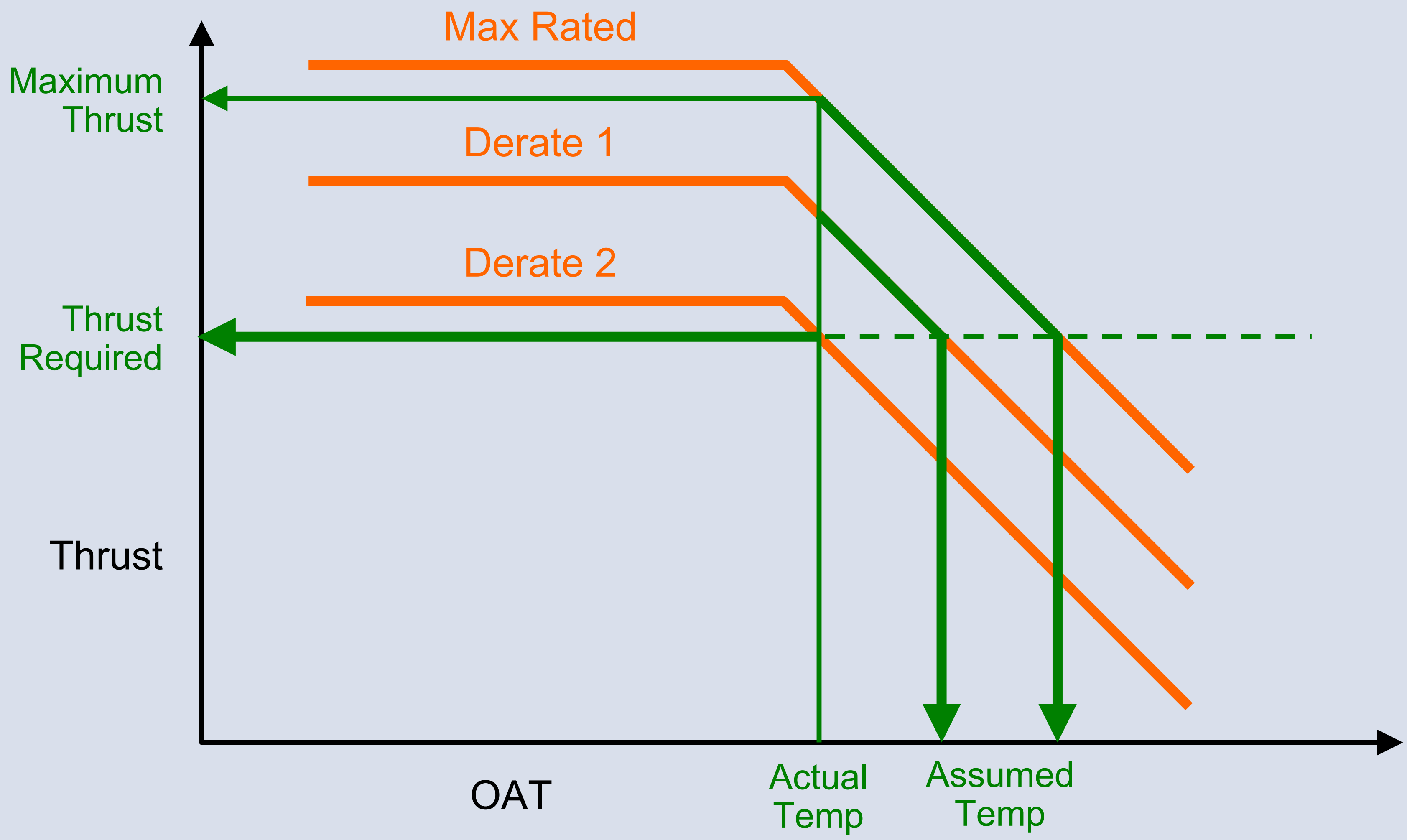
ABOVE STD: +KG/MB	26	25	25	25
BELOW STD: -KG/MB	75	78	78	78

ENGINE-OUT PROCEDURE: MAINTAIN RWY HDG

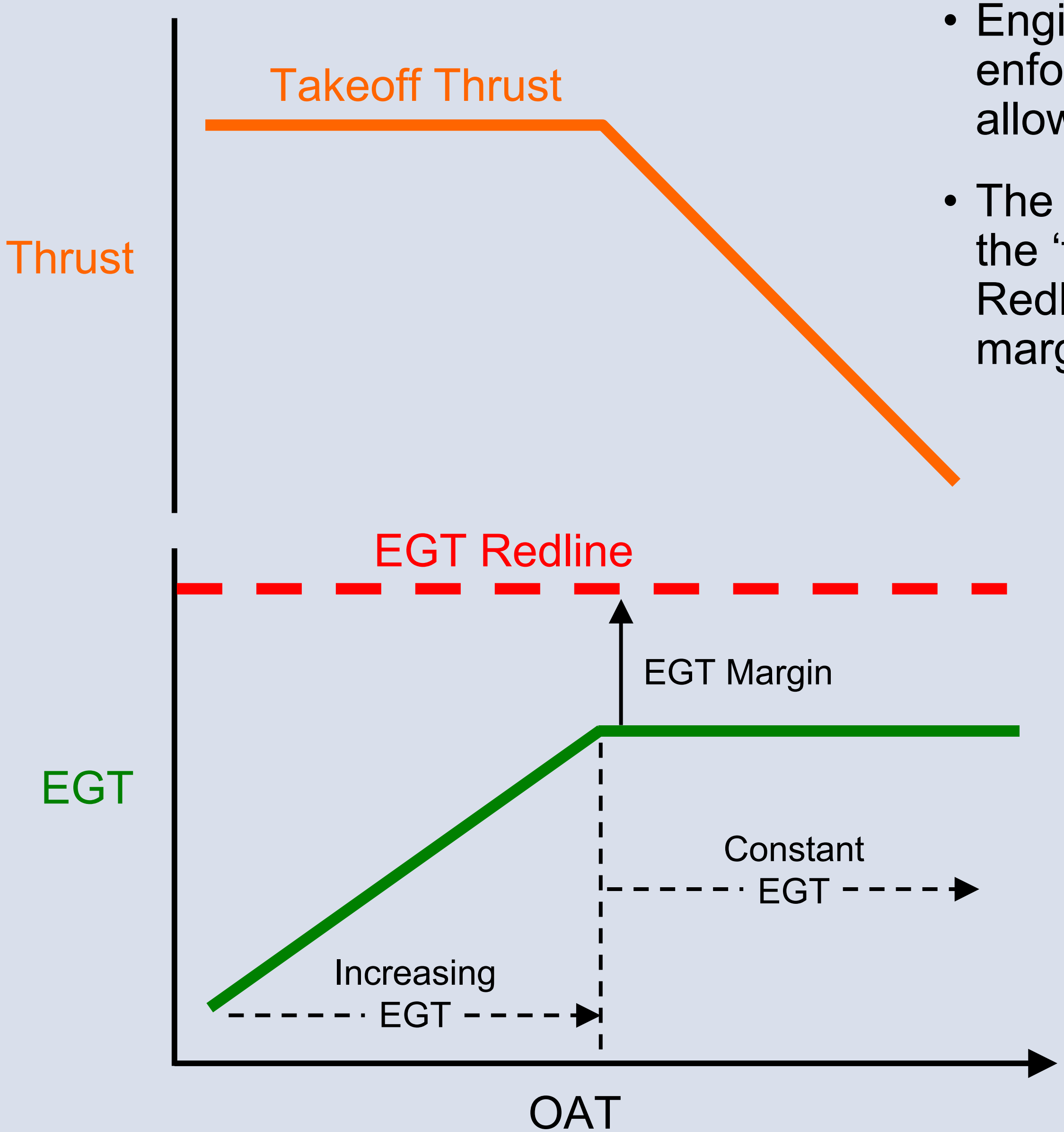
MINIMUM LEVEL-OFF HEIGHT FOR FLAP RETRACTION AND ACCELERATION: 1000 FT

OAT 30°C, No Wind
TOW = 70,000 kg

Derate Combined with Assumed Temperature

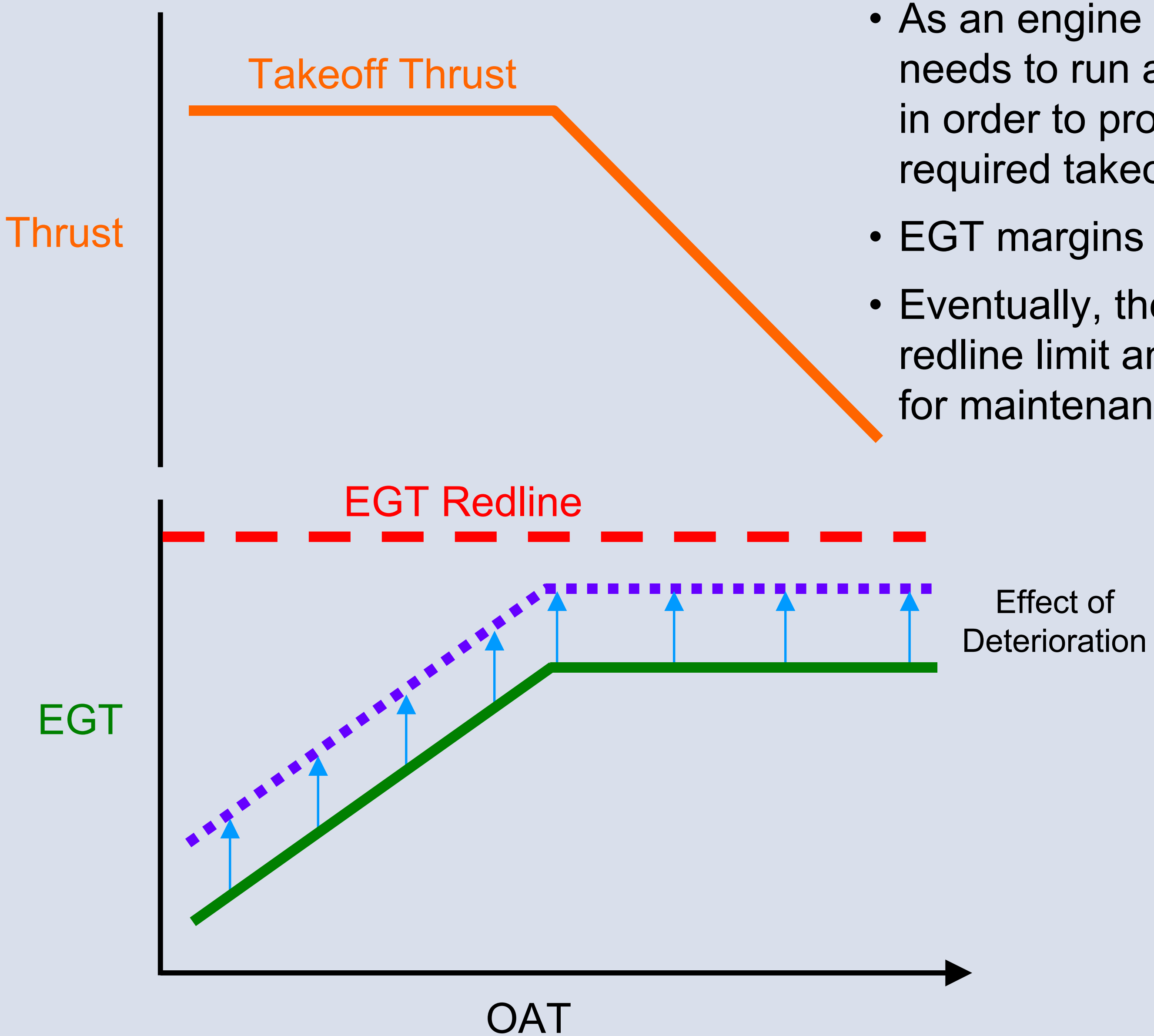


Exhaust Gas Temperature (EGT)



- Engine temperature limits are enforced via a limit on maximum allowable EGT.
- The difference between the EGT in the 'full rate' thrust region and the Redline EGT is termed the 'EGT margin'.

Exhaust Gas Temperature (EGT)



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

End of Propulsion (2): Jet Engine Thrust Ratings

FLIGHT
OPERATIONS
ENGINEERING

Propulsion (3):
Data Presentation in the PEM

Propulsion (3): Data Presentation in the PEM

- Review of 7X7 PEM Section 3
- Calculating Propulsion Performance of an Actual Airplane

Presentation of Thrust and Fuel Flow Data In the Performance Engineer's Manual (PEM)

(Note: In this section we will only be demonstrating the Boeing methods of presenting engine data. We will not be discussing methods used by other manufacturers.)

Presentation of Takeoff Thrust

Refer to 7X7 PEM, Section 3, Page 3.3

- The Performance Engineer's Manual (PEM) presents tables of net takeoff thrust.
- Thrust is shown for a range of:
  - Mach numbers
  - Temperatures
  - Pressure altitudes
- These tables present installed, minimum engine, net thrust/δ levels, for use in computing takeoff performance.
- Different tables are provided for A/C bleeds on and off

Question #1:

For a sea level takeoff at a true airspeed of 101.6 kts, and an OAT of 27.5 degrees C, air conditioning bleeds on, what is the takeoff thrust per engine?

Refer to PEM page 3.4

"Generalized" Thrust Chart

Refer to 7X7 PEM, Section 3, Page 3.16

- This PEM chart presents "corrected" installed net thrust/δ as a function of Mach number and %CN1.
- The chart is valid for any phase of flight. But, it represents an average engine thrust level, and as such should not be used for takeoff calculations.
- If we plotted net thrust versus speed and %N1, it would be necessary to prepare a different graph for each altitude (because thrust is a function of air density)
- Instead, we plot "corrected" thrust versus Mach and %CN1. This allows the presentation of the data for all altitudes in one single chart.

$$\text{Corrected thrust} = \frac{F_N}{\delta}$$

$$\%CN1 = \frac{\%N1}{\theta_T^X}$$

Question #2:

A 7X7 is cruising at FL330, standard day, Mach .79. The total thrust required is 8,800 pounds. What is the %N1 required for this cruise condition?

Refer to PEM page 3.16

Idle Thrust

Refer to 7X7 PEM, Section 3, Page 3.17

- It is sometimes necessary to know the thrust of the engines at idle power. This level of thrust would be used, for example, to calculate descent performance.
- The 7X7 PEM presents idle thrust/δ as a function of Mach and altitude.

Question #3:

A descending 7X7 is currently at 25,000 feet, and 420 knots TAS, on a standard day. What is the idle thrust per engine for this condition?

Refer to PEM page 3.17

Presentation of Fuel Flow Data

Refer to 7X7 PEM, Section 3, Pages 3.19 – 3.24

- Fuel flow data is presented in a variety of ways in different PEM's.
- The 7X7 PEM provides a series of charts that present fuel flow as a function of corrected thrust and Mach number. Individual charts are provided for specific altitudes, and each assumes standard day temperatures.
- A separate chart provides corrections for non-standard day temperatures.
- To better understand these charts we need to discuss a few new concepts and definitions.

Fuel Heating Value

- Fuels are simply a liquid form of potential energy, with the stored energy being released when the fuel is ignited. The amount of potential energy contained per unit of volume is not the same for all fuels, even for the same type of fuel such as Jet A1.
- The potential energy content is called its heating value (usually abbreviated as LHV), and is usually measured in British Thermal Units (BTU's) per pound of fuel.
- One BTU is the heat energy required to raise the temperature of one pound of water by one degree Fahrenheit.

Fuel Heating Value

- If the energy content of the fuel being used is low, the volume of fuel consumed must be greater in order to produce the energy needed to power the airplane.
- An average energy content of jet fuel which is used by Boeing as a standard value in fuel flow calculations is 18,580 BTU's per pound.
- For precision when calculating fuel flow rates for fuel having non-standard LHV's, the nominal fuel flow must be adjusted by the ratio of the standard LHV to the actual LHV.

Boeing uses 18,580 BTU/LB

$$W_{F_{Non-Std}} = W_{F_{Std}} * \left(\frac{LHV_{Std}}{LHV_{Non-Std}} \right)$$

Question #4:

4a) A 7X7 is cruising at FL350, Mach .79, standard day. The value of FN/δ required is 17,000 pounds per engine. What is the predicted fuel flow per engine?

Refer to PEM page 3.21

4b) What would be the predicted fuel flow per engine if the actual LHV of the fuel were measured to be 18,460 BTU per pound?

Fuel Flow Corrections for Non-Standard Temperatures

Refer to 7X7 PEM, Section 3, Page 3.18

- Fuel flow is also affected by air temperature. The fuel flows in the preceding charts were only valid for standard day, ISA, conditions. As such, these values must be adjusted to predict fuel flows for non-standard temperature conditions.
- This PEM chart provides the fuel flow adjustments for non-ISA temperatures.

Question #5:

Assume the same conditions as in question number 4, except increase the temperature to ISA + 10 degrees C. What is the predicted fuel flow per engine at this temperature? (Assume LHV = standard = 18,580 BTU/LB)

Refer to PEM page 3.18

"Corrected" Fuel Flow

Refer to 7X7 PEM, Section 7, Pages 7.13 – 7.15

- Many fuel flow charts or tables present "generalized" fuel flow, so that one chart or table can be used for all temperatures. For example, the data in the 7X7 fuel flow tables is generalized.
- To generalize fuel flow data, it is necessary to present the fuel flow as "corrected fuel flow" (sometimes called 'referred' fuel flow).

$$\text{Corrected fuel flow} = \frac{W_F}{\delta_T \, \theta_T^X}$$

“Corrected” Fuel Flow

Refer to 7X7 PEM, Section 7, Pages 7.13 – 7.15

$$\text{Corrected fuel flow} = \frac{W_F}{\delta_T\, \theta_T^X}$$

W_F = the fuel flow rate

δ_T = the total pressure ratio, $\frac{p_T}{p_o}$

θ_T^X = the total temperature ratio, $\frac{T_T}{T_o}$ raised to the power ‘x’

"Corrected" Fuel Flow

Refer to 7X7 PEM, Section 7, Pages 7.13 – 7.15

- Notice that corrected fuel flow is expressed in terms of *total* pressure ratio and *total* temperature ratio raised to the 'x' power.
- The fuel flow data for different engines will not all generalize in exactly the same way, due to design differences. In order to make the data generalize, different engines use different values of 'x', the exponent for the total temperature ratio.
- For the 7X7, the value of 'x' is .60, so that the equation for corrected fuel flow is:

$$\text{Corrected fuel flow (7X7)} = \frac{W_F}{\delta_T \, \theta_T^{.60}}$$

Bleed Valve Operation

Refer to 7X7 PEM, Section 7, Pages 7.16 and 7.17

- "Bleed valves" are automatically controlled valves on the engine which open and close on a schedule set by the engine manufacturer.
- The purpose and design of these valves varies between manufacturers, engine types. For example, some engines incorporate "surge bleed" valves which are scheduled to open and close with the purpose of maintaining steady flow through the engine, thereby preventing "surging".
- The 7X7 engines incorporate bleed valves designed to switch the source of the high-pressure air required by the airplane from the 5th stage to the 9th stage compressor. This switching occurs whenever the engine is operated at thrust levels that are too low to provide the required air pressure from the 5th stage.

Bleed Valve Operation

Refer to 7X7 PEM, Section 7, Pages 7.16 and 7.17

- The PEM table on page 7.16 shows average FN/δ's below which the high-stage bleed valves will open, and above which the high-stage bleed valves will be closed.
- The FN/δ's at which the valves will actually open/close varies slightly from these average values, depending upon the given conditions, and whether the engine is being accelerated or decelerated.
- The PEM table on page 7.17 shows the increase in corrected fuel flow for the opening of the high-stage bleed.

Miscellaneous Engine Data

Refer to 7X7 PEM, Section 3, Pages 3.25 – 3.28

- Additional engine data is included in the 7X7 PEM for determining corrected N2, and EGT, as functions of corrected %N1 and Mach.
- This data can be used for checking the estimated nominal speed of the low-speed rotor, to ensure proper operation of the engine.
- For similar reasons, it may be desirable to know the estimated EGT as a function of corrected %N1.
- This type of data is seldom used in airplane performance calculations.

End of Propulsion (3): Data Presentation in the PEM