AIRCRAFT TECHNICAL BOOK COMPANY

B1

AVIATION MAINTENANCE TECHNICIAN CERTIFICATION SERIES

GAS TURBINE ENGINE

15

COMPLIANT WITH EASA European Aviation Safety Agency EASA PART 66/147

EASA 2023-989 COMPLIANT

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VERSION	EFFECTIVE DATE	DESCRIPTION OF REVISION(S)
001	2016.01	Module creation and release.
002	2016.08	Format Updates
003	2017.11	Content updates and subject clarification.
004	2019.01	Fine tuned Submodule content sequence based on Appendix-A. Updated layout and styling.
004.1	2022.06	Inclusion of Measurement Standards for clarification, page iv. Minor appearance and format updates.
004.2	2023.04	Minor appearance and format updates.
005	2024.09	Regulatory update for EASA 2023-989 compliance.

Module was reorganized based upon the EASA 2023-989 subject criteria. Enhancements included in this version 005 are:

15.1 *Geared turbofan engines* - topic added.
15.3 *Turboprop and Turboshaft Engine Inlets* - topic added.
15.4 *Multispool designs* - topic added.
15.4 *Axial compressor blades, vanes, tips, and roots* - topic added.
15.4 *Compressor Rotor; drum, disk, and blisk types* - topic added.
15.4 *Combination compressors* - topic added.
15.4 *Compressor anti–stall bleed system* - topic added.
15.6 *Counter rotating turbines* - topic added.
15.8 *Labyrinth Seals* - topic added.
15.9 *Alternative and drop–in fuel* - topic added.
15.11 *Electronic power augmentation* - topic added.
15.13 *Large engine starter generators* - topic added.
15.13 *FADEC ignition system on GE CFM 56* - topic added.
15.15 *Power Augmentation* - replaced with alternative turbine construction.
All Submodule questions/answers updated.
Additional author and format enhancements.

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THRUST

Using the formula below, compute the force necessary to accelerate a mass of 50 pounds by 100 ft/sec².

$$F = \frac{MA}{G}$$

$$F = \frac{50\text{ lb} \times 100\text{ ft/sec}^2}{32.2\text{ ft/sec}^2}$$

$$F = \frac{5\,000\text{ lb-ft/sec}^2}{32.2\text{ ft/sec}^2}$$

$$F = 155\text{ lb}$$

This illustrates that if the velocity mass per second is increased by 100, the resulting thrust is 155 pounds.

Since the turbojet engine accelerates air, the following formula can be used to determine jet thrust:

$$F = \frac{M_S\,(V_2 - V_1)}{G}$$

Where:

F = Force in pounds
M_S = Mass flow in lb/sec
V_1 = Inlet velocity
V_2 = Jet velocity (exhaust)
$V_2 - V_1$ = Change in velocity; difference between inlet velocity and jet velocity
G = Acceleration of gravity or 32.2 ft/sec²

As an example, to use the formula for changing the velocity of 100 pounds of mass airflow per second from 600 ft/sec to 800 ft/sec, the formula can be applied as follows:

$$F = \frac{100\text{ lb/sec }(800\text{ ft/sec} - 600\text{ ft/sec})}{32.2\text{ ft/sec}^2}$$

$$F = \frac{20\,000\text{ lb/sec}}{32.2\text{ ft/sec}^2}$$

$$F = 621\text{ lb}$$

As shown by the formula, if the mass airflow per second and the difference in the velocity of the air from the intake to the exhaust are known, it is easy to compute the force necessary to produce the change in the velocity. Therefore, the thrust of the engine must be equal to the force required to accelerate the air mass through the engine. Then, by using the symbol "*Fn*" for thrust pounds, the formula becomes:

$$Fn = \frac{M_S\,(V_2 - V_1)}{G}$$

Thrust of a gas turbine engine can be increased by two methods: increasing the mass flow of air through the engine or increasing the gas velocity. If the exhaust velocity of the turbojet engine remains constant with respect to the aircraft, the thrust decreases if the speed of the aircraft is increased. This is because V1 increases in value. This does not present a serious problem, however, because as the aircraft speed increases, more air enters the engine, and the engine's exhaust velocity increases. The resultant net thrust is almost constant with increased airspeed.

GROSS (STATIC) THRUST

Gross or static thrust is developed when the engine is on the ground and stationary. Velocity of the airflow entering the engine changes and affects thrust when the aircraft is in flight. [**Figure 2-1**]

NET THRUST

Net thrust is the actual thrust developed by the engine at any given moment. In order to calculate net thrust the acceleration imparted to the airflow should be known. This actual or true acceleration is the difference in velocity between the incoming and outgoing airflow.

Net Thrust = Gross Thrust - Ram Drag

If the mass airflow per second and the difference in the velocity of the air from the intake to the exhaust are known, you can compute the force necessary to produce the change in the velocity. Therefore, the thrust of the engine must be equal to the force required to accelerate the air mass through the engine.

CHOKED NOZZLE THRUST

Bernoulli's principle (when a fluid has its velocity increased at a given point, the pressure of the stream at that point is less than the rest of the stream) is applied to gas turbine engines through the design of convergent and divergent air ducts. The convergent duct increases velocity and decreases pressure. The divergent duct decreases velocity and increases pressure. The convergent principle is usually used for the exhaust nozzle. The divergent principle is used in the compressor and diffuser where the air is slowing and pressurizing.

When an exhaust nozzle is convergent the velocity of gases leaving the rear of the engine increases. This is desirable for the development of maximum thrust. As the gases approach the speed of sound, the nozzle is said to be choked and choked nozzle thrust is produced. This means the highest efficiency has been obtained in the engine for subsonic flight. However, at the speed of sound, the exhaust gases will produce a shock wave which deteriorates performance. [**Figure 2-2**]

THRUST HORSEPOWER

Thrust horsepower can be computed when the net thrust and the speed of the airplane are known. One horsepower is equal to 33 000 foot-pounds of work per minute, which is the same as 375 mile/pounds per hour. When an airplane is flying at 375 mph,

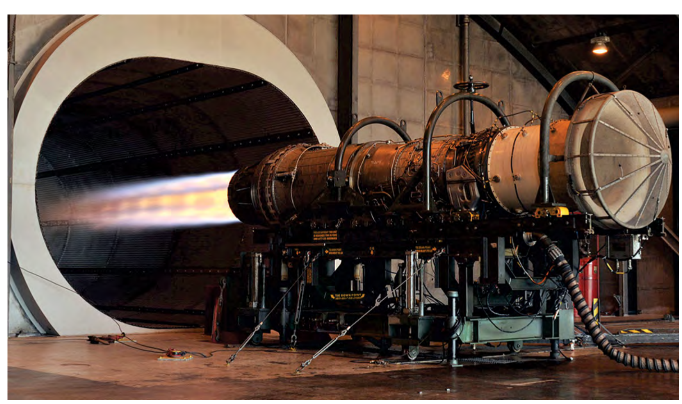

Figure 2-1. Gross thrust from a static turbojet engine.

each pound of thrust is the equivalent of one horsepower. When the speed of the airplane is doubled, the amount of horsepower produced by each pound of thrust is also doubled.

THRUST DISTRIBUTION

The thrust developed by an engine can be thought of as being contributed by the various sections of the engine during the continuous combustion cycle. Thrust distribution can be seen by examining the loads produced in a representative turbojet engine. [**Figure 2-3**]

Note that in the forward part of the engine, due to Newton's second law, loads are in the forward direction. As the gases go throughout the nozzle guide vanes and the turbine, loads shift to the rearward direction. Power is extracted and drag occurs. Drag, which continues as the gases make their way throughout the exhaust section, is a significant force. The resultant thrust is in the forward direction.

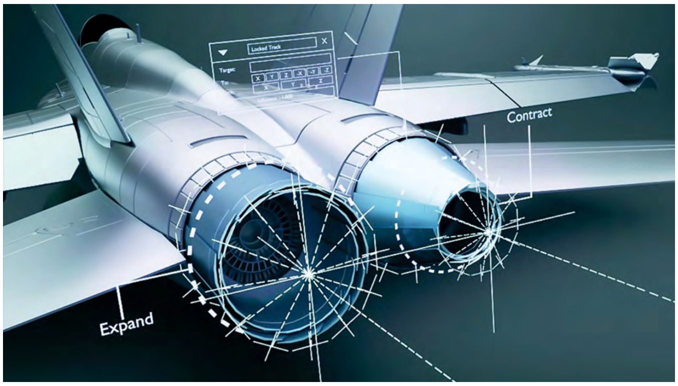

Figure 2-2. Variable exhaust ducts on military aircraft create convergent or divergent conditions.

RESULTANT THRUST

In the forward part of the engine, due to Newton's second law, loads are in the forward direction. As the gases go throughout the nozzle guide vanes and the turbine, loads shift to the rearward direction. Power is extracted and drag occurs. Drag, which continues as the gases make their way throughout the exhaust section, is a significant force. The resultant thrust is in the forward direction. The resultant thrust of the engine is the sum of the thrust forces of all the engine main components, including the compressor, combustion chamber, turbine and the exhaust sections.

EQUIVALENT SHAFT HORSEPOWER

A gas turbine engine that delivers power through a shaft to operate something other than a propeller is referred to as a turboshaft engine. Turboshaft engines are similar to turboprop engines. The power take off may be coupled directly to the engine turbine or the shaft may be driven by a free turbine. The free turbine is located downstream of the engine turbine, being connected to the main engine only by the hot stream of gases. This principle is used in the majority of turboshaft engines and used extensively in helicopters and hovercraft.

SPECIFIC FUEL CONSUMPTION

The usual method of describing the fuel economy of aircraft engines is specific fuel consumption. Specific fuel consumption (SFC) is the fuel flow measured in (lbs/hr) divided by thrust (lbs). Equivalent specific fuel consumption is used for turboprop engines and is measured as fuel flow in pounds per hour divided by a turboprop's equivalent shaft horsepower. Comparisons can be made between various engines on this basis. At low speed, reciprocating and turboprop engines have better economy than turbojet or turbofan engines. However, because of losses in propeller efficiency, a turboprop engine's efficiency becomes limited above 400 mph.

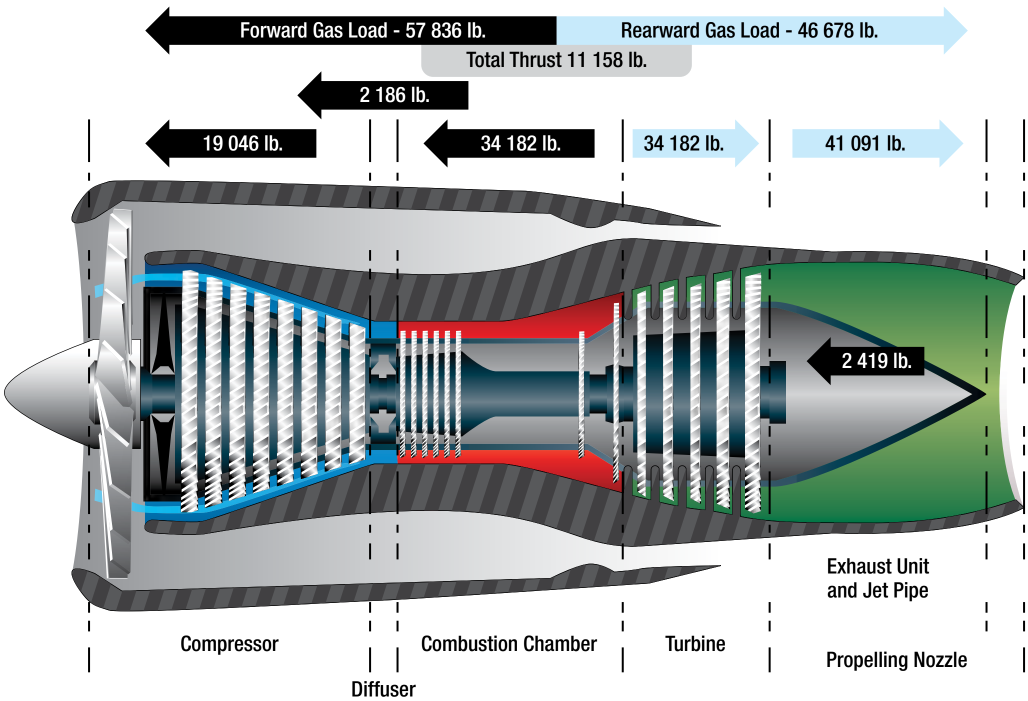

Figure 2-3. Forward and rearward load production on a turbojet engine.

In the interest of fuel economy and aircraft range, the thrust or shaft horsepower per weight should be at its maximum with the fuel consumption as low as possible. Obviously, the more thrust we can obtain per pound of fuel, the more efficient the engine is.

ENGINE EFFICIENCIES

Thermal efficiency is a prime factor in gas turbine performance. It is the ratio of net work produced by the engine to the chemical energy supplied in the form of fuel. The three most important factors affecting the thermal efficiency are turbine inlet temperature, compression ratio, and the component efficiencies of the compressor and turbine. Other factors that affect thermal efficiency are compressor inlet temperature and combustion efficiency. **Figure 2-4** shows the effect that changing compression ratio (compressor pressure ratio) has on thermal efficiency when compressor inlet temperature and the component efficiencies of the compressor and turbine remain constant.

The effects that compressor and turbine component efficiencies have on thermal efficiency when turbine and compressor inlet temperatures remain constant are shown in **Figure 2-5**. In actual operation, the turbine engine exhaust temperature varies directly with turbine inlet temperature at a constant compression ratio.

RPM is a direct measure of compression ratio; therefore, at constant rpm, maximum thermal efficiency can be obtained by maintaining the highest possible exhaust temperature. Since engine life is greatly reduced at high turbine inlet temperatures, the operator should not exceed the exhaust temperatures specified for continuous operation. **Figure 2-6** illustrates the effect of turbine inlet temperature on turbine blade life. In the previous discussion, it was assumed that the state of the air at the inlet to the compressor remains constant. Since this is a practical application of a turbine engine, it becomes necessary to analyze the effect of varying inlet conditions on the thrust or power produced. The three principal variables that affect inlet conditions are the speed of the aircraft, the altitude of the aircraft, and the ambient temperature. To make the analysis simpler, the combination of these three variables can be represented by a single variable called stagnation density.

The power produced by a turbine engine is proportional to the stagnation density at the inlet. The next three illustrations show how changing the density by varying altitude, airspeed, and outside air temperature affects the power level of the engine. **Figure 2-7** shows that the thrust output improves rapidly with a reduction in outside air temperature (OAT) at constant altitude, rpm, and

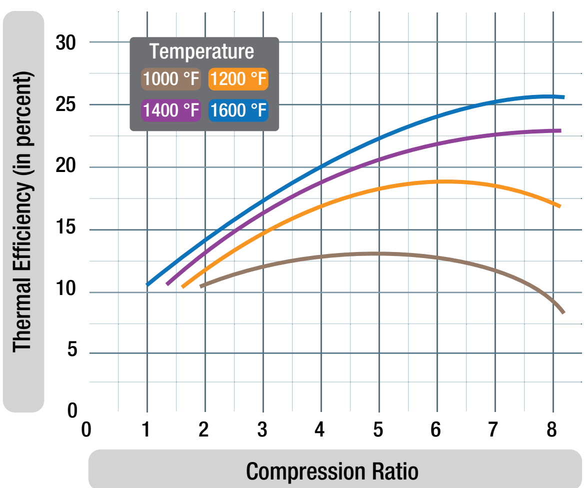

Figure 2-4. The effect of compression ratio on thermal efficiency.

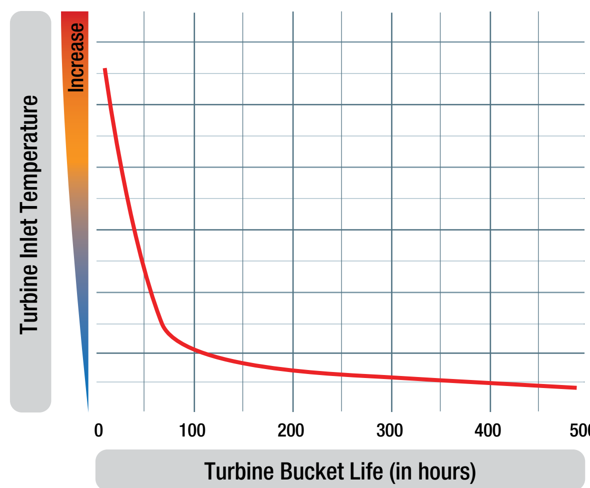

Figure 2-6. Effect of turbine inlet temperature on turbine bucket life.

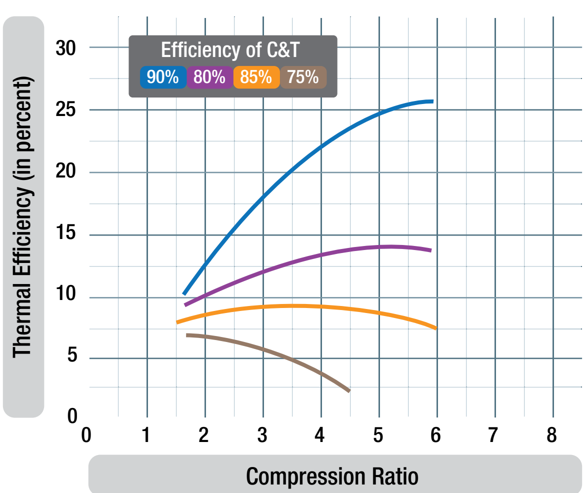

Figure 2-5. Turbine and compressor efficiency vs. thermal efficiency.

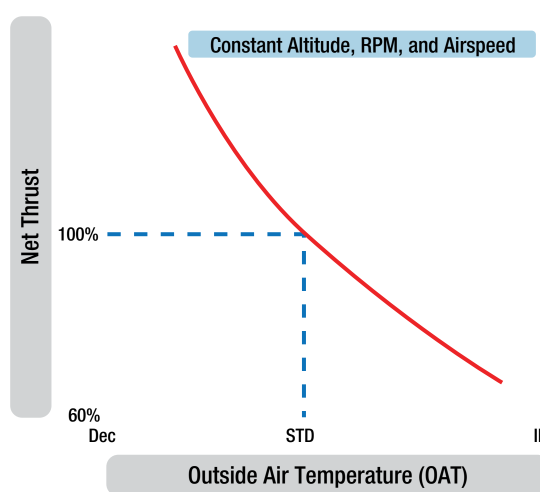

Figure 2-7. Effect of OAT on thrust output.

airspeed. This increase occurs partly because the energy required per pound of airflow to drive the compressor varies directly with the temperature, leaving more energy to develop thrust. In addition, the thrust output increases since the air at reduced temperature has an increased density. The increase in density causes the mass flow through the engine to increase.

The altitude effect on thrust, as shown in **Figure 2-8**, can also be discussed as a density and temperature effect. In this case, an increase in altitude causes a decrease in pressure and temperature. Since the temperature lapse rate is lower than the pressure lapse rate as altitude is increased, the density is decreased. Although the decreased temperature increases thrust, the effect of decreased density more than offsets the effect of the colder temperature. The net result of increased altitude is a reduction in the thrust output.

The effect of airspeed on the thrust of a gas-turbine engine is shown in **Figure 2-9.** To explain the airspeed effect, it is necessary to understand first the effect of airspeed on the factors that combine to produce net thrust: specific thrust and engine airflow. Specific thrust is the net thrust in pounds developed per pound of airflow per second. It is the remainder of specific gross thrust minus specific ram drag. As airspeed is increased, ram drag increases rapidly. The exhaust velocity remains relatively constant; thus, the effect of the increase in airspeed results in decreased specific thrust. [**Figure 2-9**]

In the low-speed range, the specific thrust decreases faster than the airflow increases and causes a decrease in net thrust. As the airspeed increases into the higher range, the airflow increases faster than the specific thrust decreases and causes the net thrust to increase until sonic velocity is reached. The effect of the combination on net thrust is illustrated in **Figure 2-10**.

RAM RECOVERY

A rise in pressure above existing outside atmospheric pressure at the engine inlet, as a result of the forward velocity of an aircraft, is referred to as ram pressure. Since any ram effect causes an increase in compressor entrance pressure over atmospheric, the resulting pressure rise causes an increase in the mass airflow and gas velocity, both of which tend to increase thrust. Although ram effect increases engine thrust, the thrust being produced by the engine decreases for a given throttle setting as the aircraft gains airspeed. Therefore, two opposing trends occur when an aircraft's speed is increased. What actually takes place is the net result of these two different effects. An engine's thrust output temporarily decreases as aircraft speed increases from static, but soon ceases to decrease. Moving toward higher speeds, thrust output begins to increase again due to the increased pressure of ram recovery.

BYPASS RATIO

Turbofan engines can be low bypass or high bypass. The amount of air that is bypassed around the core of the engine determines the bypass ratio. As can be seen in **Figure 2-11**, the air generally driven by the fan does not pass through the internal working core of the engine. The amount of air flow in lbs/sec from the fan bypass compared to the amount of air that flows through the core of the engine is the bypass ratio.

$$\text{Bypass ration} = \frac{\text{100 lb/sec flow fan}}{\text{20 lb/sec flow core}} = \text{5:1 bypass ratio}$$

Turbofan engines are generally categorized as high bypass or low bypass in accordance with their bypass ratios. Most transport category aircraft use high bypass engines. Some low-bypass

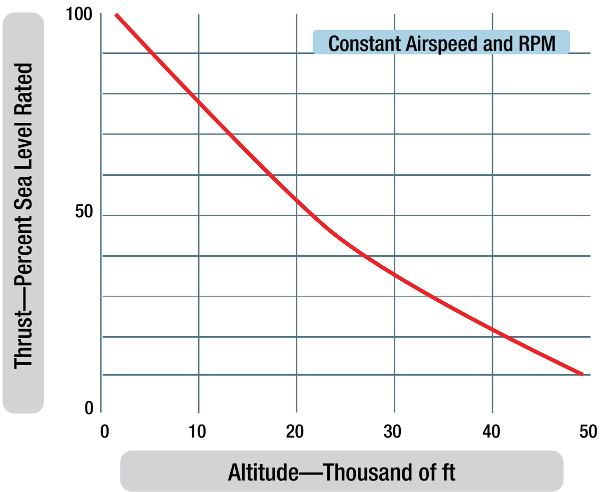

Figure 2-8. Effect of altitude on thrust output.

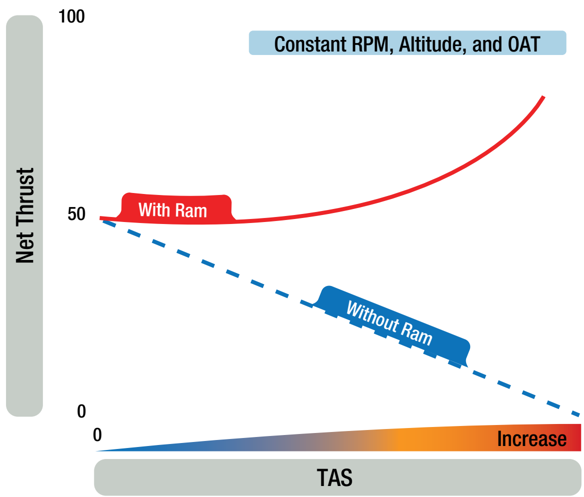

Figure 2-9. Effect of airspeed on net thrust.

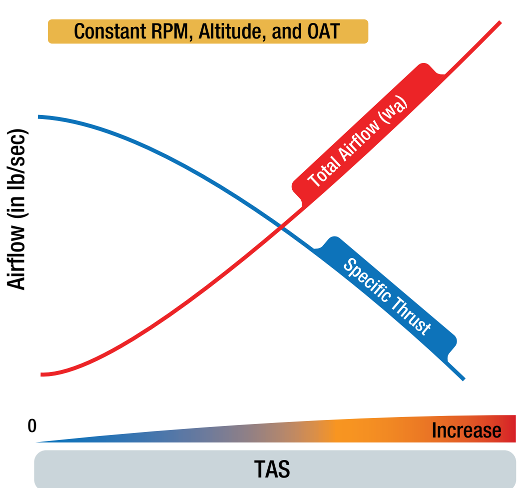

Figure 2-10. Effect of airspeed on specific thrust and total engine airflow.