

# Jet Aircrafts & Generations of Jet Fighter Aircrafts



Renna Madrid

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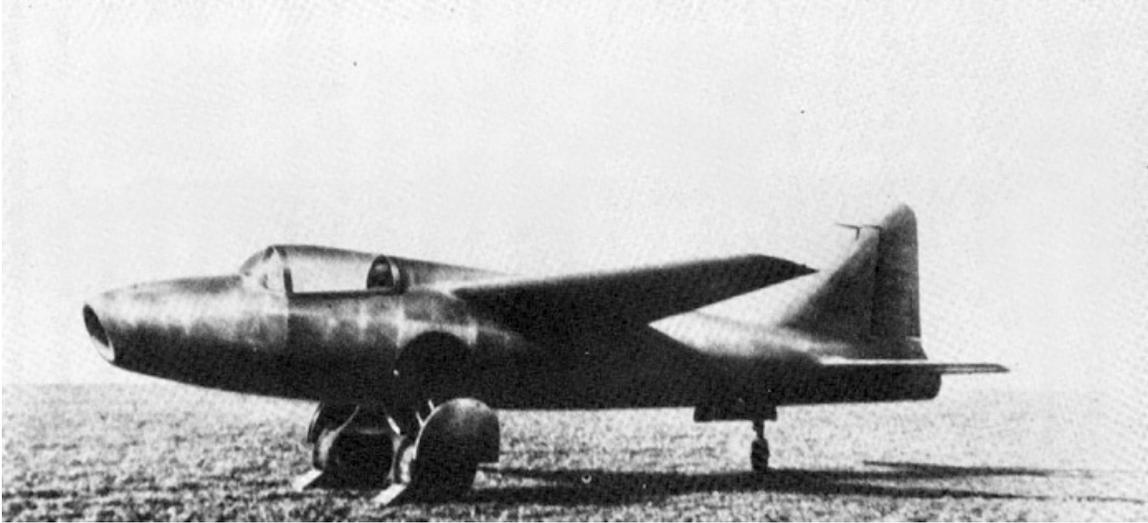
## Chapter- 1

# Jet Aircraft

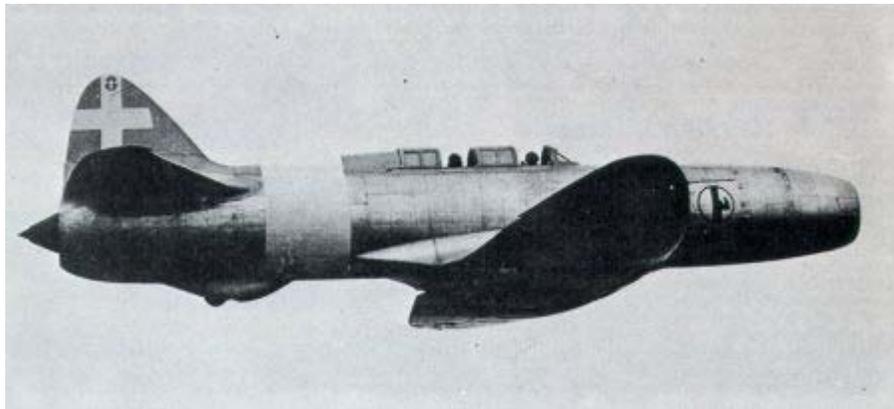
A **jet aircraft** is an aircraft propelled by jet engines. Jet aircraft generally fly much faster than propeller-powered aircraft and at higher altitudes – as high as 10,000–15,000 metres (33,000–49,000 ft). At these altitudes, jet engines achieve maximum efficiency over long distances. The engines in propeller powered aircraft achieve their maximum efficiency at much lower altitudes. Some jet aircraft can move faster than sound.

Two engineers, Frank Whittle in the United Kingdom and Hans von Ohain in Germany, developed the concept independently during the late 1930s. The concept had already been discussed as early as August 1928 by Frank Whittle at Flying School, Wittering, but Hans von Ohain also wrote in February 1936 to Ernst Heinkel, telling him of the design and its possibilities. However, it can be argued that A. A. Griffith, who published a paper in July 1926 on compressors and turbines, which he had been studying at the RAE, also deserves priority credit.

## History



Heinkel He 178, the world's first aircraft to fly purely on turbojet power



Caproni Campini N1 in flight

A number of jet powerplants were suggested from the first instances of powered flight. René Lorin, Morize, Harris proposed systems for creating a jet efflux. In 1910 Henri Coandă filed a patent on a jet propulsion system which used piston-engine exhaust gases to add heat to an otherwise pure air stream compressed by rotating fan blades in a duct.

The "turbojet", was invented in the 1930s, independently by Frank Whittle and Hans von Ohain. The first turbojet aircraft to fly was the Heinkel He 178 prototype of the German Air Force, the *Luftwaffe*, piloted by Erich Warsitz on August 27, 1939.

The first flight of a jet engined aircraft to come to popular attention was the Italian Caproni Campini N.1 motorjet prototype that flew on August 27, 1940. Test pilot Major Mario De Bernardi of the *Regia Aeronautica* was at the controls. It was the first jet

aircraft recognised by the Fédération Aéronautique Internationale (at the time the German He 178 program was still kept secret). Campini had proposed the motorjet in 1932.

The British experimental Gloster E.28/39 first took to the air on May 15, 1941, powered by Sir Frank Whittle's turbojet, and piloted by Glosters test pilot Flt Lt PG Sayer. After the United States was shown the British work, it produced the Bell XP-59A with a version of the Whittle engine built by General Electric, which flew on October 1st, 1942, piloted by Robert M. Stanley.

The first operational jet fighter was the Messerschmitt Me 262., made by Germany during late World War II. It was the fastest conventional aircraft of World War II – although the rocket-powered Messerschmitt Me 163 *Komet* was faster. It had first flown in 1941 but mass production started in 1944 with the first squadrons operational that year, too late for a decisive effect on the outcome of the war. About the same time, mid 1944, the United Kingdom's Gloster Meteor was being committed to defence of the UK against the V1 flying bomb – itself a jet powered aircraft – and then ground-attack operations over Europe in the last months of the war. In 1944 Germany introduced into service the Arado Ar 234 jet reconnaissance and bomber, though chiefly used in the former role. USSR tested its own Bereznyak-Isayev BI-1 in 1942, but the project was scrapped by Joseph Stalin in 1945. The Imperial Japanese Navy also developed jet aircraft in 1945, including the Nakajima J9Y Kikka, a crude copy of the Me 262. By the end of 1945, the US had introduced their next jet fighter, the Lockheed P-80 Shooting Star into service and the UK its second fighter design, the de Havilland Vampire

The US introduced the North American B-45 Tornado, their first jet bomber, into service in 1948. Although capable of carrying nuclear weapons it was used for reconnaissance over Korea.

On November 8, 1950, during the Korean War, United States Air Force Lt. Russell J. Brown, flying in an F-80, intercepted two North Korean MiG-15s near the Yalu River and shot them down in the first jet-to-jet dogfight in history.

The UK put the English Electric Canberra into service in 1951. Designed to fly higher and faster than any interceptor it carried no defensive armament.

BOAC operated the first commercial jet service, from London to Johannesburg, in 1952 with the de Havilland Comet jetliner. The Comet was initially ahead of rivals, but a series of crashes gave time for the Boeing 707 to enter service in 1958 and dominate the market for civilian airliners.

Turbofan aircraft began entering service in the 1960s and 1970s, and this is the most common type of jet in use today.

The fastest military jet plane was the SR-71 Blackbird at Mach 3.35 (2,275 mph, 3,661 km/h). The fastest commercial jet plane was the Tupolev Tu-144 at Mach 2.35 (1,555 mph, 2,503 km/h).

## Modern jet aircraft



Bahrain Royal Flight Boeing 747SP

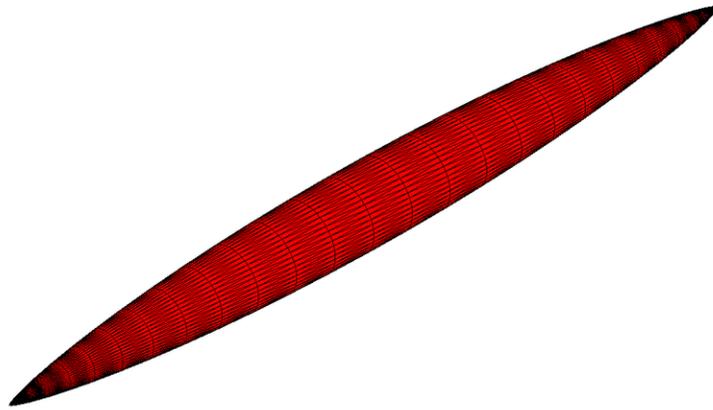
Modern airliners cruise at speeds of .75 to .85 Mach, or 75% to 85% of the speed of sound.

## Other jets

Most people use the term 'jet aircraft' to denote gas turbine based airbreathing jet engines, but rockets and scramjets are both also propelled by them.

The fastest airbreathing jet aircraft is the unmanned X-43 scramjet at around Mach 9–10. The fastest manned (rocket) aircraft is the X-15 at Mach 6.85.

The Space Shuttle, while far faster than the X-43 or X-15, is not regarded as an aircraft during ascent. During re-entry it is classed (like a glider) as an unpowered aircraft.



The shape of most airliners is usually designed to have nearly the same cross-sectional area at each point along its length as the Sears-Haack body

## Aerodynamics

Many jet aircraft fly at high speeds, either supersonic or speeds just below the speed of sound ("transonic"). Aerodynamics is therefore an important consideration.

Jet aircraft are usually designed using the **Whitcomb area rule**, which says that the cross-section of the aircraft at any point must be approximately the same as the Sears-Haack body. This minimises the production of shockwaves which would waste energy.

## Jet engines

Jet engines come in several main types:

- turbojet
- turbofan (which come in two main forms low bypass turbofan and high bypass turbofan)
- rocket

The types are used for different aircraft. Turbojets are seldom used, but was used on Concorde; it has a high exhaust speed and low frontal cross-section, and so is best suited to high-speed flight. Low bypass turbofans have a lower exhaust speed than turbojets and are used for transonic and low supersonic speeds. High bypass turbofans are used for subsonic aircraft and are quite efficient and are widely used for airliners.

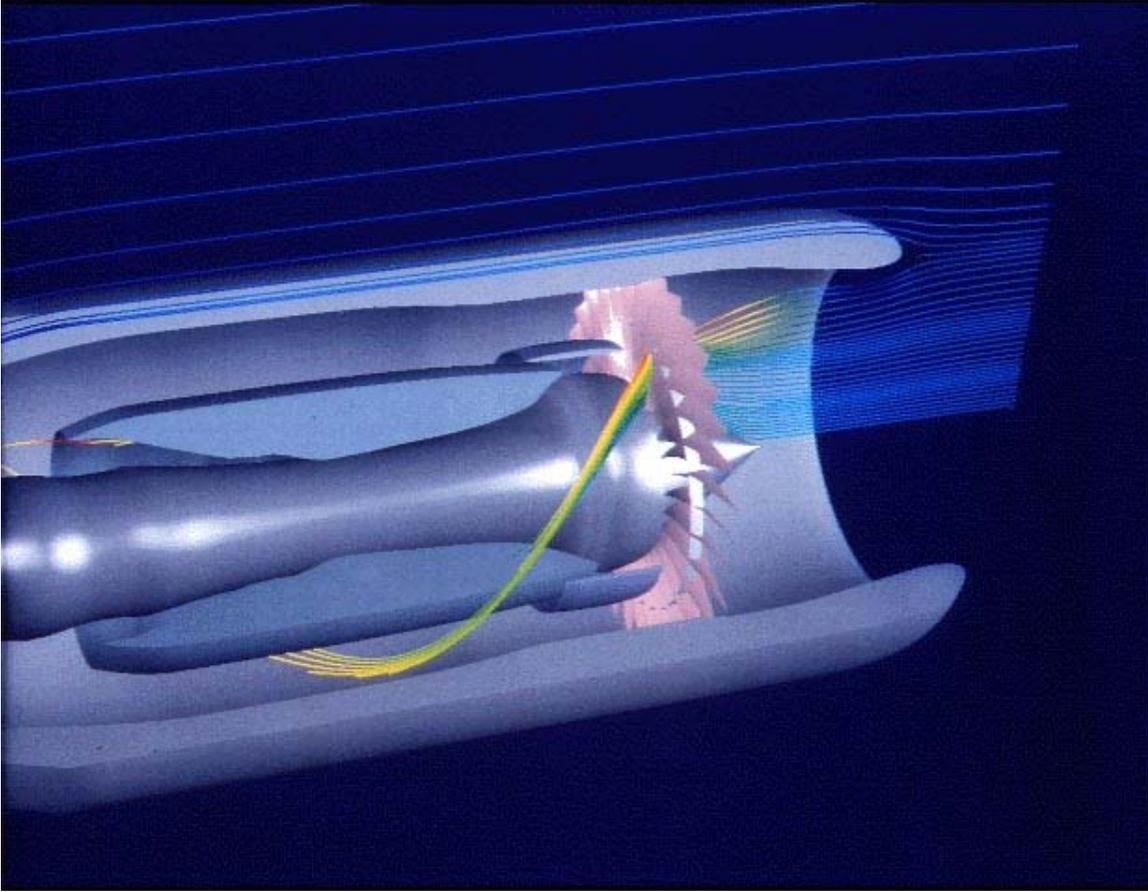
Rockets have extremely fast exhaust speeds and are mainly used when high speeds or extremely high altitudes are needed.

## Chapter- 2

# Jet Engine



A Pratt & Whitney F100 turbofan engine for the F-15 Eagle being tested in the hush house at Florida Air National Guard base. The tunnel behind the engine muffles noise and allows exhaust to escape



Low bypass turbofan's airflow

A **jet engine** is a reaction engine that discharges a fast moving jet of fluid to generate thrust by *jet propulsion* and in accordance with Newton's laws of motion. This broad definition of jet engines includes turbojets, turbofans, rockets, ramjets, pulse jets and pump-jets. In general, most jet engines are internal combustion engines but non-combusting forms also exist.

In common parlance, the term *jet engine* loosely refers to an internal combustion airbreathing jet engine (a *duct engine*). These typically consist of an engine with a rotary (rotating) air compressor powered by a turbine ("Brayton cycle"), with the leftover power providing thrust via a propelling nozzle. These types of jet engines are primarily used by jet aircraft for long distance travel. Early jet aircraft used turbojet engines which were relatively inefficient for subsonic flight. Modern subsonic jet aircraft usually use high-bypass turbofan engines which give high speeds, as well as (over long distances) better fuel efficiency than many other forms of transport.

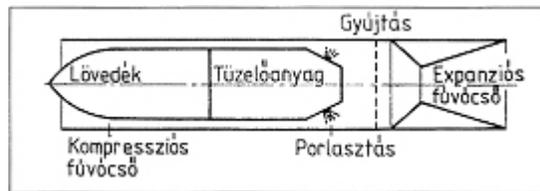
## History

Jet engines can be dated back to the invention of the aeolipile before the first century AD. This device used steam power directed through two nozzles to cause a sphere to spin

rapidly on its axis. So far as is known, it was not used for supplying mechanical power, and the potential practical applications of this invention were not recognized. It was simply considered a curiosity.

Jet propulsion only took off, literally and figuratively, with the invention of the gunpowder-powered rocket by the Chinese in the 13th century as a type of fireworks, and gradually progressed to propel formidable weaponry. However, although very powerful, at reasonable flight speeds rockets are very inefficient and so jet propulsion technology stalled for hundreds of years.

The earliest attempts at airbreathing jet engines were hybrid designs in which an external power source first compressed air, which was then mixed with fuel and burned for jet thrust. In one such system, called a *thermojet* by Secondo Campini but more commonly, motorjet, the air was compressed by a fan driven by a conventional piston engine. Examples of this type of design were the Caproni Campini N.1, and the Japanese Tsu-11 engine intended to power Ohka kamikaze planes towards the end of World War II. None were entirely successful and the N.1 ended up being slower than the same design with a traditional engine and propeller combination.

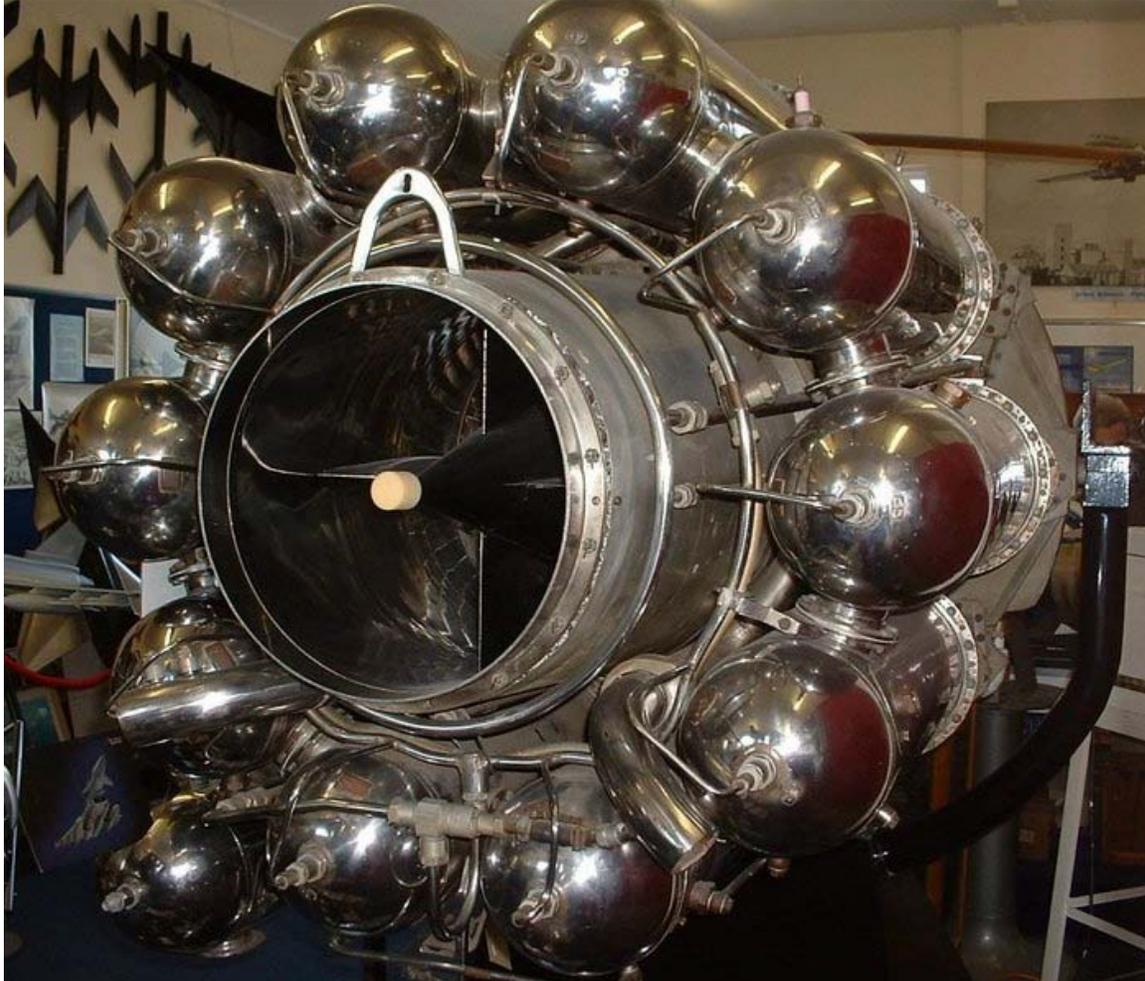


Albert Fonó's ramjet-cannonball from 1915

Even before the start of World War II, engineers were beginning to realize that the piston engine was self-limiting in terms of the maximum performance which could be attained; the limit was due to issues related to propeller efficiency, which declined as blade tips approached the speed of sound. If engine, and thus aircraft, performance were ever to increase beyond such a barrier, a way would have to be found to radically improve the design of the piston engine, or a wholly new type of powerplant would have to be developed. This was the motivation behind the development of the gas turbine engine, commonly called a "jet" engine, which would become almost as revolutionary to aviation as the Wright brothers' first flight.

The key to a practical jet engine was the gas turbine, used to extract energy from the engine itself to drive the compressor. The gas turbine was not an idea developed in the 1930s: the patent for a stationary turbine was granted to John Barber in England in 1791. The first gas turbine to successfully run self-sustaining was built in 1903 by Norwegian engineer Ægidius Elling. Limitations in design and practical engineering and metallurgy prevented such engines reaching manufacture. The main problems were safety, reliability, weight and, especially, sustained operation.

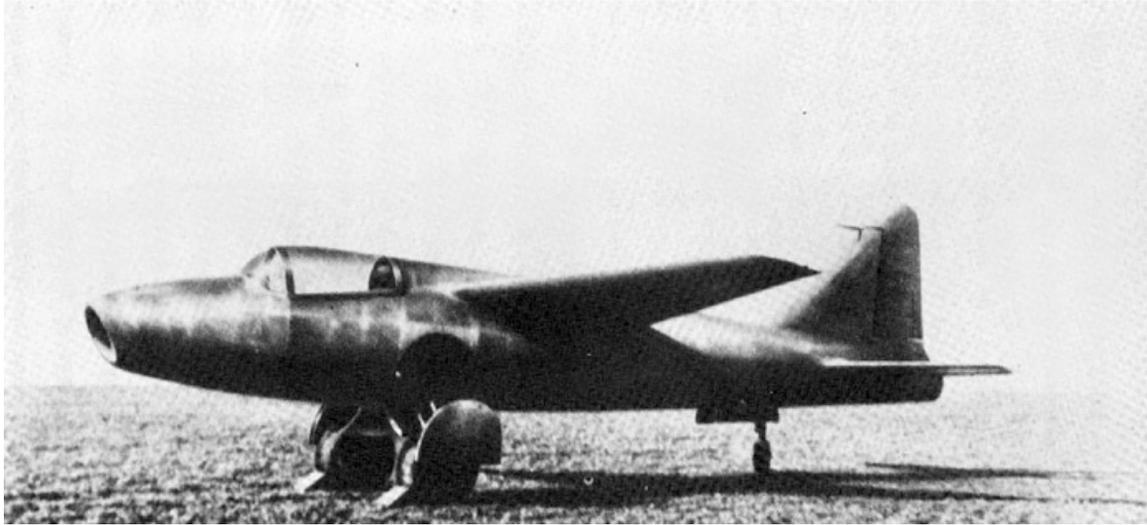
The first patent for using a gas turbine to power an aircraft was filed in 1921 by Frenchman Maxime Guillaume. His engine was an axial-flow turbojet. Alan Arnold Griffith published *An Aerodynamic Theory of Turbine Design* in 1926 leading to experimental work at the RAE.



The Whittle W.2/700 engine flew in the Gloster E.28/39, the first British aircraft to fly with a turbojet engine, and the Gloster Meteor

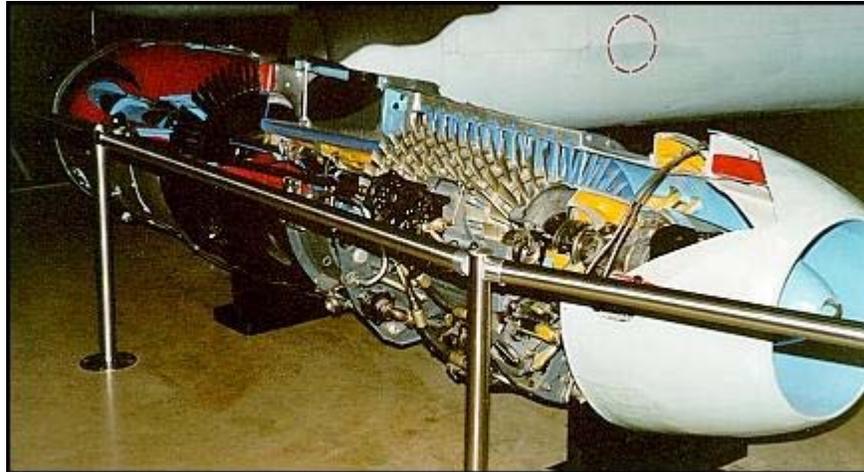
In 1928, RAF College Cranwell cadet Frank Whittle formally submitted his ideas for a turbo-jet to his superiors. In October 1929 he developed his ideas further. On 16 January 1930 in England, Whittle submitted his first patent (granted in 1932). The patent showed a two-stage axial compressor feeding a single-sided centrifugal compressor. Practical axial compressors were made possible by ideas from A.A.Griffith in a seminal paper in 1926 ("An Aerodynamic Theory of Turbine Design"). Whittle would later concentrate on the simpler centrifugal compressor only, for a variety of practical reasons. Whittle had his first engine running in April 1937. It was liquid-fueled, and included a self-contained fuel pump. Whittle's team experienced near-panic when the engine would not stop, accelerating even after the fuel was switched off. It turned out that fuel had leaked into the engine and accumulated in pools, so the engine would not stop until all the leaked

fuel had burned off. Whittle was unable to interest the government in his invention, and development continued at a slow pace.



Heinkel He 178, the world's first aircraft to fly purely on turbojet power

In 1935 Hans von Ohain started work on a similar design in Germany, apparently unaware of Whittle's work. His first device was strictly experimental and could only run under external power, but he was able to demonstrate the basic concept. Ohain was then introduced to Ernst Heinkel, one of the larger aircraft industrialists of the day, who immediately saw the promise of the design. Heinkel had recently purchased the Hirth engine company, and Ohain and his master machinist Max Hahn were set up there as a new division of the Hirth company. They had their first HeS 1 centrifugal engine running by September 1937. Unlike Whittle's design, Ohain used hydrogen as fuel, supplied under external pressure. Their subsequent designs culminated in the gasoline-fuelled HeS 3 of 1,100 lbf (5 kN), which was fitted to Heinkel's simple and compact He 178 airframe and flown by Erich Warsitz in the early morning of August 27, 1939, from Rostock-Marienehe aerodrome, an impressively short time for development. The He 178 was the world's first jet plane.



A cutaway of the Junkers Jumo 004 engine

Austrian Anselm Franz of Junkers' engine division (*Junkers Motoren* or **Jumo**) introduced the axial-flow compressor in their jet engine. Jumo was assigned the next engine number in the RLM **109-0xx** numbering sequence for gas turbine aircraft powerplants, "004", and the result was the Jumo 004 engine. After many lesser technical difficulties were solved, mass production of this engine started in 1944 as a powerplant for the world's first jet-fighter aircraft, the Messerschmitt Me 262 (and later the world's first jet-bomber aircraft, the Arado Ar 234). A variety of reasons conspired to delay the engine's availability, causing the fighter to arrive too late to improve Germany's position in World War II. Nonetheless, it will be remembered as the first use of jet engines in service.

Meanwhile, in Britain the Gloster E28/39 had its maiden flight on 15 May 1941 and the Gloster Meteor finally entered service with the RAF in July 1944.

Following the end of the war the German jet aircraft and jet engines were extensively studied by the victorious allies and contributed to work on early Soviet and US jet fighters. The legacy of the axial-flow engine is seen in the fact that practically all jet engines on fixed wing aircraft have had some inspiration from this design.

By the 1950s the jet engine was almost universal in combat aircraft, with the exception of cargo, liaison and other specialty types. By this point some of the British designs were already cleared for civilian use, and had appeared on early models like the de Havilland Comet and Avro Canada Jetliner. By the 1960s all large civilian aircraft were also jet powered, leaving the piston engine in low-cost niche roles such as cargo flights.

The efficiency of turbojet engines was still rather worse than piston engines but by the 1970s, with the advent of high bypass turbofan jet engines, an innovation not foreseen by the early commentators such as Edgar Buckingham, at high speeds and high altitudes that seemed absurd to them, fuel efficiency was about the same as the best piston and propeller engines.

## Uses

Jet engines are usually used as aircraft engines for jet aircraft. They are also used for cruise missiles and unmanned aerial vehicles.

In the form of rocket engines they are used for fireworks, model rocketry, spaceflight, and military missiles.

Jet engines have also been used to propel high speed cars, particularly drag racers, with the all-time record held by a rocket car. A turbofan powered car ThrustSSC currently holds the land speed record.

Jet engine designs are frequently modified for non-aircraft applications, as industrial gas turbines. These are used in electrical power generation, for powering water, natural gas, or oil pumps, and providing propulsion for ships and locomotives. Industrial gas turbines can create up to 50,000 shaft horsepower. Many of these engines are derived from older military turbojets such as the Pratt & Whitney J57 and J75 models. There is also a derivative of the P&W JT8D low-bypass turbofan that creates up to 35,000 HP.

## Types

There are a large number of different types of jet engines, all of which achieve forward thrust from the principle of *jet propulsion*.

### Airbreathing

Nearly all aircraft are propelled by airbreathing jet engines, and most of the airbreathing jet engines that are in use are turbofan jet engines which give good efficiency at speeds just below the speed of sound.

### Turbine powered

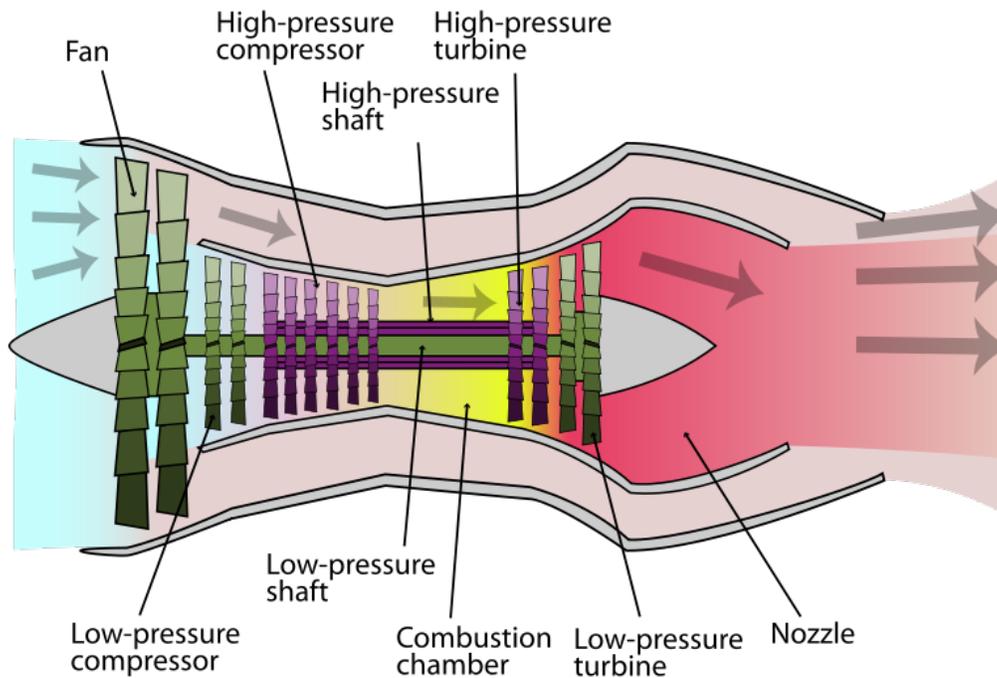
Gas turbines are rotary engines that extract energy from a flow of combustion gas. They have an upstream compressor coupled to a downstream turbine with a combustion chamber in-between. In aircraft engines, those three core components are often called the "gas generator." There are many different variations of gas turbines, but they all use a gas generator system of some type.

### Turbojet

A turbojet engine is a gas turbine engine that works by compressing air with an inlet and a compressor (axial, centrifugal, or both), mixing fuel with the compressed air, burning the mixture in the combustor, and then passing the hot, high pressure air through a turbine and a nozzle. The compressor is powered by the turbine, which extracts energy from the expanding gas passing through it. The engine converts internal energy in the

fuel to kinetic energy in the exhaust, producing thrust. All the air ingested by the inlet is passed through the compressor, combustor, and turbine, unlike the turbofan engine described below.

### Turbofan



Schematic diagram illustrating the operation of a low-bypass turbofan engine.

A turbofan engine is a gas turbine engine that is very similar to a turbojet. Like a turbojet, it uses the gas generator core (compressor, combustor, turbine) to convert internal energy in fuel to kinetic energy in the exhaust. Turbofans differ from turbojets in that they have an additional component, a fan. Like the compressor, the fan is powered by the turbine section of the engine. Unlike the turbojet, some of the flow accelerated by the fan bypasses the gas generator core of the engine and is exhausted through a nozzle. The bypassed flow is at lower velocities, but a higher mass, making thrust produced by the fan more efficient than thrust produced by the core. Turbofans are generally more efficient than turbojets at subsonic speeds, but they have a larger frontal area which generates more drag.

There are two general types of turbofan engines, low bypass and high bypass. Low bypass turbofans have a bypass ratio of around 2:1 or less, meaning that for each kilogram of air that passes through the core of the engine, two kilograms or less of air bypass the core. Low bypass turbofans often used a mixed exhaust nozzle meaning that the bypassed flow and the core flow exit from the same nozzle. High bypass turbofans have larger bypass ratios, sometimes on the order of 5:1 or 6:1. These turbofans can produce much more thrust than low bypass turbofans or turbojets because of the large

mass of air that the fan can accelerate, and are often more fuel efficient than low bypass turbofans or turbojets.

### **Turboprop and turboshaft**

Turboprop engines are jet engine derivatives that extract work from the hot-exhaust jet to turn a rotating shaft, which is then used to produce thrust by some other means. While not strictly jet engines in that they rely on an auxiliary mechanism to produce thrust, turboprops are very similar to other turbine-based jet engines, and are often described as such.

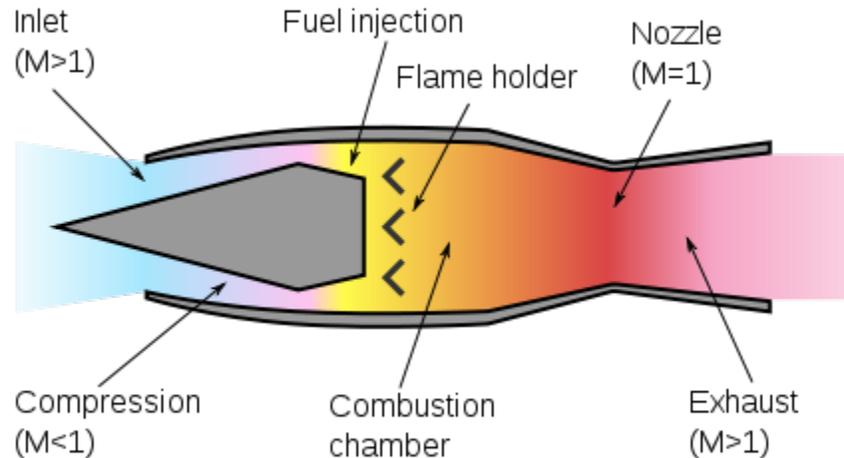
In turboprop engines, a portion of the engines' thrust is produced by spinning a propeller, rather than relying solely on high-speed jet exhaust. As their jet thrust is augmented by a propeller, turboprops are occasionally referred to as a type of hybrid jet engine. While many turboprops generate the majority of their thrust with the propeller, the hot-jet exhaust is an important design point, and maximum thrust is obtained by matching thrust contributions of the propeller to the hot jet. Turboprops generally have better performance than turbojets or turbofans at low speeds where propeller efficiency is high, but become increasingly noisy and inefficient at high speeds.

Turboshaft engines are very similar to turboprops, differing in that nearly all energy in the exhaust is extracted to spin the rotating shaft. They therefore generate little to no jet thrust. Turboshaft engines are often used to power helicopters.

### **Propfan**

A propfan engine (also called "unducted fan", "open rotor", or "ultra-high bypass") is a jet engine that uses its gas generator to power an exposed fan, similar to turboprop engines. Like turboprop engines, propfans generate most of their thrust from the propeller and not the exhaust jet. The primary difference between turboprop and propfan design is that the propeller blades on a propfan are highly swept to allow them to operate at speeds around Mach 0.8, which is competitive with modern commercial turbofans. These engines have the fuel efficiency advantages of turboprops with the performance capability of commercial turbofans. While significant research and testing (including flight testing) has been conducted on propfans, no propfan engines have entered production.

## Ram powered



A schematic of a ramjet engine, where "M" is the Mach number of the airflow.

Ram powered jet engines are airbreathing engines similar to gas turbine engines and they both follow the Brayton cycle. Gas turbine and ram powered engines differ, however, in how they compress the incoming airflow. Whereas gas turbine engines use axial or centrifugal compressors to compress incoming air, ram engines rely only on air compressed through the inlet or diffuser. Ram powered engines are considered the most simple type of air breathing jet engine because they can contain no moving parts.

### Ramjet

Ramjets are the most basic type of ram powered jet engines. They consist of three sections; an inlet to compressed oncoming air, a combustor to inject and combust fuel, and a nozzle expel the hot gases and produce thrust. Ramjets require a relatively high speed to efficiently compress the oncoming air, so ramjets cannot operate at a standstill and they are most efficient at supersonic speeds. A key trait of ramjet engines is that combustion is done at subsonic speeds. The supersonic oncoming air is dramatically slowed through the inlet, where it is then combusted at the much slower, subsonic, speeds. The faster the oncoming air is, however, the less efficient it becomes to slow it to subsonic speeds. Therefore ramjet engines are limited to approximately Mach 5.

### Scramjet

Scramjets are mechanically very similar to ramjets. Like a ramjet, they consist of an inlet, a combustor, and a nozzle. The primary difference between ramjets and scramjets is that scramjets do not slow the oncoming airflow to subsonic speeds for combustion, they use supersonic combustion instead. The name "scramjet" comes from "supersonic combusting ramjet." Since scramjets use supersonic combustion they can operate at speeds above Mach 6 where traditional ramjets are too inefficient. Another difference

between ramjets and scramjets comes from how each type of engine compresses the oncoming air flow: while the inlet provides most of the compression for ramjets, the high speeds at which scramjets operate allow them to take advantage of the compression generated by shock waves, primarily oblique shocks.

Very few scramjet engines have ever been built and flown. In May 2010 the Boeing X-51 set the endurance record for the longest scramjet burn at over 200 seconds.

### Non-continuous combustion

Type	Description	Advantages	Disadvantages
<b>Motorjet</b>	Obsolete type that worked like a turbojet but instead of a turbine driving the compressor a piston engine drives it.	Higher exhaust velocity than a propeller, offering better thrust at high speed	Heavy, inefficient and underpowered. Example: Caproni Campini N.1.
<b>Pulsejet</b>	Air is compressed and combusted intermittently instead of continuously. Some designs use valves.	Very simple design, commonly used on model aircraft	Noisy, inefficient (low compression ratio), works poorly on a large scale, valves on valved designs wear out quickly
<b>Pulse detonation engine</b>	Similar to a pulsejet, but combustion occurs as a detonation instead of a deflagration, may or may not need valves	Maximum theoretical engine efficiency	Extremely noisy, parts subject to extreme mechanical fatigue, hard to start detonation, not practical for current use

### Rocket

The rocket engine uses the same basic physical principles as the jet engine for propulsion via thrust, but is distinct in that it does not require atmospheric air to provide oxygen; the rocket carries all components of the propellant.

This type of engine is used for launching satellites, space exploration and manned access, and permitted landing on the moon in 1969.

Rocket engines are used for high altitude flights as they have a lack of reliance on atmospheric oxygen and this allows them to operate at arbitrary altitudes, or anywhere where very high accelerations are needed since rocket engines themselves have a very high thrust-to-weight ratio.

However, the high exhaust speed and the heavier, oxidiser-rich propellant results in far more propellant use than turbfans although, even so, at high speeds they become energy-efficient.

An approximate equation for the net thrust of a rocket engine is:

$$F = \dot{m}g_0 I_{sp-vac} - A_e P$$

Where  $F$  is the thrust,  $I_{sp(vac)}$  is the specific impulse,  $g_0$  is a standard gravity,  $\dot{m}$  is the propellant flow in kg/s,  $A_e$  is the area of the exhaust bell at the exit, and  $P$  is the atmospheric pressure.

Type	Description	Advantages	Disadvantages
<b>Rocket</b>	Carries all propellants and oxidants on-board, emits jet for propulsion	Very few moving parts, Mach 0 to Mach 25+, efficient at very high speed (> Mach 5.0 or so), thrust/weight ratio over 100, no complex air inlet, high compression ratio, very high speed (hypersonic) exhaust, good cost/thrust ratio, fairly easy to test, works in a vacuum—indeed works best on vehicle structure at high speed, fairly small surface area to keep cool, and no turbine in hot exhaust stream. Very high temperature combustion and high expansion ratio nozzle gives very high efficiency- at very high speeds.	Needs lots of propellant—very low specific impulse—typically 100–450 seconds. Extreme thermal stresses of combustion chamber can make reuse harder. Typically requires carrying oxidiser on-board which increases risks. Extraordinarily noisy.

## Hybrid

Combined cycle engines simultaneously use 2 or more different jet engine operating principles.

Type	Description	Advantages	Disadvantages
<b>Turborocket</b>	A turbojet where an additional oxidizer such as oxygen is added to the airstream to increase maximum altitude	Very close to existing designs, operates in very high altitude, wide range of altitude and airspeed	Airspeed limited to same range as turbojet engine, carrying oxidizer like LOX can be dangerous. Much heavier than simple rockets.

**Air-  
augmented  
rocket**

Essentially a ramjet where intake air is compressed and burnt with the exhaust from a rocket

Mach 0 to Mach 4.5+ (can also run exoatmospheric), good efficiency at Mach 2 to 4

Similar efficiency to rockets at low speed or exoatmospheric, inlet difficulties, a relatively undeveloped and unexplored type, cooling difficulties, very noisy, thrust/weight ratio is similar to ramjets.

**Precooled  
jets / LACE**

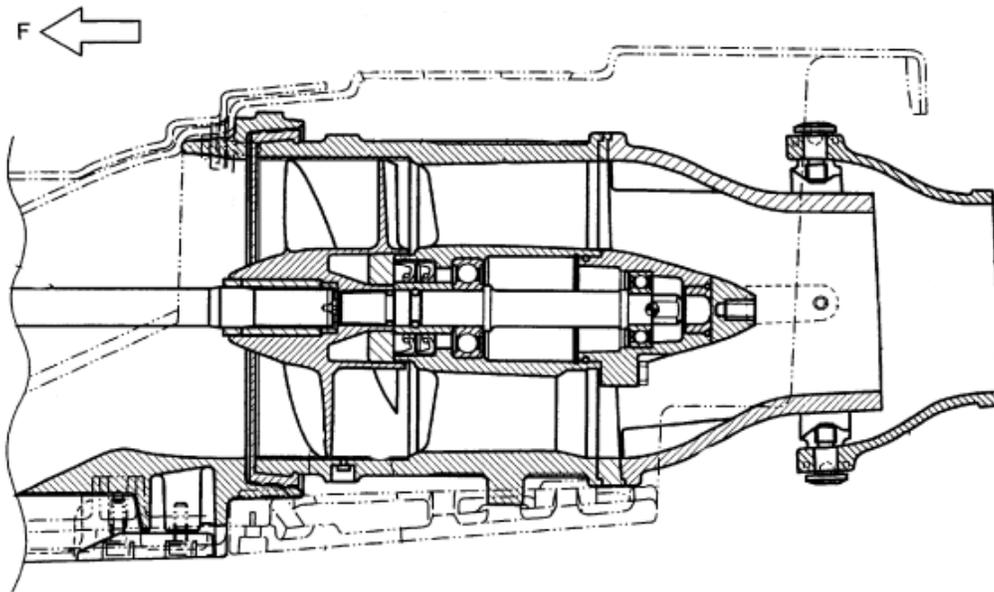
Intake air is chilled to very low temperatures at inlet in a heat exchanger before passing through a ramjet and/or turbojet and/or rocket engine.

Easily tested on ground. Very high thrust/weight ratios are possible (~14) together with good fuel efficiency over a wide range of airspeeds, Mach 0-5.5+; this combination of efficiencies may permit launching to orbit, single stage, or very rapid, very long distance intercontinental travel.

Exists only at the lab prototyping stage. Examples include RB545, Reaction Engines SABRE, ATREX. Requires liquid hydrogen fuel which has very low density and requires heavily insulated tankage.

**Water jet**

A water jet, or pump jet, is a marine propulsion system that utilizes a jet of water. The mechanical arrangement may be a ducted propeller with nozzle, or a centrifugal compressor and nozzle.



A pump jet schematic.

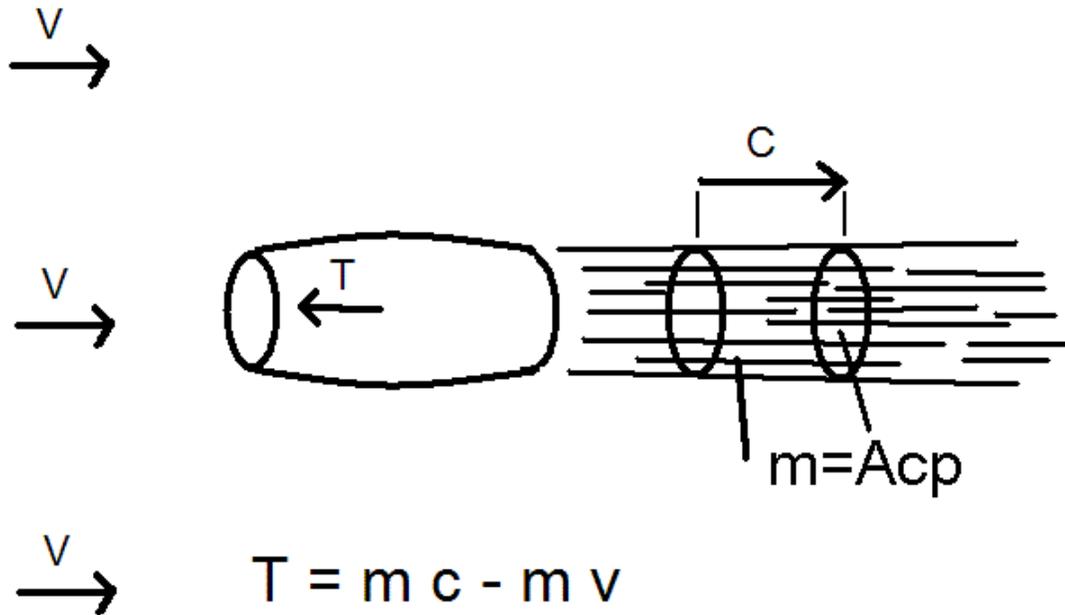
Type	Description	Advantages	Disadvantages
<b>Water jet</b>	For propelling water rockets and jetboats; squirts water out the back through a nozzle	In boats, can run in shallow water, high acceleration, no risk of engine overload (unlike propellers), less noise and vibration, highly maneuverable at all boat speeds, high speed efficiency, less vulnerable to damage from debris, very reliable, more load flexibility, less harmful to wildlife	Can be less efficient than a propeller at low speed, more expensive, higher weight in boat due to entrained water, will not perform well if boat is heavier than the jet is sized for

## General physical principles

All jet engines are reaction engines that generate thrust by emitting a jet of fluid rearwards at relatively high speed. The forces on the inside of the engine needed to create this jet give a strong thrust on the engine which pushes the craft forwards.

Jet engines make their jet from propellant from tankage that is attached to the engine (as in a 'rocket') as well as in **duct engines** (those commonly used on aircraft) by ingesting an external fluid (very typically air) and expelling it at higher speed.

## Thrust



Thrust from airbreathing jet engines depends on the difference in speed of the air before and after it goes through the jet engine, the 'master cross-section'  $A$ , and the density of the air  $\rho$

The motion impulse of the engine is equal to the fluid mass multiplied by the speed at which the engine emits this mass:

$$I = mc$$

where  $m$  is the fluid mass per second and  $c$  is the exhaust speed. In other words, a vehicle gets the same thrust if it outputs a lot of exhaust very slowly, or a little exhaust very quickly. (In practice parts of the exhaust may be faster than others, but it is the *average* momentum that matters, and thus the important quantity is called the **effective exhaust speed** -  $c$  here.)

However, when a vehicle moves with certain velocity  $v$ , the fluid moves towards it, creating an opposing ram drag at the intake:

$$mv$$

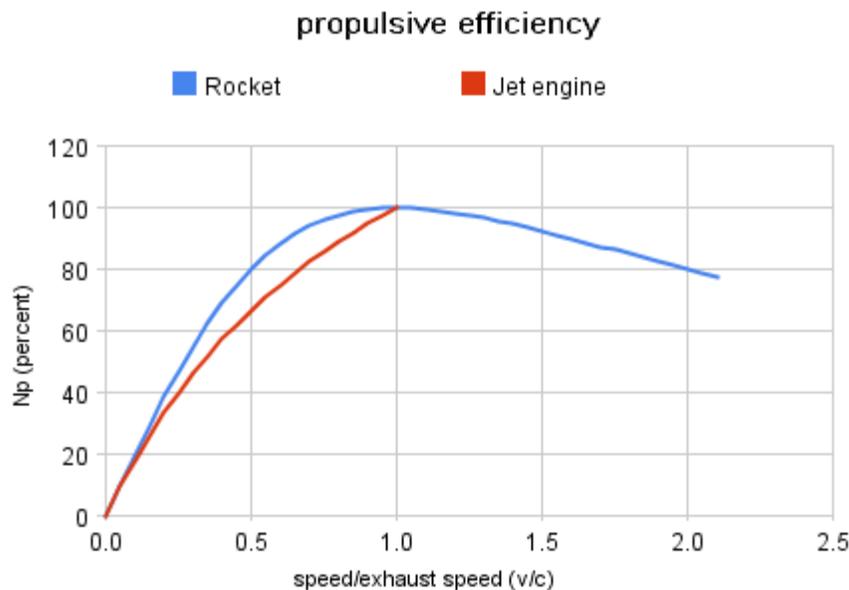
Most types of jet engine have an intake, which provides the bulk of the fluid exiting the exhaust. Conventional rocket motors, however, do not have an intake, the oxidizer and fuel both being carried within the vehicle. Therefore, rocket motors do not have ram drag; the gross thrust of the nozzle is the net thrust of the engine. Consequently, the thrust characteristics of a rocket motor are different from that of an air breathing jet engine, and thrust is independent of speed.

The jet engine with an intake duct is only useful if the velocity of the gas from the engine,  $c$ , is greater than the vehicle velocity,  $v$ , as the net engine thrust is the same as if the gas were emitted with the velocity  $c - v$ . So the thrust is actually equal to

$$S = m(c - v)$$

This equation shows that as  $v$  approaches  $c$ , a greater mass of fluid must go through the engine to continue to accelerate at the same rate, but all engines have a designed limit on this. Additionally, the equation implies that the vehicle can't accelerate past its exhaust velocity as it would have negative thrust.

## Energy efficiency



Dependence of the energy efficiency ( $\eta$ ) upon the vehicle speed/exhaust speed ratio ( $v/c$ ) for air-breathing jet and rocket engines

Energy efficiency ( $\eta$ ) of jet engines installed in vehicles has two main components, *cycle efficiency* ( $\eta_c$ )- how efficiently the engine can accelerate the jet, and *propulsive efficiency* ( $\eta_p$ )-how much of the energy of the jet ends up in the vehicle body rather than being carried away as kinetic energy of the jet.

Even though overall energy efficiency  $\eta$  is simply:

$$\eta = \eta_p \eta_c$$

### **Propulsive efficiency**

For all jet engines the *propulsive efficiency* is highest when the engine emits an exhaust jet at a speed that is the same as, or nearly the same as, the vehicle velocity as this gives the smallest residual kinetic energy. (Note:) The exact formula for air-breathing engines moving at speed  $v$  with an exhaust velocity  $c$  is given in the literature as: is

$$\eta_p = \frac{2}{1 + \frac{c}{v}}$$

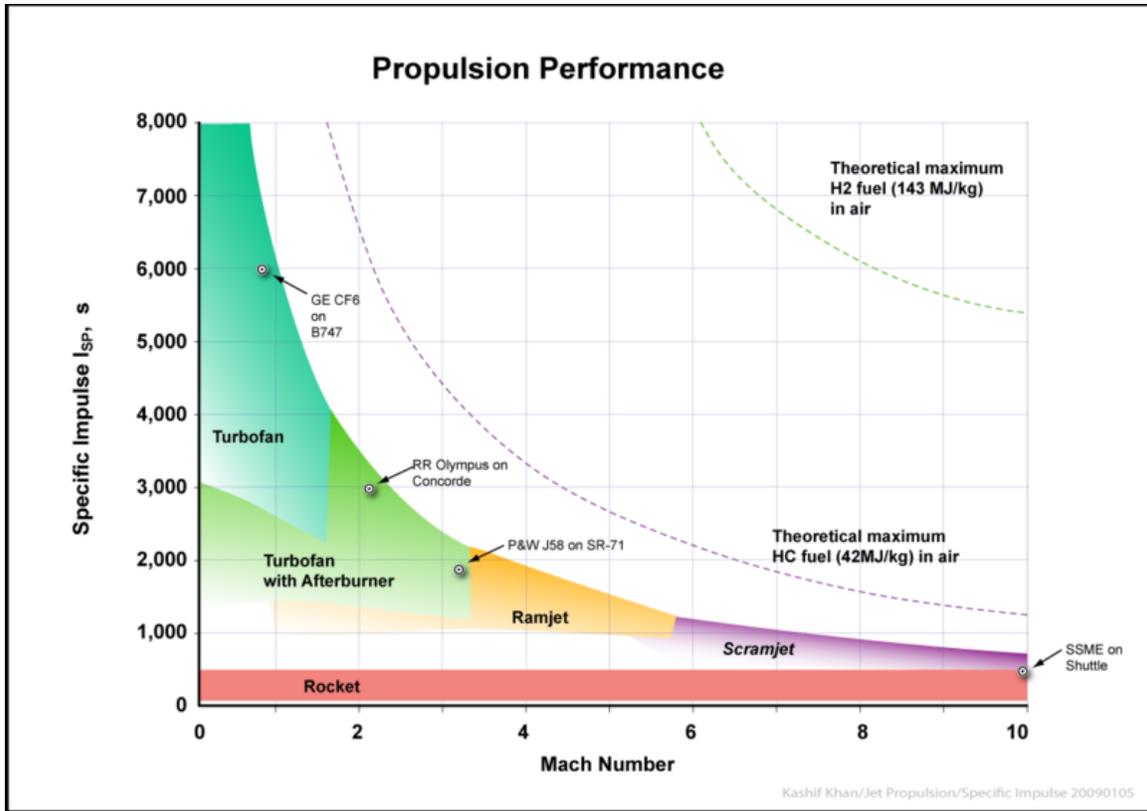
And for a rocket:

$$\eta_p = \frac{2\frac{v}{c}}{1 + \left(\frac{v}{c}\right)^2}$$

### **Cycle efficiency**

In addition to propulsive efficiency, another factor is cycle efficiency; essentially a jet engine is typically a form of heat engine. Heat engine efficiency is determined by the ratio of temperatures that are reached in the engine, in this case at the entry to the propulsive nozzle, to the temperature that they are exhausted at, which in turn is limited by the overall pressure ratio that can be achieved.

Cycle efficiency is highest in rocket engines (~60+%), as they can achieve extremely high combustion temperatures and can have very large, energy efficient nozzles. Cycle efficiency in turbojet and similar is nearer to 30%, the practical combustion temperatures and nozzle efficiencies are much lower.



Specific impulse as a function of speed for different jet types with kerosene fuel (hydrogen  $I_{sp}$  would be about twice as high). Although efficiency plummets with speed, greater distances are covered, it turns out that efficiency per unit distance (per km or mile) is roughly independent of speed for jet engines as a group; however airframes become inefficient at supersonic speeds

### Fuel/propellant consumption

A closely related (but different) concept to energy efficiency is the rate of consumption of propellant mass. Propellant consumption in jet engines is measured by **Specific Fuel Consumption**, **Specific impulse** or **Effective exhaust velocity**. They all measure the same thing. Specific impulse and effective exhaust velocity are strictly proportional, whereas specific fuel consumption is inversely proportional to the others.

For airbreathing engines such as turbojets energy efficiency and propellant (fuel) efficiency are much the same thing, since the propellant is a fuel and the source of energy. In rocketry, the propellant is also the exhaust, and this means that a high energy propellant gives better propellant efficiency but can in some cases actually can give *lower* energy efficiency.

Engine type	Scenario	SFC in lb/(lbf·h)	SFC in g/(kN·s)	Specific impulse (s)	Effective exhaust velocity (m/s)
NK-33 rocket engine	Vacuum	10.9	309	330	3,240
SSME rocket engine	Space shuttle vacuum	7.95	225	453	4,423
Ramjet	Mach 1	4.5	127	800	7,877
J-58 turbojet	SR-71 at Mach 3.2 (Wet)	1.9	53.8	1,900	18,587
Rolls-Royce/Snecma Olympus 593	Concorde Mach 2 cruise (Dry)	1.195	33.8	3,012	29,553
CF6-80C2B1F turbofan	Boeing 747-400 cruise	0.605	17.1	5,950	58,400
General Electric CF6 turbofan	Sea level	0.307	8.696	11,700	115,000

It can be seen that the subsonic turbofans such as General Electric's CF6 uses a lot less fuel to generate thrust for a second than Concorde's turbojet, the 593. However, since energy is force times distance and the distance per second is greater for Concorde, the actual power generated by the engine for the same amount of fuel is higher for Concorde at Mach 2 cruise than the CF6- Concorde's engines are more efficient for *thrust per mile*, indeed, the most efficient ever.

### Thrust-to-weight ratio

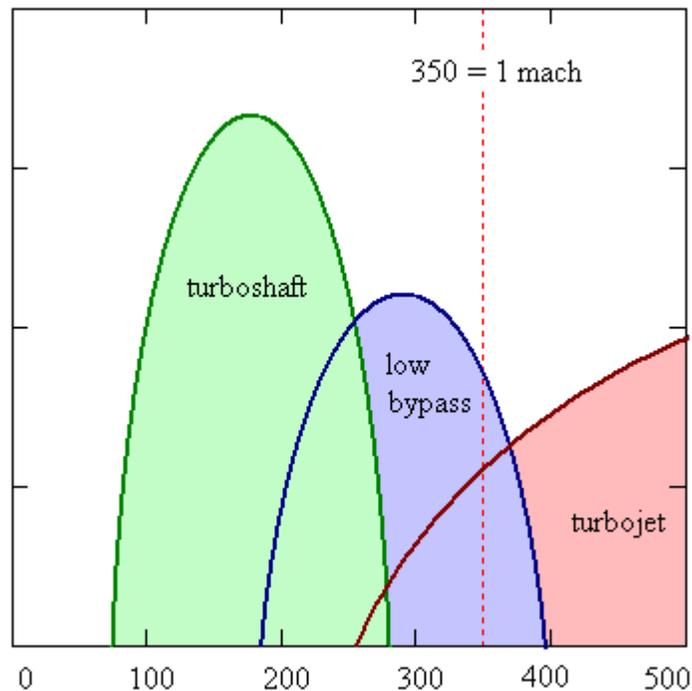
The thrust to weight ratio of jet engines of similar principles varies somewhat with scale, but mostly is a function of engine construction technology. Clearly for a given engine, the lighter the engine, the better the thrust to weight is, the less fuel is used to compensate for drag due to the lift needed to carry the engine weight, or to accelerate the mass of the engine.

As can be seen in the following table, rocket engines generally achieve very much higher thrust to weight ratios than duct engines such as turbojet and turbofan engines. This is primarily because rockets almost universally use dense liquid or solid reaction mass which gives a much smaller volume and hence the pressurisation system that supplies the nozzle is much smaller and lighter for the same performance. Duct engines have to deal with air which is 2-3 orders of magnitude less dense and this gives pressures over much larger areas, and which in turn results in more engineering materials being needed to hold the engine together and for the air compressor.

Jet or Rocket engine	Mass, kg	Jet or rocket thrust, kN	Thrust-to-weight ratio
RD-0410 nuclear rocket engine	2000	35.2	1.8
J-58 (SR-71 Blackbird jet engine)	2722	150	5.2
Concorde's Rolls-Royce/Snecma Olympus 593 turbojet with reheat	3175	169.2	5.4
RD-0750 rocket engine, three-propellant mode	4621	1413	31.2
RD-0146 rocket engine	260	98	38.5
Space Shuttle's SSME rocket engine	3177	2278	73.2
RD-180 rocket engine	5393	4152	78.6
F-1 (Saturn V first stage)	8391	7740.5	94.1
NK-33 rocket engine	1222	1638	136.8

*Rocket thrusts are vacuum thrusts unless otherwise noted*

### Comparison of types



Comparative suitability for (left to right) turboshaft, low bypass and turbojet to fly at 10 km altitude in various speeds. Horizontal axis - speed, m/s. Vertical axis displays engine efficiency.

Propeller engines are useful for comparison. They accelerate a large mass of air but by a relatively small maximum change in speed. This low speed limits the maximum thrust of any propeller driven airplane. However, because they accelerate a large mass of air, propeller engines, such as turboprops, can be very efficient.

On the other hand, turbojets accelerate a much smaller mass of the air and burned fuel, but they emit it at the much higher speeds possible with a de Laval nozzle. This is why they are suitable for supersonic and higher speeds.

Low bypass turbofans have the mixed exhaust of the two air flows, running at different speeds ( $c_1$  and  $c_2$ ). The thrust of such engine is

$$S = m_1 (c_1 - v) + m_2 (c_2 - v)$$

where  $m_1$  and  $m_2$  are the air masses, being blown from the both exhausts. Such engines are effective at lower speeds, than the pure jets, but at higher speeds than the turboshafts and propellers in general. For instance, at the 10 km altitude, turboshafts are most effective at about Mach 0.4 (0.4 times the speed of sound), low bypass turbofans become more effective at about Mach 0.75 and turbojets become more effective than mixed exhaust engines when the speed approaches Mach 2-3.

Rocket engines have extremely high exhaust velocity and thus are best suited for high speeds (hypersonic) and great altitudes. At any given throttle, the thrust and efficiency of a rocket motor improves slightly with increasing altitude (because the back-pressure falls thus increasing net thrust at the nozzle exit plane), whereas with a turbojet (or turbofan) the falling density of the air entering the intake (and the hot gases leaving the nozzle) causes the net thrust to decrease with increasing altitude. Rocket engines are more efficient than even scramjets above roughly Mach 15.

## **Altitude and speed**

With the exception of scramjets, jet engines, deprived of their inlet systems can only accept air at around half the speed of sound. The inlet system's job for transonic and supersonic aircraft is to slow the air and perform some of the compression.

The limit on maximum altitude for engines is set by flammability- at very high altitudes the air becomes too thin to burn, or after compression, too hot. For turbojet engines altitudes of about 40 km appear to be possible, whereas for ramjet engines 55 km may be achievable. Scramjets may theoretically manage 75 km. Rocket engines of course have no upper limit.

At more modest altitudes, flying faster compresses the air in at the front of the engine, and this greatly heats the air. The upper limit is usually thought to be about Mach 5-8, as above about Mach 5.5, the atmospheric nitrogen tends to react due to the high temperatures at the inlet and this consumes significant energy. The exception to this is

scramjets which may be able to achieve about Mach 15 or more, as they avoid slowing the air, and rockets again have no particular speed limit.

## **Noise**

Noise is due to shockwaves that form when the exhaust jet interacts with the external air. The intensity of the noise is proportional to the thrust as well as proportional to the fourth power of the jet velocity. Generally then, the lower speed exhaust jets emitted from engines such as high bypass turbofans are the quietest, whereas the fastest jets are the loudest.

Although some variation in jet speed can often be arranged from a jet engine (such as by throttling back and adjusting the nozzle) it is difficult to vary the jet speed from an engine over a very wide range. Engines for supersonic vehicles such as Concorde, military jets and rockets need to have supersonic exhaust to support their top speeds, making them especially noisy even at low speed.

## Chapter- 3

# First Generation Jet Fighter Aircraft



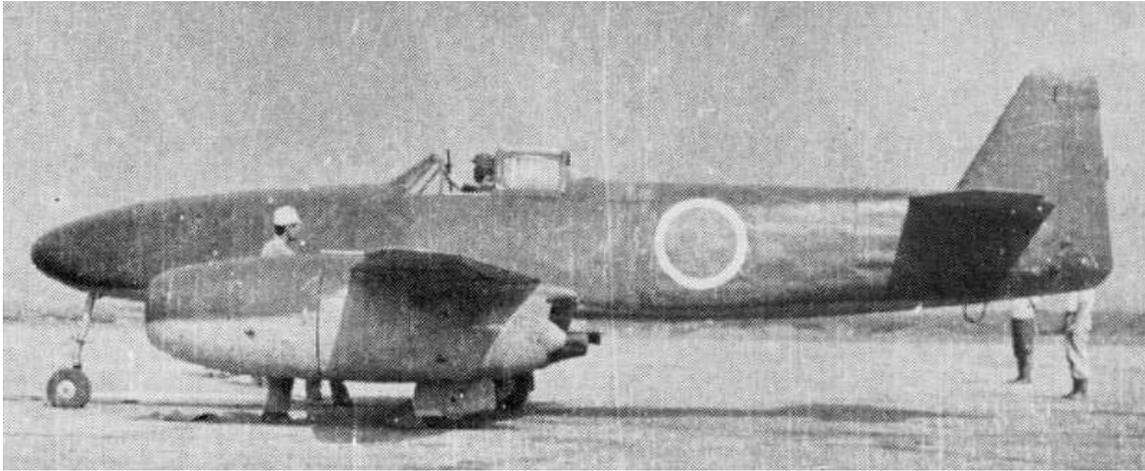
The Me 262, the first jet fighter

Aircraft classified as **first generation jet fighters** are the first attempts at creation of military aircraft using jet engines. A few were developed during the closing days of World War II but saw very limited combat operations. The generation can be split into two broad groups: World War II era fighters such as the Me 262 and mature first generation fighters such as the F-86 used in the Korean War.

The "generations" of fighter aircraft are a relatively modern concept based on claims for "Fifth Generation" fighters. They are rough categories based on similar designs and do not correspond to a rigid definition.

# World War II Era

## Prototypes



The Imperial Japanese Navy's 1945 Nakajima J9Y 'Kikka'.

The initial attempts were straight-winged subsonic planes based heavily on the design concepts that had worked well in piston-powered aircraft. Some of these fighters were tested using piston engines to evaluate the airframes before the jets to power them were available or reliable enough to sustain flight.

The first operational turbojet aircraft, the He 178, was a German design that first flew in 1939. It was used as the basis of the later He 280, a design passed over for the Me 262. A similar British design, the Gloster E.28/39 had provisions for some armament, but the guns were not fitted on either prototype.

The P-59 Airacomet was the first American jet fighter to be put into service but it was widely seen as an inferior design and never saw combat. The piston-engined P-51 Mustang could reach higher top speeds and had a much greater range.

The Japanese had some experimental models, such as the Nakajima J9Y "Kikka", but none saw operational use.

## Aircraft that entered service

The plans for the first operational jet fighter, the Messerschmitt Me 262 "Schwalbe" were drawn up in 1939, and the airplane first flew under jet power in 1942. The Me 262 was not operational until 1944, and its effectiveness was crippled by the deteriorating infrastructure of Nazi Germany. World War II ended before jet fighters were common. The United States and the United Kingdom also had jet fighters operational before the end of the war, but neither saw much use. The British Meteor was used to intercept Germany's V-1 cruise missiles. The American Lockheed P-80 entered service in the

closing phases of the war and was deployed to Europe but arrived too late to see any combat.

The earliest jet fighters did not carry radar or other sophisticated avionics and had similar equipment to the piston-engined counterparts used during the war. Machine guns and cannon were the primary armament, though the Me 262 also used air to air rockets against Allied bomber formations and could carry unguided bombs.

The significant operational aircraft in this group include:

-  Nazi Germany
  - Messerschmitt Me 262
  - Heinkel He 162
-  United Kingdom
  - Gloster Meteor

Other aircraft were built or developed during the war, did not see combat. Many entered general service in the immediate post-war years. Examples include:

-  France
  - Dassault Ouragan
-  United Kingdom
  - de Havilland Vampire
  - Hawker Sea Hawk
  - Supermarine Attacker
-  United States
  - Bell P-59 Airacomet
  - Lockheed P-80 Shooting Star
  - McDonnell FH Phantom
  - Ryan Aeronautical FR Fireball (see below)
-  Soviet Union
  - Mikoyan-Gurevich MiG-9 'Fargo'
  - Yakovlev Yak-15/17 'Feather'

The Russian aircraft were based heavily on British engines (including a reverse-engineered Rolls-Royce Nene engine) and German designs, and were developed after the end of World War II. The French Ouragan was also a design of the late 1940s rather than a wartime effort.

## Hybrid Propulsion

Early jet engines had poor acceleration, and the FR Fireball was a mixed-propulsion aircraft with a propeller in front and a jet engine in the back designed for use on an aircraft carrier. The Russian Mikoyan-Gurevich I-250 and Sukhoi Su-5 were similar concepts but used a motorjet instead of a turbojet and were not designed for carrier use.

Further experiments after the war with mixed propulsion included the XF2R Dark Shark and the XF-84H Thunderscreech, one of the loudest aircraft ever flown. The Thunderscreech, however, was a contemporary of the clearly second generation F-104 Starfighter, and was a much later design. None of these hybrid-propulsion planes saw combat or major use, though the Fireball was used operationally for two years.

## Korean War



A MiG-15 in Polish markings

After World War II, some additional aircraft were built using refinements of the ideas used in the first attempts. Some of these included a swept wing and some could break the sound barrier in a dive, but almost all of them lacked the thrust to do so in level flight. Radar was used in dedicated interceptors and night fighters but early models required a dedicated radar operator. These aircraft are mostly associated with the Korean War. Some interceptor designs, such as the F-94 used rockets such as the Mk 4/Mk 40 Folding-Fin Aerial Rocket as their primary weapon instead of guns.

### Interceptors/Night fighters

-  Canada
  - Avro CF-100 Canuck
-  United Kingdom
  - de Havilland Venom / de Havilland Sea Venom
-  Soviet Union
  - Yakovlev Yak-25 'Flashlight'
-  United States
  - Northrop F-89 Scorpion
  - Lockheed F-94 Starfire
  - Douglas F3D Skyknight

## Fighter-bombers

-  France
  - Dassault Mystère I/II/III
  - Dassault Mystère IV
-  Sweden
  - Saab 21R
-  United States
  - Republic F-84 Thunderjet
  - Republic F-84F Thunderstreak

## Air superiority fighters

Many of these also had fighter-bomber variants.

-  Australia /  United States
  - CAC Sabre
-  Canada /  United States
  - Canadair Sabre
-  People's Republic of China
  - Shenyang J-5
-  Sweden
  - Saab Tunnan
  - Saab Lanser
-  United Kingdom
  - de Havilland Vampire
  - de Havilland Venom
-  United States
  - North American F-86 Sabre
  - McDonnell F2H Banshee
  - McDonnell F3H Demon
-  Soviet Union
  - Lavochkin La-15 'Fantail'
  - Mikoyan-Gurevich MiG-15 'Fagot'
  - Mikoyan-Gurevich MiG-17 'Fresco'
  - Yakovlev Yak-23 'Flora'

## Cancelled fighters

-  Argentina
  - I.Ae. 27 Pulqui I
  - FMA IAe 33 Pulqui II
-  France
  - Aérocentre NC 1080
-  Italy
  - Aerfer Ariete / Aerfer Leone / Aerfer Sagittario 2

-  Japan
  - Nakajima J9Y
  - Nakajima Ki-201
-  Nazi Germany
  - Focke-Wulf Ta-183
  - Heinkel He 280
  - Horten Ho 229
  - Messerschmitt Me P.1101
  - Messerschmitt Me P.1106
-  Switzerland
  - FFA N-20
-  United Kingdom
  - Gloster E.1/44
  - Gloster E.28/39
  - Saunders-Roe SR.A/1
-  Soviet Union
  - Alekseyev I-211 / Alekseyev I-215
  - Lavochkin La-150
  - Lavochkin La-168
  - Sukhoi Su-9 / Sukhoi Su-11
  - Sukhoi Su-15 (1949)
  - Sukhoi Su-17 (1949)
  - Yakovlev Yak-19
  - Yakovlev Yak-25 (1947) / Yakovlev Yak-30 (1948)
  - Yakovlev Yak-50 (1949)

A notable post-war fighter that was never used operationally was the FMA IAe 33 Pulqui II, a prototype fighter built in Argentina. The Pulqui II was designed by a team which included former German engineers lead by Kurt Tank and was based on initial designs for the Focke-Wulf Ta 183, the proposed successor to the Me 262. The Pulqui II itself was a successor to the I.Ae. 27 Pulqui I, a prototype jet fighter developed in Argentina by Emile Dewoitine in the late 1940s and the first of its type to fly in South America.

## The End of the First Generation

By the 1950s, the next major group of fighter aircraft were planes that used air to air missiles as their primary armament and could routinely exceed the speed of sound in level flight. First generation fighters were limited to engagements in visual range, and the expected performance of new missiles, like the AIM-7 Sparrow, with semi-active radar homing, forced changes in aircraft design.

There is not a bright, clearly-defined line between first- and second-generation fighters, and some early second-generation fighters, such as the F-8 Crusader, still had guns as their primary armament. Infrared-guided or so-called "heat-seeking" missiles such as the AIM-9 Sidewinder and early beam-riding missiles like the Kaliningrad K-5 were used on late first-generation aircraft.

# **Experimental First Generation Jet Fighters**

## **Flying Ram**

The Northrop XP-79 flying wing was an unusual aircraft that only flew once, resulting in the death of the pilot. It was originally designed as a rocket powered aircraft but later used turbojets. While the plane carried machine guns, the wings were also reinforced to allow the plane to survive ramming attacks.

## **Parasite Fighters**

Early jet fighters did not have the range to escort bombers all the way to the target and back, the same problem that had plagued the B-17 and its contemporaries during the bombing campaigns of World War II. Having the bomber carry a fighter as well as turrets to defend itself led to some unusual designs, none of which were implemented.

- XF-85 Goblin, carried in the bomb bay.
- FICON project using the F-84

## **Aircraft still in use**

A few of the aircraft from this generation are still in use by the air forces of smaller nations, typically in the ground attack role and not as fighters. A notable mention of this is the Shenyang J-5, a Chinese aircraft developed from the MiG-17, which is used by North Korea in the ground attack role and in other countries as a trainer.

## Chapter- 4

# Example of First Generation Jet Fighter Aircraft

## Messerschmitt Me 262

### Me 262 *Schwalbe*



Messerschmitt Me 262A

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<b>Role</b>	Fighter
<b>Manufacturer</b>	Messerschmitt
<b>First flight</b>	18 April 1941 with piston engine 18 July 1942 with jet engines
<b>Introduction</b>	April 1944
<b>Retired</b>	1945, <i>Luftwaffe</i> 1951, Czechoslovakia
<b>Primary users</b>	<i>Luftwaffe</i> Czechoslovak Air Force (S-92)
<b>Number built</b>	1,430

The **Messerschmitt Me 262 *Schwalbe*** ("Swallow") was the world's first operational jet-powered fighter aircraft. Design work started before World War II began, but engine problems prevented the aircraft from attaining operational status until mid-1944.

Compared with Allied fighters of its day, including the jet-powered Gloster Meteor, it was much faster and better armed.

In combat, when properly flown, it proved difficult to counter due to its speed. Me 262 pilots claimed a total of 509 Allied kills (although higher claims are sometimes made against the loss of about 100 Me 262s. The design was pressed into a variety of roles, including light bomber, reconnaissance and even experimental night fighter versions.

The Me 262 is considered to have been the most advanced German aviation design in operational use during World War II. The Allies countered its potential effectiveness in the air by relentlessly attacking the aircraft on the ground, or while they were taking off or landing. Maintenance during the deteriorating war situation and a lack of fuel also reduced the effectiveness of the aircraft as a fighting force. In the end, the Me 262 had a negligible impact on the course of the war due to its late introduction and the small numbers that were deployed in operational service.

The Me 262 influenced the designs of post-war aircraft such as the North American F-86 and Boeing B-47.

## Design and development



Hans Guido Mutke's Me 262A on display at the Deutsches Museum

The Me 262 was already being developed as *Projekt P.1065* before the start of World War II. Plans were first drawn up in April 1939, and the original design was very similar to the plane that eventually entered service. The progression of the original design into service was delayed greatly by technical issues involving the new jet engines. Funding for the jet program was also initially lacking as many high-ranking officials thought the war could easily be won with conventional aircraft. Among those was Hermann Göring, head of the *Luftwaffe*, who cut back the engine development program to just 35 engineers in February 1940, Willy Messerschmitt, who desired to maintain mass production of the

Bf 109 and the projected Me 209, and Major General Adolf Galland, who supported Messerschmitt through the early development years, flying the Me 262 himself on 22 April 1943. By that time problems with engine development had slowed production of the aircraft considerably.

In mid-1943 Adolf Hitler envisioned the Me 262 as an offensive ground-attack/bomber rather than a defensive interceptor. The configuration of a high speed, light payload *Schnellbomber* ("Fast Bomber") was intended to penetrate enemy air superiority during the expected Allied invasion of France. His edict resulted in the development of (and concentration on) the *Sturmvogel* variant. It is debatable to what extent Hitler's interference extended the delay in bringing the *Schwalbe* into operation. Albert Speer, then Minister of Armaments and War Production, claimed in his memoirs Hitler originally blocked mass-production of the Me 262 before agreeing in early 1944. He rejected arguments the aircraft would be more effective as a fighter against Allied bombers then destroying large parts of Germany and wanted it as a bomber for revenge attacks. According to Speer, Hitler felt its superior speed compared to other fighters of the era meant it could not be attacked and so preferred it for high altitude straight flying.

Although it is often stated the Me 262 is a "swept wing" design, the production Me 262 had a leading edge sweep of only 18.5°, too slight to achieve any significant advantage in increasing the critical Mach number. Sweep was added after the initial design of the aircraft, when the engines proved to be heavier than originally expected, primarily to position the center of lift properly relative to the centre of mass. 1 March 1940, instead of moving the wing forward on its mount, the outer wing was repositioned slightly aft. The trailing edge of the mid-section of the wing remained unswept. Based on data from the AVA Göttingen and windtunnel results, the middle section's leading edge was later swept to the same angle as the outer panels.

The first test flights began on 18 April 1941, with the Me 262 V1 example, bearing its *Stammkennzeichen* radio code letters of PC+UA, but since its intended BMW 003 turbojets were not ready for fitting, a conventional Junkers Jumo 210 engine was mounted in the V1 prototype's nose, driving a propeller, to test the Me 262 V1 airframe. When the BMW 003 engines were finally installed, the Jumo was retained for safety, which proved wise as both 003s failed during the first flight and the pilot had to land using the nose-mounted engine alone.



Messerschmitt Me 262 *Schwalbe* – this captured airframe, Wrknr. 111711, *FE-0107*, 711, crashed ~two miles S of Xenia, Ohio, 20 August 1946, test pilot Walter J. McAuley, Jr., of the Flight Performance Section, Flight Test Division, Wright Field, Ohio, successfully parachuting to safety. This brand new airframe had been surrendered on 31 March 1945 by Messerschmitt test pilot Hans Fay who defected during a functional check flight rather than fly it to an operational unit, landing at Rhein-Main, Frankfurt, the first Me 262 to fall into Allied hands.

The V3 third prototype airframe, with the code PC+UC, became a true "jet" when it flew on 18 July 1942 in Leipheim near Günzburg, Germany, piloted by Fritz Wendel. This was almost nine months ahead of the British Gloster Meteor's first flight on 5 March 1943. The conventional gear, forcing a tail-down attitude on the ground, of the Me 262 V3 caused its jet exhaust to deflect off the runway, with the wing's turbulence negating the effects of the elevators in the tail-down attitude, and the first attempt was cut short. On the second attempt, Wendel solved the problem by tapping the aircraft's brakes at takeoff speed, lifting the horizontal tail above and out of the wing's turbulence.

The aircraft was originally designed with a tailwheel undercarriage and the first four prototypes (Me 262 V1-V4) were built with this configuration, but it was discovered on an early test run that the engines and wings "blanked" the stabilizers, giving almost no control on the ground, as well as serious runway surface damage from the hot jet exhaust. Changing to a tricycle undercarriage arrangement, initially a fixed undercarriage on the "V5" fifth prototype, then fully retractable on the sixth (V6, with *Stammkennzeichen* code VI+AA) and succeeding aircraft, corrected this problem.

The BMW 003 jet engines, which were proving unreliable, were replaced by the newly available Junkers Jumo 004. Test flights continued over the next year, but the engines continued to be unreliable. Airframe modifications were complete by 1942, but hampered by the lack of engines, serial production did not begin until 1944, but deliveries were low, with 28 Me 262s in June, 59 in July, but only 20 in August. This delay in engine availability was in part due to the shortage of strategic materials, especially metals and alloys able to handle the extreme temperatures produced by the jet engine. Even when the engines were completed, they had an expected operational lifetime of approximately 50 continuous flight hours; most 004s lasted just 12 hours, even with adequate maintenance. A pilot familiar with the Me 262 and its engines could expect approximately 20–25 hours of life from the 004s. Changing a 004 engine was intended to require three hours, but this typically took eight to nine due to poorly made parts and inadequate training of ground crews.

Turbojet engines have less thrust at low speed than propellers, and as a result, low-speed acceleration is relatively poor. It was more noticeable for the Me 262 as early jet engines (before the invention of afterburners) responded slowly to throttle changes. The introduction of a primitive autothrottle late in the war only helped slightly. Conversely, the higher power of jet engines at higher speeds meant the Me 262 enjoyed a much higher rate of climb. Used tactically, this gave the jet fighter an even greater speed advantage in climb rate than level flight at top speed.

With one engine out, the Me 262 still flew well, with speeds of 450–500 km/h (280–310 mph), but pilots were warned never to fly slower than 300 km/h (190 mph) on one engine, as the asymmetrical thrust would cause serious problems.

Operationally, the Me 262 had an endurance of 60 to 90 minutes.

## Operational history



Me 262 A-1a

In April 1944, *Erprobungskommando 262* was formed at Lechfeld just south of Augsburg, Bavaria as a test unit (*Jäger Erprobungskommando Thierfelder*) to introduce the 262 into service and train a core of pilots to fly it. On 26 July 1944, *Leutnant* Alfred Schreiber with the 262 A-1a W.Nr. 130 017 damaged a Mosquito reconnaissance aircraft of No. 540 Squadron RAF PR Squadron, which was allegedly lost in a crash landing upon landing at an air base in Italy. Other sources state the aircraft was damaged during evasive manoeuvres and escaped. It was the first victory for a turbojet fighter aircraft in aviation history. Major Walter Nowotny was assigned as commander after the death of Werner Thierfelder in July 1944, and the unit redesignated *Kommando Nowotny*. Essentially a trials and development unit, it holds the distinction of having mounted the world's first jet fighter operations. Trials continued slowly, with initial operational missions against the Allies in August 1944 allegedly downing 19 Allied aircraft for six Me 262s lost, although these claims have never been verified by cross-checking with USAAF records. The RAF Museum holds no intelligence reports of RAF aircraft engaging in combat with Me 262s in August, although there is a report of an unarmed encounter between an Me 262 and a Mosquito. Despite orders to stay grounded, Nowotny chose to fly a mission against an enemy bomber formation flying some 30,000 feet above, on 8 November 1944. He claimed two P-51Ds destroyed before suffering engine failure at high altitude. Then, while diving and trying desperately to restart his engines, he was attacked and forced to bail out by other Mustangs. Some US historians proposed

that Nowotny's victor was P-51D pilot Lt Robert W Stevens of the 364thFG According to other sources, he was shot down and killed by First Lieutenant Edward "Buddy" Haydon of the 357th Fighter Group, USAAF and Captain Ernest "Feeb" Fiebelkorn of the 20th Fighter Group, USAAF.

Actually, the exact circumstances surrounding the end of Walter Nowotny remain uncertain to this day. It is also possible that he was hit by "friendly" flak. The *Kommando* was then withdrawn for further training and a revision of combat tactics to optimise the 262's strengths.



Bundesarchiv, Bild 141-2497  
Foto: o. Ang. | 1944/1945 ca.

#### Me 262 A, circa 1944/45

By January 1945, *Jagdgeschwader 7* (JG 7) had been formed as a pure jet fighter wing, although it would be several weeks before it was operational. In the meantime, a bomber unit – *I Gruppe, Kampfgeschwader 54* (KG 54) – had re-equipped with the Me 262 A-2a fighter-bomber for use in a ground-attack role. However, the unit lost 12 jets in action in two weeks for minimal returns.

*Jagdverband 44* (JV 44) was another Me 262 fighter unit, of *Staffel* (squadron) size given the low numbers of available personnel, formed in February 1945 by Lieutenant General Adolf Galland, who had recently been dismissed as Inspector of Fighters. Galland was able to draw into the unit many of the most experienced and decorated *Luftwaffe* fighter pilots from other units grounded by lack of fuel.

During March, Me 262 fighter units were able, for the first time, to mount large scale attacks on Allied bomber formations. On 18 March 1945, 37 Me 262s of JG 7 intercepted a force of 1,221 bombers and 632 escorting fighters. They shot down 12 bombers and one fighter for the loss of three Me 262s. Although a 4:1 ratio was exactly what the *Luftwaffe* would have needed to make an impact on the war, the absolute scale of their success was minor, as it represented only one per cent of the attacking force. In 1943 and early 1944, the USAAF had been able to keep up offensive operations despite loss ratios of 5% and more, and the few available Me 262s could not inflict sufficient losses to hamper their operations.



Side view of a Me 262B-1a/U1 night fighter, WrkNr. 110306, with radar antenna on the nose and second seat for a radar operator. This airframe was surrendered to the RAF at Schleswig in May 1945.

Several two-seat trainer variants of the Me 262, the Me 262 B-1a, had been adapted through the *Umrüst-Bausatz 1* factory refit package as night fighters, complete with on-board FuG 218 *Neptun* high-VHF band radar, using *Hirschgeweih* ("stag's antlers") antennae with a set of shorter dipole elements than the *Lichtenstein SN-2* had used, as the B-1a/U1 version. Serving with 10 *Staffel*, *Nachtjagdgeschwader 11*, near Berlin, these few aircraft (alongside several single-seat examples) accounted for most of the 13 Mosquitoes lost over Berlin in the first three months of 1945. However, actual intercepts were generally or entirely made using *Wilde Sau* methods, rather than AI radar-controlled interception. As the two-seat trainer was largely unavailable, many pilots had to make their first flight in a jet in a single-seater without an instructor.

Despite its deficiencies, the Me 262 clearly signaled the beginning of the end of piston-engined aircraft as effective fighting machines. Once airborne, it could accelerate to speeds well over 800 km/h (500 mph), over 150 km/h (90 mph) faster than any Allied fighter operational in the European Theater of Operations.

The Me 262's top ace was probably *Hauptmann* Franz Schall with 17 kills which included six four-engine bombers and 10 P-51 Mustang fighters, although night fighter ace *Oberleutnant* Kurt Welter claimed 25 Mosquitos and two four-engine bombers shot down by night and two further Mosquitos by day flying the Me 262. Most of Welter's claimed night kills were achieved in standard radar-less aircraft, even though Welter had tested a prototype Me 262 fitted with FuG 218 Neptun radar. Another candidate for top ace on the aircraft was *Oberstleutnant* Heinrich Bär, who claimed 16 enemy aircraft while flying the Me 262.

### **Anti-bomber tactics**

The Me 262 was so fast that new tactics had to be devised to attack American bombers. In the head-on attack, the closing speed, of about 350 yd per second (320 m), was too high for accurate shooting. Even from astern, the closing speed was too great for the short-ranged 30 mm cannon to be used to maximum effect. Therefore, a roller-coaster attack was devised. The 262s approached from astern and about 6,000 ft higher (1,800 m) than the bombers. From about 3 mi behind (4.8 km), they went into a shallow dive that took them through the escort fighters with little risk of interception. When they were about 1 mi astern (1.6 km) and 1,500 feet (460 m) below the bombers, they pulled up sharply to reduce their excess speed. On levelling off, they were 1,000 yd astern (0.91 km) and overtaking the bombers at about 100 mph (160 km/h), well placed to attack them. Since 30 mm cannon were not accurate above 650 yd (590 m), and since it was necessary to break off at 200 yd (180 m) to avoid colliding with the target, Me 262 pilots would normally commence firing at 550 yd (500 m). Allied bomber gunners found their electric gun turrets had problems tracking the jets. Target acquisition was difficult because the jets closed into firing range quickly and remained in firing position only briefly, using their standard attack profile which proved to be more effective.



Me 262 with R4M under wing rockets on display at the Technikumuseum Speyer, Germany

Capt. Eric Brown, CBE, DSC, AFC, RN, Chief Naval Test Pilot and C.O. Captured Enemy Aircraft Flight, that tested the Me 262 in RAE Farnborough, noted: "This was a Blitzkrieg aircraft. You whack in at your bomber. It was never meant to be a dogfighter, it was meant to be a destroyer of bombers... The great problem with it was it did not have dive brakes. For example, if you want to fight and destroy a B-17, you come in on a dive. The 30mm cannon were not so accurate above 650 yards. So you normally came in at 600 yards and would open fire on your B-17. And your closing speed was still high and since you had to break away at 200 yards to avoid a collision, you only had two seconds firing time. Now, in two seconds, you can't sight. You can fire randomly and hope for the best. If you want to sight and fire, you need to double that time to four seconds. And with dive brakes, you could have done that."

Eventually, new combat tactics were developed to counter the Allied bombers' defences. Me 262s, equipped with R4M rockets, would approach from the side of a bomber formation, where their silhouettes were widest, and while still out of range of the 12.7 mm (.50 in) guns, fire a salvo of rockets. The high explosive warhead of only one or two of these rockets was capable of downing even the famously rugged B-17; a strike on an enemy aircraft meant its total annihilation. Although this tactic was effective, it came too late to have a real effect on the war. This method of attacking bombers became the

standard until the invention and mass deployment of guided missiles. Some nicknamed this tactic the "*Luftwaffe's* Wolf Pack", as the fighters would often make runs in groups of two or three, fire their rockets, then return to base.

On 1 September 1944, USAAF General Carl Spaatz expressed the fear that if greater numbers of German jets appeared, they could inflict losses heavy enough to force cancellation of the Allied daylight bombing offensive.

### **Counter-jet tactics**

The Me 262 was difficult for its opponents to counter, once in the air, because of its high speed and rate of climb which made it extremely hard to intercept. As with all other early jets, the Me 262's engines did not provide a lot of thrust at low air speeds (a key criterion for good turn performance), and throttle response was slow. Another disadvantage shared by all early jet engines was the relatively high risk of flameout if the throttle was used too aggressively (such as was common in a dogfight). Pilots were therefore instructed to operate the throttle gently and avoid quick changes in setting. Later in the war, an automatic throttle regulator was introduced to try to solve this, but it only partly alleviated the problem. On the plus side, thrust at high speed was much greater than on propeller-driven aircraft.

Furthermore the Me 262 had, by contemporary standards, quite a high wing loading (60.2 lbs/ft<sup>2</sup>, 294.0 kg/m<sup>2</sup>) and its turn radius at low speeds was therefore correspondingly wide. This coupled with the slow throttle response and high chance of a flameout, resulted in Me 262 pilots being told to avoid low speed dogfights with the Allied piston engine fighters. The high speed of the Me 262 also presented problems when engaging enemy aircraft, the high speed convergence allowing Me 262 pilots little time to line up their targets or acquire the appropriate amount of deflection. This is a problem which faces any aircraft which is approaching another one from behind at much higher speed, as the slower going aircraft in front will always be able to pull a tighter turn, forcing the faster aircraft to overshoot. This was a problem the Me 262 faced a lot, as its cruising speed alone was up to 200 km/h (120 mph) faster than that of any piston-engine fighter of the period. Oberst Johannes Steinhoff experienced this problem when he encountered a dozen Russian fighters early in 1945, the much higher speed of his Me 262 making it extremely difficult for him to get his guns on the small Russian fighters. He recalled:

“I passed one that looked as if it was hanging motionless in the air (I am too fast!). The one above me went into a steep right-hand turn, his pale blue underside standing out against the purple sky. Another banked right in front of the Me's nose. Violent jolt as I flew through his airscrew eddies. Maybe a wing's length away. That one in the gentle left-hand curve! Swing her round. I was coming from underneath, eye glued to the sight (pull her tighter!). A throbbing in the wings as my cannon pounded briefly. Missed him. Way behind his tail. It was exasperating. I would never be able to shoot one down like this. They were like a sack of fleas. A prick of doubt: is this really such a good fighter?

Could one in fact, successfully attack a group of erratically banking fighters with the Me 262?"

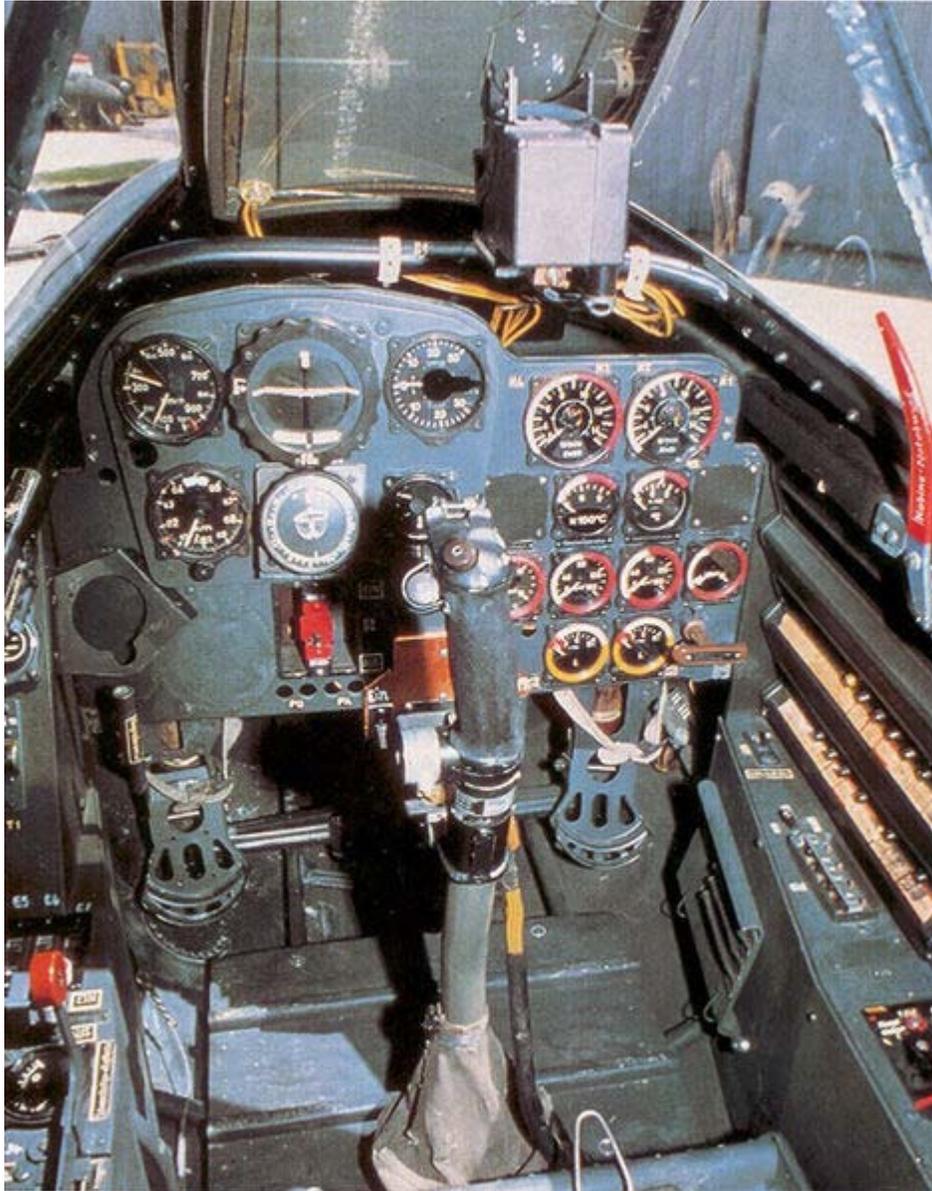
*Luftwaffe* pilots did however eventually learn how to handle the Me 262's higher speed, and the Me 262 soon proved a formidable air superiority fighter, with pilots such as Franz Schall managing to shoot down 12 enemy fighters in the Me 262, 10 of them being American P-51 Mustangs. Other notable Me 262 aces included Georg-Peter Eder, also with 12 enemy fighters to his credit (including 9 P-51s), Walther Dahl with 11 (including three La-7s and six P-51s) and Heinz-Helmut Baudach with 6 (including 1 Spitfire and 2 P-51s) amongst many others.

Despite its high wing loading and lack of low speed thrust, pilots soon learned that the Me 262 was quite maneuverable, especially if attention was drawn to its effective maneuvering speeds. The controls were light and effective right up to the maximum permissible speed and perfectly harmonized. The addition of full span leading edge slats helped increase the overall lift produced by the wing by as much as 25 to 35% in tight turns or at low speeds, greatly improving the aircraft's turn performance as well as its landing and take off characteristics. (The slats lowered the stalling speed of the aircraft to a respectable 160 to 170 km/h depending on load out.) And as many pilots soon found out, the Me 262's clean design also meant that it, like all jets, held its speed in tight turns much better than conventional propeller driven fighters, which was a great potential advantage in a dogfight as it meant better energy retention in maneuvers. *Luftwaffe* test pilot and flight instructor Hans Fey stated, "The 262 will turn much better at high than at slow speeds, and due to its clean design, will keep its speed in tight turns much longer than conventional type aircraft."

Too fast to catch for the escorting Allied fighters, the Me 262s were almost impossible to head off. As a result, Me 262 pilots were relatively safe from the Allied fighters, as long as they did not allow themselves to get "suckered" into low speed turning contests and saved their maneuvering for higher speeds. Combating the Allied fighters could be effectively done the same way as the US Navy fighters fought the more nimble, but slower, Japanese fighters in the Pacific.

Allied pilots soon found the only reliable way of dealing with the jets, as with the even faster Me 163 *Komet* rocket fighters, was to attack them on the ground and during takeoff or landing. *Luftwaffe* airfields identified as jet bases were frequently bombed by medium bombers, and Allied fighters patrolled over the fields to attack jets trying to land. The *Luftwaffe* countered by installing *flak* alleys along the approach lines in order to protect the Me 262s from the ground and providing top cover with the most advanced *Luftwaffe* single engined fighters, the Focke-Wulf Fw 190D *Langnasen-Dora*, and the just-available in 1945 Focke-Wulf Ta 152H fighters, during takeoff and landing. Nevertheless, in March–April 1945, Allied fighter patrol patterns over Me 262 airfields resulted in numerous losses of jets and serious attrition of the force.

## High speed research



Me 262 interior

Willy Messerschmitt regarded the Me 262 as only an interim type when it went into production.

Swept wings had been proposed as early as 1935 by Adolf Busemann, and Messerschmitt had researched the topic from 1940. In April 1941, he proposed fitting a 35° swept wing (*Pfeilflügel II*, literally "arrow wing II") to the Me 262, the same wing sweep angle that would later be used on both the American F-86 Sabre and Soviet MiG-15 fighter jets. Though this was not implemented, he continued with the projected HG II and HG III

(*Hochgeschwindigkeit*, "high speed") derivatives in 1944, which were designed with a 35° and 45° wing sweep, respectively.

Interest in high-speed flight, which led him to initiate work on swept wings starting in 1940, is evident from the advanced developments Messerschmitt had on his drawing board in 1944. While the Me 262 HG I actually flight tested in 1944 had only small changes compared to combat aircraft, most notably a low-profile canopy (tried as the *Rennkabine* (literally "racing cabin") on the Me 262 V9 prototype for a short time) to reduce drag, the HG II and HG III designs were far more radical. The projected HG II combined the low-drag canopy with a 35° wing sweep and a butterfly tail. The HG III had a conventional tail, but a 45° wing sweep and turbines embedded in the wing roots.

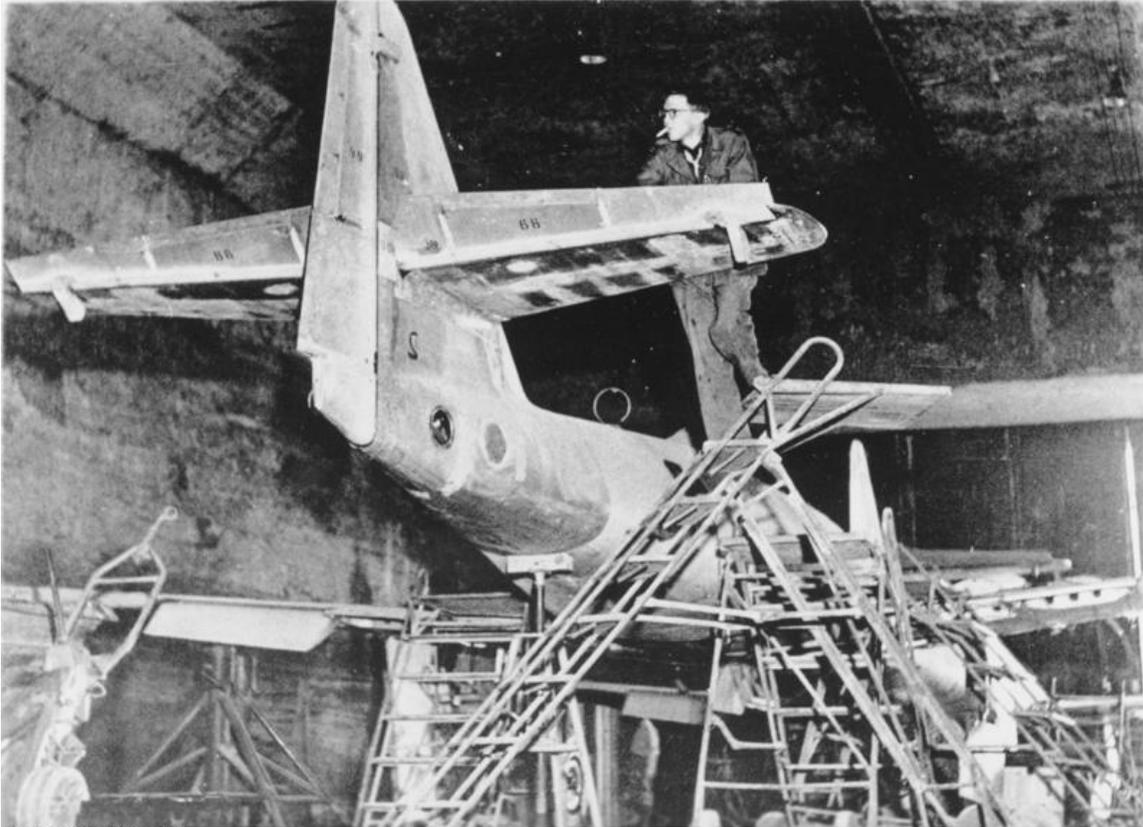
Messerschmitt also conducted a series of flight tests with the series production Me 262. In dive tests, it was determined that the Me 262 went out of control in a dive at Mach 0.86, and that higher Mach numbers would lead to a nose-down trim that could not be countered by the pilot. The resulting steepening of the dive would lead to even higher speeds and disintegration of the airframe due to excessive negative g loads.

The HG series of Me 262 derivatives was estimated to be capable of reaching transonic Mach numbers in level flight, with the top speed of the HG III being projected as Mach 0.96 at 6,000 m (19,690 ft) altitude. Despite the necessity to gain experience in high-speed flight for the HG II and III designs, Messerschmitt undertook no attempts to exceed the Mach 0.86 limit for the Me 262.

After the war, the Royal Aircraft Establishment, at that time one of the leading institutions in high-speed research, re-tested the Me 262 to help with British attempts at exceeding Mach 1. The RAE achieved speeds of up to Mach 0.84 and confirmed the results from the Messerschmitt dive tests. Similar tests were run by the Soviets. No attempts were made to exceed the Mach limit established by Messerschmitt.

After Willy Messerschmitt's death, the former Me 262 pilot Hans Guido Mutke claimed to be the first person to exceed Mach 1, on 9 April 1945 in a Me 262 in a "straight-down" 90° dive. This claim is disputed because it is only based on Mutke's memory of the incident, which recalls effects other Me 262 pilots observed below the speed of sound at high indicated airspeed, but with no altitude reading required to determine the actual speed. Furthermore, the pitot tube used to measure airspeed in aircraft can give falsely elevated readings as the pressure builds up inside the tube at high speeds. Finally, the Me 262 wing had only a slight sweep incorporated for trim (center of gravity) reasons and likely would have suffered structural failure due to divergence at high transonic speeds. One airframe (Me 262 HG1 V9, Werknummer 130 004, with *Stammkennzeichen* of VI+AD) was prepared with the low-profile *Rennkabine* racing canopy and may have achieved an unofficial record speed for a turbojet-powered aircraft of 975 km/h (606 mph), altitude unspecified.

## **Production**



Bundesarchiv, Bild 141-2738  
Foto: o. Ang. | 1945

### Underground manufacture of Me 262s

While Germany was bombed intensively, production of the Me 262 was dispersed into low-profile production facilities, sometimes little more than clearings in the forests of Germany and occupied nations. Through the end of February to the end of March 1945, approximately 60 Me 262s were destroyed in attacks on Obertraubling and 30 at Leipheim (the Neuberg jet plant was bombed on 19 March.) Large, heavily protected underground factories were constructed to take up production of the Me 262, safe from bomb attacks, but the war ended before they could be completed. At *B8 Bergkristall-Esche II* at St. Georgen/Gusen, Austria, forced labourers of *Concentration Camp Gusen II* produced fully equipped fuselages for the Me 262 at a monthly rate of 450 units on large assembly lines from early 1945. Wings for the Me 262 were produced in Germany's oldest motorway tunnel at Engelberg to the west of Stuttgart. In the end, slightly over 1,400 Me 262s of all versions were produced. As few as 200 Me 262s made it to combat units due to fuel shortages, pilot shortages, and the lack of airfields that could support the Me 262.

## Postwar history and flyable reproductions



Reproduction of a Messerschmitt Me 262 at the Berlin Air Show 2006

After the end of the war, the Me 262 and other advanced German technologies were quickly swept up by the Americans (as part of the USAAF's Operation Lusty), British, and Soviets. Many Me 262s were found in readily-repairable condition and were confiscated.

During testing, the Me 262 was found to have advantages over the early models of the Gloster Meteor. It was faster, had better cockpit visibility to the sides and rear (mostly due to the canopy frame and the discoloration caused by the plastics used in the Meteor's construction), and was a superior gun platform, as the early Meteors had a tendency to snake at high speed and exhibited "weak" aileron response. The Me 262 did have a shorter combat range than the Meteor.

The USAAF compared the P-80 Shooting Star and Me 262 concluding, "Despite a difference in gross weight of nearly 2,000 lb (900 kg), the Me 262 was superior to the P-80 in acceleration, speed and approximately the same in climb performance. The Me 262 apparently has a higher critical Mach number, from a drag standpoint, than any current Army Air Force fighter." The Army Air Force also tested an example of the Me 262A-1a/U3 (US flight evaluation serial FE-4012), an unarmed photoreconnaissance version, which was fitted with a fighter nose and given an overall smooth finish. It was used for performance comparisons against the P-80. During testing between May and August

1946, the aircraft completed eight flights, lasting four hours and 40 minutes. Testing was discontinued after four engine changes were required during the course of the tests, culminating in two single-engine landings.

These aircraft were extensively studied, aiding development of early U.S. and Soviet jet fighters. The F-86 Sabre, designed by the engineer Edgar Schmued, used the Me 262 airfoil (Messerschmitt Wing A) and a slat design similar to that of the Me 262.

The Czechoslovak aircraft industry continued to produce single-seater (designated **Avia S-92**) and two-seater (designated **Avia CS-92**) variants of the Me 262 after World War II. From August 1946, a total of nine single-seater S-92 and three two-seater CS-92 planes were completed and test flown. They were introduced in 1947 and in 1950 were supplied to the 5th Fighter Squadron, becoming the first jet fighters to serve in the Czechoslovak Air Force. These were kept flying until 1951 when they were replaced in service by more advanced jet fighters of Soviet origin. Both versions are on display at the Prague Aviation museum in Kbely.



Reproduction of a Messerschmitt Me 262 in 2006

In January 2003, the American Me 262 Project completed flight testing to allow for delivery of near-exact reproductions of several versions of the Me 262 including at least two B-1c two-seater variants, one A-1c single seater and two "convertibles" that could be

switched between the A-1c and B-1c configurations. All are powered by General Electric J85 engines and feature additional safety features, such as upgraded brakes and strengthened landing gear. The "c" suffix refers to the new J-85 powerplant and has been informally assigned with the approval of the Messerschmitt Foundation in Germany (the Werk Number of the reproductions picked up where the last wartime produced Me-262 left off – a continuous airframe serial number run with a 50 year production break). Flight testing of the first newly manufactured Me 262 A-1c (single-seat) variant was completed in August 2005. The first of these machines went to a private owner in the southwestern United States, while the second was delivered to the Messerschmitt Foundation at Manching, Germany. This aircraft conducted a private test flight in late April 2006, and made its public debut in May at the ILA 2006. The new Me 262 flew during the public flight demonstrations. Me 262 Werk Number 501241 was delivered to the Collings Foundation as White 1 of JG 7. This aircraft will be offering ride-along flights starting in 2008.

## Chapter- 5

# Second Generation and Third Generation Jet Fighter Aircrafts

## Second generation jet fighter Aircraft

The **second generation jet fighters** existed between the mid-1950s to the early 1960s.



English Electric Lightning

## Development

The development of second-generation fighters were shaped by technological breakthroughs, lessons learned from the aerial battles of the Korean War, and a focus on conducting operations in a nuclear warfare environment. Technological advances in aerodynamics, propulsion and aerospace building materials (primarily aluminum alloys) permitted designers to experiment with aeronautical innovations, such as swept wings,

delta wings, and area-ruled fuselages. Widespread use of after-burning turbojet engines made these the first production aircraft to break the sound barrier, and the ability to sustain supersonic speeds in level flight became a common capability amongst fighters of this generation.



Dassault Mirage III

## Electronics

Fighter designs also took advantage of new electronics technologies that made effective radars small enough to be carried aboard smaller aircraft. Onboard radars permitted detection of enemy aircraft beyond visual range, thereby improving the handoff of targets by longer-ranged ground-based warning and tracking radars. Similarly, advances in guided missile development allowed air-to-air missiles to begin supplementing the gun as the primary offensive weapon for the first time in fighter history. During this period, passive-homing infrared-guided (IR) missiles became commonplace, but early IR missile sensors had poor sensitivity and a very narrow field of view (typically no more than 30°), which limited their effective use to only close-range, tail-chase engagements. Radar-guided (RF) missiles were introduced as well, but early examples proved unreliable. These semi-active radar homing (SARH) missiles could track and intercept an enemy aircraft "painted" by the launching aircraft's onboard radar. Medium- and long-range RF air-to-air missiles promised to open up a new dimension of "beyond-visual-range" (BVR) combat, and much effort was placed in further development of this technology.



MiG-21F interceptor

## Weapons

The prospect of a potential third world war featuring large mechanized armies and nuclear weapon strikes led to a degree of specialization along two design approaches: interceptors (like the English Electric Lightning and Mikoyan-Gurevich MiG-21F) and fighter-bombers (such as the Republic F-105 Thunderchief and the Sukhoi Su-7). Dogfighting, per se, was deemphasized in both cases. The interceptor was an outgrowth of the vision that guided missiles would completely replace guns and combat would take place at beyond visual ranges. As a result, interceptors were designed with a large missile payload and a powerful radar, sacrificing agility in favour of high speed, altitude ceiling and rate of climb. With a primary air defence role, emphasis was placed on the ability to intercept strategic bombers flying at high altitudes. Specialized point-defence interceptors often had limited range and little, if any, ground-attack capabilities. Fighter-bombers could swing between air superiority and ground-attack roles, and were often designed for a high-speed, low-altitude dash to deliver their ordnance. Television- and IR-guided air-to-surface missiles were introduced to augment traditional gravity bombs, and some were also equipped to deliver a nuclear bomb.

## Third generation jet fighter

The **third-generation jet fighters** existed between the early 1960s to the 1970s.



McDonnell Douglas F-4E Phantom II

## Development

The third generation witnessed continued maturation of second-generation innovations, but it is most marked by renewed emphases on manoeuvrability and traditional ground-attack capabilities. Over the course of the 1960s, increasing combat experience with guided missiles demonstrated that combat would devolve into close-in dogfights. Analog avionics began to be introduced, replacing older "steam-gauge" cockpit instrumentation. Enhancements to improve the aerodynamic performance of third-generation fighters included flight control surfaces such as canards, powered slats, and blown flaps. A number of technologies would be tried for Vertical/Short Takeoff and Landing, but thrust vectoring would be successful on the Harrier jump jet.

## Electronics

Growth in air combat capability focused on the introduction of improved air-to-air missiles, radar systems, and other avionics. While guns remained standard equipment (early models of F-4 being a notable exception), air-to-air missiles became the primary weapons for air superiority fighters, which employed more sophisticated radars and medium-range RF AAMs to achieve greater "stand-off" ranges, however, kill

probabilities proved unexpectedly low for RF missiles due to poor reliability and improved electronic countermeasures (ECM) for spoofing radar seekers. Infrared-homing AAMs saw their fields of view expand to 45°, which strengthened their tactical usability. Nevertheless, the low dogfight loss-exchange ratios experienced by American fighters in the skies over Vietnam led the U.S. Navy to establish its famous "TOPGUN" fighter weapons school, which provided a graduate-level curriculum to train fleet fighter pilots in advanced Air Combat Maneuvering (ACM) and Dissimilar Air Combat Training (DACT) tactics and techniques.

## Weapons

This era also saw an expansion in ground-attack capabilities, principally in guided missiles, and witnessed the introduction of the first truly effective avionics for enhanced ground attack, including terrain-avoidance systems. Air-to-surface missiles (ASM) equipped with electro-optical (E-O) contrast seekers – such as the initial model of the widely used AGM-65 Maverick – became standard weapons, and laser-guided bombs (LGBs) became widespread in effort to improve precision-attack capabilities. Guidance for such precision-guided munitions (PGM) was provided by externally mounted targeting pods, which were introduced in the mid-1960s.

It also led to the development of new automatic-fire weapons, primarily chain-guns that use an electric engine to drive the mechanism of a cannon; this allowed a single multi-barrel weapon (such as the 20 mm Vulcan) to be carried and provided greater rates of fire and accuracy. Powerplant reliability increased and jet engines became "smokeless" to make it harder to visually sight aircraft at long distances.



Saab 37 Viggen

## Specialization

Dedicated ground-attack aircraft (like the Grumman A-6 Intruder, SEPECAT Jaguar and LTV A-7 Corsair II) offered longer range, more sophisticated night attack systems or lower cost than supersonic fighters. With variable-geometry wings, the supersonic F-111 introduced the Pratt & Whitney TF30, the first turbofan equipped with afterburner. The ambitious project sought to create a versatile common fighter for many roles and services. It would serve well as an all-weather bomber, but lacked the performance to defeat other fighters. The McDonnell F-4 Phantom was designed around radar and missiles as an all-weather interceptor, but emerged as a versatile strike bomber nimble enough to prevail in air combat, adopted by the U.S. Navy, Air Force and Marine Corps. Despite numerous shortcomings that would be not be fully addressed until newer fighters, the Phantom claimed 280 aerial kills, more than any other U.S. fighter over Vietnam. With range and payload capabilities that rivalled that of World War II bombers such as B-24 Liberator, the Phantom would become a highly successful multi-role aircraft.

## Chapter- 6

# Example of Second Generation Jet Fighter Aircraft

## English Electric Lightning

### Lightning



Lightning F.3 in 1964

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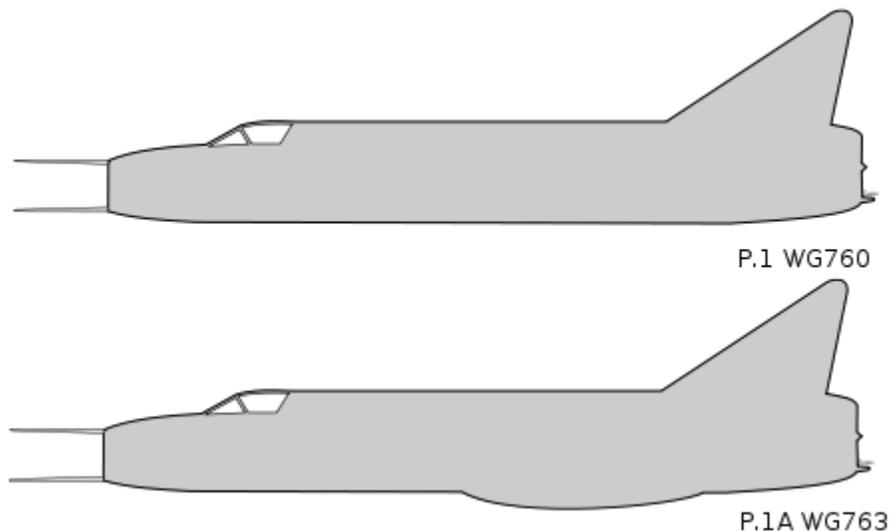
<b>Role</b>	Interceptor
<b>National origin</b>	United Kingdom
<b>Manufacturer</b>	English Electric British Aircraft Corporation
<b>First flight</b>	4 August 1954 (P 1A) 4 April 1957
<b>Introduced</b>	December 1959
<b>Retired</b>	1988 (RAF)
<b>Primary users</b>	Royal Air Force Kuwait Air Force Royal Saudi Air Force
<b>Number built</b>	337 (including prototypes)

The **English Electric Lightning** is a supersonic jet fighter aircraft of the Cold War era, noted for its great speed and unpainted natural metal exterior finish. It is the only all-British Mach 2 fighter aircraft. The aircraft was renowned for its capabilities as an interceptor; RAF pilots described it as "being saddled to a skyrocket". English Electric

was later incorporated into the British Aircraft Corporation, later marks being developed and produced as the **BAC Lightning**.

The Lightning was used throughout much of its service life by the Royal Air Force and the Royal Saudi Air Force. The aircraft was a regular performer at airshows and was the first aircraft capable of supercruise. The Lightning was also one of the highest performance planes ever used in formation aerobatics. The Lightning aircraft is now largely retired to museums, but three examples still fly at "Thunder City" in Cape Town, South Africa.

## Design and development



The two P.1 research aircraft

The specification for the aircraft followed the cancellation of the Air Ministry's 1942 E.24/43 supersonic research aircraft specification which had resulted in the Miles M.52 programme. It was soon realised that the aircraft should be regarded as a prototype fighter to satisfy the British Air Ministry's 1949 specification F23/49 rather than being research aircraft. The Lightning design shared a number of innovations first planned for the Miles M.52 including the shock cone and all-moving tailplane or stabilator. The prototypes, known as **P.1**, were built to Ministry of Supply Operational Requirement ER.103 of 1947 for a transonic research aircraft. The first of the two P.1s *WG760* flew for the first time from RAF Boscombe Down on 4 August 1954.

The P.1's chief designer was W.E.W "Teddy" Petter, formerly chief designer at Westland Aircraft. The design was controversial and the Short SB5 was built to test wing sweep and tailplane combinations. The original combination was proved correct. The forerunner of the Lightning series was the P.1A and P.1B flying "proof-of-concept" aircraft. Looking very much like the production series, the prototypes were distinguished by the rounded-triangular intakes, short fins and lack of radar or operational equipment. Initial

prototypes were powered by un-reheated Armstrong Siddeley Sapphire turbojets, although the Rolls-Royce Avon was used in subsequent aircraft. On 25 November 1958, the P.1B became the first British aircraft to fly at Mach 2.

The P.1 and P.1A prototypes proved several unique features of the Lightning design: stacked/staggered engines, a notched delta wing, and a low-mounted tailplane. The most notable of these was the vertically stacked, longitudinally staggered engines. Faced with the conflicting needs of minimizing frontal area, providing undisturbed engine airflow across a wide speed range, and packaging two engines to provide sufficient thrust to meet performance goals, Petter conceived a configuration where twin engines were fed by a single nose inlet, the flow was split vertically aft of the cockpit, and the nozzles were closely stacked. This scheme effectively tucked one engine behind the cockpit. The result was a low frontal area, an efficient inlet, and excellent single-engine handling. Unfortunately, this stacked configuration also made engine maintenance difficult, and fluid leakage from the upper engine could cause fires.

The fuselage was tightly packed, leaving no room for fuel tankage or main landing gear. This left the wings. The notched delta wing did not have the volume of a standard delta, so space was a premium, and creative solutions were the rule. Each wing contained a somewhat conventional three-section main fuel tank and leading-edge tank, holding 312 gal, but interestingly, the wing flap also contained a 33 gal fuel tank. An additional 5 gal was contained in a "recuperator"--used to ensure continued fuel flow during negative-g operation—bringing the aircraft's total internal fuel capacity to 700 gal (3,180 l). The main landing gear was sandwiched outboard of the main tanks and aft of the leading edge tanks, with the flap fuel tanks behind. The long main gear legs retracted toward the wingtip, necessitating an exceptionally thin main tyre inflated to high pressure (330-350 psi). Little volume was wasted, but even with all this creative packaging, the Lightning prototypes had a barely usable endurance, tyre life was short, and heavy underwing stores could not be carried.

To increase the flexibility of the design, a conformal ventral store was added. This store took two forms: a rocket engine, and a fuel tank. The rocket engine store was to contain a Napier Double Scorpion motor and 200 gal of high-test peroxide (HTP, concentrated hydrogen peroxide) for oxidizer and to drive the rocket's turbopump. Fuel for the rocket would have been drawn from the Lightning's internal tankage. The rocket engine was intended to boost the Lightning's performance against a supersonic, high altitude bomber threat, but in the end, this threat never emerged, and the Lightning's basic performance was deemed sufficient to handle the current threat. The rocket engine store production was cancelled in 1958.

The ventral store did see wide use in the form of the fuel tank. The first version of this tank was jettisonable and held 250 gal (247 gal usable, 1,120 l). This tank was carried by all early Lightnings, and in practice was only removed for aircraft maintenance. Eventually, a non-jettisonable version was designed to further address the Lightning's enduring fuel shortage, and this version was carried by later marks of Lightning.

The first operational Lightning, the **F.1**, was designed as a point defence interceptor to defend mainland Britain from bomber attack. To best perform this intercept mission, emphasis was placed on rate-of-climb, acceleration, and speed, rather than range and combat endurance. It was equipped with two 30 mm Aden Cannon in front of the cockpit windscreen and an interchangeable fuselage weapon pack containing either an additional two ADEN cannon, 48, two inch air-to-air rockets, or two de Havilland Firestreak air-to-air missiles, a heavy fit optimized for attack of large aircraft. The Ferranti A.I.23 radar supported autonomous search, automatic target tracking, and ranging for all weapons, while the pilot attack sight provided gyroscopically-derived lead angle and back-up stadiametric ranging for gun firing. The radar and gunsight were collectively designated the AIRPASS: Airborne Interception Radar and Pilot Attack Sight System.

The next two Lightning variants, the **F.1A** and **F.2**, saw steady but relatively minor refinement of the basic design; however, the next variant, the **F.3**, was a major departure. The **F.3** had higher thrust Avon 301R engines, a larger, squared-off fin and strengthened intake bullet allowing a service clearance to Mach 2.0 (the **F.1**, **F.1A** and **F.2** were limited to Mach 1.7), the A.I.23B radar and Red Top missile offering a limited forward hemisphere attack capability—and most notoriously—deletion of the nose cannon. The new engines and fin made the **F.3** the highest performance Lightning yet, but with an even higher fuel consumption and resulting shorter range. The next variant, the **F.6**, was already in development, but there was a need for an interim solution to partially address the **F.3**'s shortcomings. The **F.3A** was that interim solution.

The **F.3A** introduced two improvements: a new, non-jettisonable, 610 gal (2,770 l) ventral fuel tank, and a new, kinked, conically-cambered wing leading edge—of course, incorporating a slightly larger leading edge fuel tank, raising the total usable internal fuel to 716 gal (3,250 l). The conically-cambered wing noticeably improved maneuverability, especially at higher altitudes, and the ventral tank nearly doubled available fuel. The increased fuel was very welcome, but the lack of cannon armament was felt to be a deficiency. It was thought that cannon were desirable to fire warning shots in the intercept mission.

The **F.6** was the ultimate Lightning version to see British service. Originally, it was nearly identical to the **F.3A** with the exception that it had provisions to carry 260 gal (1,180 l) ferry tanks on pylons over the wings. These tanks were jettisonable in an emergency, and gave the **F.6** a substantially improved deployment capability. There remained one glaring shortcoming: the lack of cannon. This was finally rectified in the form of a modified ventral tank with two ADEN cannon in the front. The addition of the cannon and their ammunition decreased the tank's fuel capacity from 610 gal to 535 gal (2,430 l), but the cannon made the **F.6** a “real fighter” again.

The final British Lightning was the **F.2A**. This was an **F.2** upgraded with the cambered wing, the squared fin, and the 610 gal ventral. The **F.2A** retained the A.I.23 and Firestreak missile, the nose cannon, and the earlier Avon 211R engines. Although the **F.2A** lacked the thrust of the later Lightnings, it had the longest tactical range of all Lightning variants, and was used for low-altitude interception over Germany.

The **F.53** was the “Export Lightning.” It was an attempt to add multi-role capability to the optimized point defense interceptor design. The F.53 was based on the F.6 airframe and avionics, but incorporated an additional pair of hardpoints on the outer wing. These hardpoints could be fitted with pylons for air-to-ground ordnance, though in practice, they were rarely used. The Export Lightning had all of the advantages of the British Lightnings: exceptional climb rate, well-mannered maneuvering, and a hard-hitting punch. Unfortunately, the Export Lightning also retained the difficulty of maintenance, and serviceability rates suffered. Still, the F.53 was generally well regarded by its pilots, and its adaptation to multiple roles is a testimony to the exceptional talent of its designers.

In 1963, BAC Warton worked on the preliminary design of a two-seat Lightning development with a variable-geometry wing, based on the Lightning T.5 with a revised undercarriage. Initially proposed as a carrier-based aircraft, the VG Lightning concept was revised into a land-based interceptor intended for the RAF the following year. However no VG Lightning was ever built.

In September 2008, the Institution of Mechanical Engineers conferred on the Lightning its "Engineering Heritage Award". Former pilots and engineers, who were involved with the plane during the 1950s and 1960s, gathered at the BAE Systems site at Warton Aerodrome to mark the engineering feat.

## Operational history



English Electric Lightning of the Saudi Air Force

The first operational aircraft, a pre-production P 1B (*XG336*), arrived at RAF Coltishall in Norfolk in December 1959. From 1960 the production F.1 served initially with 74 Squadron. An improved variant the F.2 first flew on 11 July 1961 and entered service with 19 Squadron at the end of 1962. The F.3 was first flown on 16 June 1962 and the longer-range F.6 on 16 June 1965. The versions sold to Saudi Arabia were essentially similar to the T 5 and F.6 models in UK service and this final production batch reverted to the classic natural metal external finish which lasted well in the drier Arabian climate.

During the 1960s, as strategic awareness increased and a multitude of alternative fighter designs were developed by Warsaw Pact and NATO members, the Lightning's range and firepower shortcomings became increasingly apparent. The withdrawal of McDonnell Douglas F-4 Phantoms from Royal Navy service enabled these slower but much longer-ranged aircraft to be added to the RAF's interceptor force alongside those withdrawn from Germany which were being replaced by SEPECAT Jaguars in the ground attack role. Later the Tornado F3s also arrived to defend UK airspace. While slower and less agile than the Lightning, the Tornado carries a much larger armament load and much more advanced avionics. Lightnings were slowly phased out of service between 1974 and 1988, although much testing and modification was needed to keep them in air-worthy condition due to the high number of flight hours accumulated.



Nine Lightning F.1s of No.74 Squadron display at the 1961 SBAC show, Farnborough

The English Electric Lightning is credited with a single kill, ironically a British aircraft – a Harrier pilot ejected and the pilot-less aircraft continued to fly. The order was given to shoot down the aircraft and the Lightning did.

In their final years of UK service all RAF Lightnings were based at RAF Binbrook in Lincolnshire and many were camouflaged to make them less conspicuous when flying at low level. They tended to defend the Flamborough Head Sector of airspace above the North Sea. These later aircraft were the single-seater F.3 and F.6 and the twin seat trainer variant T 5, all constructed by British Aircraft Corporation and distinguished from earlier versions by their flat topped fins. In their last year of service their pilots regularly pushed the aircraft to their limits as they used up their remaining fatigue life.

Many Lightnings are conserved in museum collections where their clean sleek lines are evocative of the high speeds that they once attained. The Short SB5 and a P 1A are at the RAF Museum, Cosford. The Civil Aviation Authority refused a licence for the surviving airworthy examples to perform at air shows in the UK but there are three flying in South Africa.

### **Service in the Middle East: Saudi Arabia and Kuwait**

In December 1965, due to its involvement in the North Yemen Civil War and resulting conflict with Egypt, Saudi Arabia ordered 35 Lightning F.53s and six T.55s as part of the "Magic Carpet" programme. As an interim measure, five Lightning F.52s (ex-RAF Lightning F.2s) plus two Lightning T.54s (ex-RAF Lightning T.4s) were delivered to Saudi Arabia in July 1966, as well as a pre-production Lightning F.1 for ground instructional use. From 1967 the Lightning F.53s operated from the Khamis base, served by radars based at Usram. The last Lightning was delivered in 1972, during Magic Carpet phase IV. Only one plane was lost to enemy fire; it was shot down by ground fire over Yemen on 3 May 1970, just before peace was declared.

Kuwait also ordered 14 Lightnings in December 1966, comprising 12 F.53Ks and two T.55Ks. The Kuwaitis somewhat overestimated their ability to maintain such a complex aircraft, and the Lightnings were phased out of service very quickly; the last ones were replaced by Dassault Mirage F1s in 1977. Thanks to this mistake, Kuwait is one of the countries richest in Lightnings on static display; according to Intelligence sources, the Al Jaber air base has three Lightnings on display.

## Performance



Lightning XM215 at Farnborough Air Show, England, in 1964

## Speed

The maximum speed of the Lightning varied with the model. The early models, the F.1, F.1A, and F.2, had a rated top speed of Mach 1.7 at 36,000 ft in an ICAO standard atmosphere, and 650 KIAS (Knots Indicated Airspeed) at lower altitudes. The later models, the F.2A, F.3, F.3A, F.6, and F.53, had a rated top speed of Mach 2.0 at 36,000 ft, and speeds up to 700 KIAS for “operational necessity only.” These were service limits, and were exceeded on occasion, but when the bases for these limits are understood, some of the “Lightning lore” associated with higher speeds can be placed into perspective.

The first basis for these limits was excess thrust. With the Avon 200-series engines, an early model Lightning with a ventral tank and two Firestreak missiles would run out of excess thrust at Mach 1.9 on a Standard Day. With the Avon 300-series engines, a Lightning with a ventral tank and two Red Top missiles would run out of excess thrust at Mach 2.0 on a Standard Day. As excess thrust decreases toward zero, acceleration slows, and fuel to achieve the last few tenths of a Mach could be prohibitive.

Another basis was aerodynamic stability. As Mach number increases, directional stability decreases. This decrease in stability can become critical with asymmetric missile carriage

or adverse yaw induced by aileron deflection. Failure of the vertical fin could occur if yaw is not rapidly corrected with the rudder. Stability degradation led to the imposition of Mach limits on missile launch and to the adoption of a larger vertical fin on later Lightning variants to provide more stability margin at high Mach numbers.

Inlet stability was also an issue as Mach number increased. At supersonic speed, the central shock cone served as a compression surface to divert air into the annular inlet. The cone would generate an oblique shock, and the angle of this shock would increase with Mach number. As the Lightning accelerated through Mach 1, the oblique shock would be positioned in front of the intake lip. This is termed a subcritical inlet condition, and although not efficient, it is stable. In a sub-critical inlet, some portion of the compressed air is diverted outside of the inlet lip, causing spillage drag. When Mach number reached the Design Mach number, the oblique shock would be positioned just in front of the inlet lip. This critical inlet condition is the most efficient, compressing all of the air in front of the inlet with no spillage. As Mach number increases beyond Design Mach, the oblique shock enters the inlet, a condition termed supercritical. In a super-critical condition, the airflow in the inlet duct becomes supersonic. The Lightning's inlet was designed to handle only subsonic air in the duct, and a super-critical condition would reverse the normal pressure distribution, causing an adverse pressure gradient across the engines. This adverse gradient could lead to engine surge, also called compressor stall, potentially resulting in flameout and/or engine damage. In any case, if the Lightning's inlet went supercritical, engine thrust would be drastically reduced.

A supercritical condition could be delayed by translating the shock cone forward with increasing Mach, thus holding the oblique shock ahead of the inlet lip. The goal would be to delay shock ingestion to a Mach number above the speed range of the aircraft. The Lightning's nose bullet was fixed, however, so a supercritical condition was inevitable if excess thrust enabled the aircraft speed to exceed the inlet's Design Mach.

The final bases for the service limits were thermal and structural. When air is compressed by the passage of a high-speed aircraft, that air is heated. This heating increases considerably when the aircraft is traveling at supersonic speed. The front of the aircraft is exposed to the heated air, and the heat is convectively transferred to the airframe. The hottest portion of the aircraft is the nose tip, and in the Lightning's case, this tip, the inlet shock cone, was constructed of fiberglass. Fiberglass was necessary because the shock cone was also the Lightning's radome, and a metal shock cone would not pass the AI 23's radar energy.

At supersonic speed, the Lightning's shock cone would be heated, weakening the resin in the fiberglass, and exposing the material to fatigue with the thermal cycles of repetitive high-speed flights. At 36,000 ft and Mach 1.7, the heating conditions on the shock cone would be almost identical to those at Sea Level and 650 KIAS, but if the speed were increased to Mach 2.0 at 36,000 ft, the shock cone would be exposed to temperatures more than 70% higher than those at Mach 1.7. This increase dictated a strengthening of the shock cone to support regular use at speeds up to Mach 2.0 in the Lightning F.2A,

F.3, F.6, and F.53. If the shock cone failed in flight, it could result in pressurization loss, worse, foreign object ingestion and engine damage.

With the bases for the Lightning's service limits considered, it is apparent that these limits reasonably accurately reflect the performance of the aircraft itself. The small-fin variants could certainly exceed Mach 1.7, but the stability limits and shock cone thermal/strength limits would make such operation risky. The large-fin variants, especially those equipped with Avon 300-series engines could safely reach Mach 2, and given the right atmospheric conditions, might even achieve a few more tenths of a Mach. It is noteworthy, however, that the same cold conditions that might provide the excess thrust to achieve higher Mach numbers would also decrease the true airspeed at which the airframe and inlet could become unstable.

All variants of Lightning had the excess thrust to slightly exceed 700 KIAS under certain conditions, and the service limit of 650 KIAS was occasionally ignored, even when not driven by operational necessity. With the strengthened shock cone, the large-tail Lightning variants could safely approach their thrust limit, but fuel burn at high indicated airspeeds was prodigious, and the Lightning might very well run short before eking-out the last few knots. In all variants of the Lightning, the airspeed indicator scale stopped at 700 KIAS.

## **Climb**

The Lightning possessed a remarkable climb rate, and its time to reach an altitude, or time-to-climb, was exceptional. To achieve this short time-to-climb, Lightnings employed a particular climb profile, which was more shallow in angle compared to that demonstrated at air shows. The Lightning was famous for its ability to rapidly rotate at the end of the runway and climb almost vertically away, but although this near-vertical climb was impressive, it did not yield the best time to altitude, nor was it a demonstration of the ability to sustain a vertical climb. When Lightning pilots performed their trademark tail-stand, they were actually trading airspeed for altitude. The Lightnings would seemingly zoom "out of sight," accelerating away, when in fact they would slow to near stall before pushing over into level flight. During the optimum time-to-climb profile, the maximum climb angle never exceeded 30 deg.

The Lightning's optimum climb profile began with an afterburner takeoff. Immediately after takeoff, the landing gear would be retracted and the nose held down to allow rapid acceleration to 430 KIAS, then a climb initiated and stabilized at 450 KIAS. At this IAS, the climb rate would be constant at approximately 20,000 ft/min., The Lightning would reach Mach 0.87 at 13,000 ft. The pilot would then maintain Mach 0.87 until the tropopause, 36,000 ft. on a standard day. The climb rate would decrease during the constant-Mach portion of the profile. If further climb were required, the Lightning would accelerate to supersonic speed at the tropopause prior to resuming the climb at supersonic speed.

A Lightning flying its optimum climb profile would reach 36,000 ft less than 3 minutes after brake release. This was—and is—impressive performance. That the Lightning never reached the climb rates of some of its contemporaries during this profile was not important; that it reached altitude quickly, was.

The official ceiling was a secret to the general public and low security RAF documents simply stated 60,000+ ft (18 000+ m), although it was well known within the RAF to be capable of much greater heights; the official maximum altitude mainly being determined by cockpit pressurisation reliability and safety. In September 1962 Fighter Command organized a series of trial supersonic overland interceptions of Lockheed U-2As, temporarily based at RAF Upper Heyford to monitor resumed Soviet nuclear tests, at heights of around 60,000-65,000 ft. The trials took place in two stages, the second series consisting of 14 interceptions, including four successful and four abortive ones at 65,000. The late Brian Carroll, a former RAF Lightning pilot and ex-Lightning Chief Examiner, reported taking a Lightning F.53 up to 87,300 feet (26 600 m) over Saudi Arabia at which level "Earth curvature was visible and the sky was quite dark" but control-wise it was "on a knife edge".

In 1984, during a major NATO exercise, Flt Lt Mike Hale intercepted an American U-2 at a height which they had previously considered safe from interception. Records show that Hale climbed to 88,000 ft (26,800 m) in his Lightning F.3 *XR749*. This was not sustained level flight, but in a ballistic climb or a zoom climb, in which the pilot takes the aircraft to top speed and then puts the aircraft into a climb, trading speed for altitude. The normal service ceiling for this aircraft was 60,000 feet in level flight. Hale also participated in time-to-height and acceleration trials against F-104 Starfighters from Aalborg. He reports that the Lightnings won all races easily with the exception of the low level supersonic acceleration, which was a "dead heat".

Carroll reports in a side-by-side comparison of the Lightning and the F-15C Eagle (which he also flew) that "acceleration in both was impressive, you have all seen the Lightning leap away once brakes are released, the Eagle was almost as good, and climb speed was rapidly achieved. Takeoff roll is between 2,000 and 3,000 ft [600 to 900 m], depending upon military or maximum afterburner-powered takeoff. The Lightning was quicker off the ground, reaching 50 ft [15 m] height in a horizontal distance of 1,630 feet [500m]".

In British Airways trials in April 1985, Concorde was offered as a target to NATO fighters including F-15s, F-16s, F-14s, Mirages, F-104s - but only Lightning *XR749*, flown by Mike Hale and described by him as "a very hot ship, even for a Lightning", managed to overtake Concorde on a stern conversion intercept. The *XR749* now resides at the entrance of Score Group plc's gas turbine testing and servicing facility in Peterhead, Scotland.

Despite its acceleration, altitude and top speed, the Lightning found itself outclassed by newer fighters in terms of radar, avionics, weapons load, range, and air-to-air capability. More of a problem was the obsolete avionics and weapons fit, particularly the 30 mile

(very short) range 1950s radar sets: the avionics were never upgraded in RAF service since Lightnings were always supposedly just about to be replaced by something better.

Roland Beamont (Lightning development-programme chief test pilot), after flying most of the 2nd Generation Century series US fighters of that era, made it clear that in his opinion, nothing at that time had the inherent stability and control and docile handling characteristics of the P 1 series prototypes and Lightning derivatives throughout the full flight envelope. Its turn performance and buffet boundaries were well in advance of anything known to him, the Mirage III included. This remained so right up until the next generation of fighter/interceptors was developed worldwide, with underbelly intakes and straked leading edges, or canards.

## Chapter- 7

# Example of Third Generation Jet Fighter Aircraft

## McDonnell Douglas F-4 Phantom II

### F-4 Phantom II



An F-4B Phantom II of Marine fighter-attack squadron VMFA-314, the Black Knights

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<b>Role</b>	Interceptor fighter, fighter-bomber
<b>National origin</b>	United States
<b>Manufacturer</b>	McDonnell Aircraft/ McDonnell Douglas
<b>First flight</b>	27 May 1958
<b>Introduction</b>	30 December 1960
<b>Status</b>	Some in active non-U.S. service. Also in U.S. service as drones as of 2010
<b>Primary users</b>	United States Air Force United States Navy United States Marine Corps
<b>Produced</b>	1958–1981
<b>Number built</b>	5,195
<b>Unit cost</b>	US\$2.4 million when new (F-4E)

The **McDonnell Douglas F-4 Phantom II** is a tandem two-seat, twin-engined, all-weather, long-range supersonic jet interceptor fighter/fighter-bomber originally

developed for the United States Navy by McDonnell Aircraft. It first entered service in 1960 with the U.S. Navy. Proving highly adaptable, it was also adopted by the U.S. Marine Corps and the U.S. Air Force, and by the mid-1960s had become a major part of their respective air wings.

The Phantom is a large fighter with a top speed of over Mach 2. It can carry over 18,000 pounds (8,400 kg) of weapons on nine external hardpoints, including air-to-air and air-to-ground missiles, and various bombs. The F-4, like other interceptors of its time, was designed without an internal cannon, but later models incorporated a M61 Vulcan rotary cannon. Beginning in 1959, it set 15 world records, including an absolute speed record, and an absolute altitude record.

The F-4 was used extensively by these three U.S. services during the Vietnam War, serving as the principal air superiority fighter for both the Navy and Air Force, as well as being important in the ground-attack and reconnaissance roles by the close of U.S. involvement in the war. The Phantom has the distinction of being the last U.S. fighter flown to attain ace status in the 20th century. During the Vietnam War, the USAF had one pilot and two WSOs, and the US Navy one pilot and one RIO, become aces in air-to-air combat. It continued to form a major part of U.S. military air power throughout the 1970s and 1980s, being gradually replaced by more modern aircraft such as the F-15 Eagle and F-16 Fighting Falcon in the U.S. Air Force; the F-14 Tomcat and F/A-18 Hornet in the U.S. Navy; and the F/A-18 in the U.S. Marine Corps.

The F-4 Phantom II remained in use by the U.S. in the reconnaissance and Wild Weasel (suppression of enemy air defenses) roles in the 1991 Gulf War, finally leaving service in 1996. It was also the only aircraft used by both U.S. flight demonstration teams: the USAF Thunderbirds (F-4E) and the US Navy Blue Angels (F-4J). The F-4 was also operated by the armed forces of 11 other nations. Israeli Phantoms saw extensive combat in several Arab–Israeli conflicts, while Iran used its large fleet of Phantoms in the Iran–Iraq War. Phantoms remain in front line service with seven countries, and in use as an unmanned target in the U.S. Air Force. Phantom production ran from 1958 to 1981, with a total of 5,195 built, making it the most numerous American supersonic military aircraft.

## **Development**

### **Origins**

In 1952, McDonnell's Chief of Aerodynamics, Dave Lewis, was appointed by CEO Jim McDonnell to be the company's Preliminary Design Manager. With no new aircraft competitions on the horizon, internal studies concluded the Navy had the greatest need for a new and different aircraft type: an attack fighter.

In 1953, McDonnell Aircraft began work on revising its F3H Demon naval fighter, seeking expanded capabilities and better performance. The company developed several projects including a variant powered by a Wright J67 engine, and variants powered by two Wright J65 engines, or two General Electric J79 engines. The J79-powered version

promised a top speed of Mach 1.97. On 19 September 1953, McDonnell approached the United States Navy with a proposal for the "Super Demon". Uniquely, the aircraft was to be modular—it could be fitted with one- or two-seat noses for different missions, with different nose cones to accommodate radar, photo cameras, four 20 mm (.79 in) cannon, or 56 FFAR unguided rockets in addition to the nine hardpoints under the wings and the fuselage. The Navy was sufficiently interested to order a full-scale mock-up of the F3H-G/H, but felt that the upcoming Grumman XF9F-9 and Vought XF8U-1 already satisfied the need for the supersonic fighter.

The McDonnell design was therefore reworked into an all-weather fighter-bomber with 11 external hardpoints for weapons and on 18 October 1954, the company received a letter of intent for two YAH-1 prototypes. On 26 May 1955, four Navy officers arrived at the McDonnell offices and, within an hour, presented the company with an entirely new set of requirements. Because the Navy already had the A-4 Skyhawk for ground attack and F-8 Crusader for dogfighting, the project now had to fulfill the need for an all-weather fleet defense interceptor. A second crewman was added to operate the powerful radar.

### **XF4H-1 prototype**

The XF4H-1 was designed to carry four semi-recessed AAM-N-6 Sparrow III radar-guided missiles, and to be powered by two J79-GE-8 engines. As in the F-101 Voodoo, the engines sat low in the fuselage to maximize internal fuel capacity and ingested air through fixed geometry intakes. The thin-section wing had a leading edge sweep of 45° and was equipped with a boundary layer control system for better low-speed handling.

Wind tunnel testing had revealed lateral instability requiring the addition of 5° dihedral to the wings. To avoid redesigning the titanium central section of the aircraft, McDonnell engineers angled up only the outer portions of the wings by 12°, which averaged to the required 5° over the entire wingspan. The wings also received the distinctive "dogtooth" for improved control at high angles of attack. The all-moving tailplane was given 23° of anhedral to improve control at high angles of attack while still keeping the tailplane clear of the engine exhaust. In addition, air intakes were equipped with movable ramps to regulate airflow to the engines at supersonic speeds. All-weather intercept capability was achieved thanks to the AN/APQ-50 radar. To accommodate carrier operations, the landing gear was designed to withstand landings with a sink rate of 23 ft/s (7 m/s), while the nose strut could extend by some 20 in (50 cm) to increase angle of attack at takeoff.

### **Naming the aircraft**

There were proposals to name the F4H "Satan" and "Mithras", the Persian god of light. In the end, the aircraft was given the less controversial name "Phantom II", the first "Phantom" being another McDonnell jet fighter, the FH-1 Phantom. The Phantom II was briefly given the designation F-110A and the name "Spectre" by the USAF, but neither title was used.

## Prototype testing

On 25 July 1955, the Navy ordered two XF4H-1 test aircraft and five YF4H-1 pre-production fighters. The Phantom made its maiden flight on 27 May 1958 with Robert C. Little at the controls. A hydraulic problem precluded retraction of the landing gear but subsequent flights went more smoothly. Early testing resulted in redesign of the air intakes, including the distinctive addition of 12,500 holes to "bleed off" the slow-moving boundary layer air from the surface of each ramp. The aircraft soon squared off against the XF8U-3 Crusader III. Due to operator workload, the Navy wanted a two-seat aircraft and on 17 December 1958 the F4H was declared a winner. Delays with the J79-GE-8 engines meant that the first production aircraft were fitted with J79-GE-2 and -2A engines, each having 16,100 lbf (71.8 kN) of afterburning thrust. In 1959, the Phantom began carrier suitability trials with the first complete launch-recovery cycle performed on 15 February 1960 from USS *Independence*.

## Production

Early in production, the radar was upgraded to a larger AN/APQ-72, necessitating the bulbous nose, and the canopy was reworked to improve visibility and make the rear cockpit less claustrophobic. During its career the Phantom underwent many changes in the form of numerous variants developed.



A flight of USAF F-4Cs refuel from a KC-135 tanker before making a strike against targets in North Vietnam. The Phantoms are fully loaded with 750-pound general purpose bombs, Sparrow missiles and external fuel tanks.

The USAF received Phantoms as the result of Defense Secretary Robert McNamara's push to create a unified fighter for all branches of the military. After an F-4B won the "Operation Highspeed" fly-off against the F-106 Delta Dart, the USAF borrowed two Naval F-4Bs, temporarily designating them F-110A "Spectre" in January 1962, and developed requirements for their own version. Unlike the Navy focus on interception, the USAF emphasized a fighter-bomber role. With McNamara's unification of designations on 18 September 1962, the Phantom became the F-4 with the Naval version designated F-4B and USAF F-4C. The first Air Force Phantom flew on 27 May 1963, exceeding Mach 2 on its maiden flight.

Phantom II production ended in the United States in 1979 after 5,195 had been built (5,057 by McDonnell Douglas and 138 in Japan by Mitsubishi). Of these, 2,874 went to the USAF, 1,264 to the Navy and Marine Corps, and the rest to foreign customers. The last U.S.-built F-4 went to Turkey, while the last F-4 ever built was completed in 1981 as an F-4EJ by Mitsubishi Heavy Industries in Japan. As of 2008, 631 Phantoms remained in active service worldwide, while the Phantom also remains in use as a drone operated by the U.S. military.

## World records

To show off their new fighter, the Navy led a series of record-breaking flights early in Phantom development:

- **Operation Top Flight:** On 6 December 1959, the second XF4H-1 performed a zoom climb to a world record 98,557 ft (30,040 m). The previous record of 94,658 ft (28,852 m) was set by a Soviet Sukhoi T-43-1 prototype. Commander Lawrence E. Flint, Jr., USN accelerated his aircraft to Mach 2.5 at 47,000 ft (14,330 m) and climbed to 90,000 ft (27,430 m) at a 45° angle. He then shut down the engines and glided to the peak altitude. As the aircraft fell through 70,000 ft (21,300 m), Flint restarted the engines and resumed normal flight.
- On 5 September 1960, an F4H-1 averaged 1,216.78 mph (1,958.16 km/h) over a 500 km (311 mi) closed-circuit course.
- On 25 September 1960, an F4H-1 averaged 1,390.21 mph (2,237.26 km/h) over a 100 km (62 mi) closed-circuit course.
- **Operation LANA:** To celebrate the 50th anniversary of Naval aviation (L is the Roman numeral for 50 and ANA stood for Anniversary of Naval Aviation) on 24 May 1961, Phantoms flew across the continental United States in under three hours and included several tanker refuelings. The fastest of the aircraft averaged 869.74 mph (1,400.28 km/h) and completed the trip in 2 hours 47 minutes, earning the pilot (and future NASA Astronaut), Lieutenant Richard Gordon, USN and RIO, Lieutenant Bobbie Long, USN, the 1961 Bendix trophy.
- **Operation Sageburner:** On 28 August 1961, a Phantom averaged 902.769 mph (1,452.826 km/h) over a 3 mi (4.82 km) course flying below 125 ft (40 m) at all times. Commander J.L. Felsman, USN was killed during the first attempt at this record on 18 May 1961 when his aircraft disintegrated in the air after pitch damper failure.

- **Operation Skyburner:** On 22 December 1961, a modified Phantom with water injection set an absolute world record speed of 1,606.342 mph (2,585.086 km/h).
- On 5 December 1961, another Phantom set a sustained altitude record of 66,443.8 ft (20,252.1 m).
- **Operation High Jump:** A series of time-to-altitude records was set in early 1962; 34.523 seconds to 3,000 metres (9,800 ft), 48.787 seconds to 6,000 metres (20,000 ft), 61.629 seconds to 9,000 metres (30,000 ft), 77.156 seconds to 12,000 metres (39,000 ft), 114.548 seconds to 15,000 metres (49,000 ft), 178.5 seconds to 20,000 metres (66,000 ft), 230.44 seconds to 25,000 metres (82,000 ft), and 371.43 seconds to 30,000 metres (98,000 ft).

All in all, the Phantom set 16 world records. With the exception of Skyburner, all records were achieved in unmodified production aircraft. Five of the speed records remained unbeaten until the F-15 Eagle appeared in 1975.

## Design



Cockpit of F-4 Phantom II

The F-4 Phantom is tandem-seat fighter-bomber designed as a carrier-based interceptor to fill the U.S. Navy's fleet defense fighter role. Innovations in the F-4 included an advanced pulse-doppler radar and extensive use of titanium in its airframe.

Despite the imposing dimensions and a maximum takeoff weight of over 60,000 lb (27,000 kg), the F-4 had a top speed of Mach 2.23 and an initial climb of over 41,000 ft/min (210 m/s). The F-4's nine external hardpoints have a capability of up to 18,650 pounds (8,480 kg) of weapons, including air-to-air and air-to-ground missiles, and unguided, guided, and nuclear bombs. Like other interceptors of its day, the F-4 was designed without an internal cannon.

The baseline performance of a Mach 2-class fighter with long range and a bomber-sized payload would be the template for the next generation of large and light/middle-weight fighters optimized for daylight air combat.

### **Flight characteristics**

In air combat, the Phantom's greatest advantage was its thrust, which permitted a skilled pilot to engage and disengage from the fight at will. The massive aircraft, designed to fire radar-guided missiles from beyond visual range, lacked the agility of its Soviet opponents and was subject to adverse yaw during hard maneuvering. Although thus subject to irrecoverable spins during aileron rolls, pilots reported the aircraft to be very communicative and easy to fly on the edge of its performance envelope. In 1972, the F-4E model was upgraded with leading edge slats on the wing, greatly improving high angle of attack maneuverability at the expense of top speed.



F-4 Phantom II flight

The J79 engines produced noticeable amounts of black smoke, a severe disadvantage in that the enemy could spot the aircraft. This was solved on the F-4S fitted with the -10A engine variant which used a smoke-free combustor.

The F-4's biggest weakness, as it was initially designed, was its lack of an internal cannon. For a brief period, doctrine held that turning combat would be impossible at supersonic speeds and little effort was made to teach pilots air combat maneuvering. In reality, engagements quickly became subsonic. Furthermore, the relatively new heat-seeking and radar-guided missiles at the time were frequently reported as unreliable and pilots had to use multiple shots just to hit one target. To compound the problem, rules of engagement in Vietnam precluded long-range missile attacks in most instances, as visual identification was normally required. Many pilots found themselves on the tail of an enemy aircraft but too close to fire short-range Falcons or Sidewinders. Although in 1967 USAF F-4Cs began carrying SUU-16 or SUU-23 external gunpods containing a 20 mm (.79 in) M61 Vulcan Gatling cannon, USAF cockpits were not equipped with lead-computing gunsights, virtually assuring a miss in a maneuvering fight. Some Marine Corps aircraft carried two pods for strafing. In addition to the loss of performance due to drag, combat showed the externally mounted cannon to be inaccurate unless frequently boresighted, yet far more cost-effective than missiles. The lack of cannon was finally addressed by adding an internally mounted 20 mm (.79 in) M61 Vulcan on the F-4E.

## Chapter- 8

# Fourth Generation Jet Fighter Aircraft



Lockheed Martin F-16



Dassault Mirage 2000

Aircraft classified by the US government as **fourth-generation jet fighters** are those in service approximately from 1980 to 2010, representing the design concepts of the 1970s.

Fourth-generation designs are heavily influenced by lessons learned from the previous generation of combat aircraft. Long-range air-to-air missiles, originally thought to make dogfighting obsolete, proved less influential than expected precipitating a renewed emphasis on maneuverability. Meanwhile, the growing costs of military aircraft in general and the demonstrated success of multi-role aircraft such as the F-4 Phantom II gave rise to the popularity of multi-role fighters in parallel with the advances marking the so-called fourth generation.

During the period in question, maneuverability was enhanced by "relaxed static stability" made possible by introduction of the "fly-by-wire" (FBW) flight control system (FLCS), which in turn was possible due to advances in digital computers and system integration techniques. Analog avionics, required to enable FBW operations, became a fundamental requirement and began to be replaced by digital flight control systems in the latter half of the 1980s.

The further advance of microcomputers in the 1980s and 1990s permitted rapid upgrades to the avionics over the lifetimes of these fighters, incorporating system upgrades such as AESA, digital avionics buses andIRST. Due to the dramatic enhancement of capabilities in these upgraded fighters and in new designs of the 1990s that reflected these new capabilities, the US government has taken to using the designation **4.5th generation** to refer to these later designs. This is intended to reflect a class of fighters that are evolutionary upgrades of the 4th generation incorporating integrated avionics suites, advanced weapons efforts to make the (mostly) conventionally designed aircraft nonetheless less easily detectable, and trackable as a response to advancing missile and RADAR technology, see stealth technology. Inherent airframe design features exist, and include masking of turbine-blades and application of advanced sometimes radar-absorbent materials, but not the distinctive low-observable configurations of the latest aircraft, dubbed fifth-generation fighters or craft such as the F-117 and B-2.

The United States Government defines 4.5 generation fighter aircraft as fourth generation jet fighters that have been upgraded with AESA radar, high capacity data-link, enhanced avionics, and "the ability to deploy current and reasonably foreseeable advanced armaments."

## Design considerations

### Performance



Mitsubishi F-2

General performance has traditionally been the most important class of design characteristics, as it enables a fighter to gain a favorable position to use its weapons while rendering the enemy unable to use theirs. This can occur at long range (beyond visual

range or BVR) or short range (within visual range or WVR). At short range, the ideal position is to the rear of the enemy aircraft, where it is unable to aim or fire weapons and the hot exhaust makes a good target for infrared-guided missiles. At longer BVR range, the probability of a successful missile intercept is improved by launch at high energy, kinetic (the aircraft's speed towards its target) and potential (altitude advantage). Being able to maneuver violently, and without losing energy meanwhile increases the chance of evading enemy missiles, or escape out of range of the likely return-fire.

These two scenarios have competing demands — interception requires excellent linear speed, while Within Visual Range or WVR engagements require excellent turn rate, while maintaining speed, rapid acceleration, and availability of control at low-speeds and high angle of attack.

Prior to the 1970s, a popular view in the defense community was that missiles would render WVR combat obsolete and hence maneuverability useless. Combat experience proved this untrue due to the poor quality of missiles and the recurring need to identify targets visually. Though improvements in missile technology may make that vision a reality, experience has indicated that sensors are not foolproof and that fighters will still need to be able to fight and maneuver at close ranges. So whereas the premier third-generation jet fighters (e.g., the F-4 and MiG-23) were designed as interceptors with only a secondary emphasis on maneuverability, interceptors have been relegated to a secondary role in the fourth generation, with a renewed emphasis on maneuverability. While the trade-offs involved in combat aircraft design are again shifting towards BVR engagement, the management of the advancing environment of numerous information flows in the modern battle-space, and low-observability, arguably at the expense of maneuvering ability in close-combat, the application of thrust vectoring provides a way to maintain it, especially at low speed.

There are two primary contributing factors to maneuverability — the amount of thrust delivered by the engines, and the ability of the aircraft's control surfaces to efficiently generate aerodynamic forces, and hence alterations in the plane's direction. Air-combat maneuvering (ACM) involves a great deal of energy management. The greater energy a fighter has, the more flexibility it has to move where it wants. An aircraft with little energy is immobile, and a defenseless target. Note that available thrust does not necessarily equal speed; while it does give greater acceleration, the maximum speed of an aircraft is also determined by how much drag it produces. Herein lies one important trade-off. Low-drag configurations have small, often highly swept wings that disrupt the airflow as little as possible. However, that also means they have greatly reduced ability to alter the airflow to maneuver the aircraft.

There are two rough indicators of these factors. A plane's turning ability can be roughly measured by its wing loading, defined as the mass of the aircraft divided by the area of its lifting surfaces. A highly loaded wing has little capacity to produce additional lift, and so has limited turning ability, whereas a lightly loaded wing has much greater potential lifting power. A rough measure of acceleration is a plane's thrust-to-weight ratio.

## Fly-by-wire



The F/A-18 inverted above an F-14 shown here is an example of Fly-by-wire control.

The Fourth generation jet fighter defining point is Fly-by-wire, like 4.5 is defined on AESA radar. YF-16 was the world's first aircraft intentionally designed to be slightly aerodynamically unstable. This technique, called "relaxed static stability" (RSS), was incorporated to further enhance the aircraft's performance. Most aircraft are designed with *positive* static stability, which induces an aircraft to return to its original attitude following a disturbance. However, positive static stability; the tendency to remain in its current attitude; opposes the pilot's efforts to maneuver. On the other hand, an aircraft with *negative* static stability will, in the absence of control input, readily deviate from level and controlled flight.

An aircraft with negative static stability can therefore be made more maneuverable. At supersonic airspeed, a negatively stable aircraft can exhibit positive static stability due to aerodynamic center migration. To counter this tendency to depart from controlled flight—and avoid the need for constant minute trimming inputs by the pilot—the 4th gen aircraft has a quadruplex (four-channel) fly-by-wire (FBW) flight control system (FLCS). The flight control computer (FLCC), which is the key component of the FLCS, accepts the pilot's input from the stick and rudder controls, and manipulates the control surfaces in such a way as to produce the desired result without inducing a loss of control. The FLCC also takes thousands of measurements per second of the aircraft's attitude, and automatically makes corrections to counter deviations from the flight path that were not input by the pilot, coordinated turn is also obtained in such a way that it updates itself by

thousands of instructions and produces the required control thereby allowing for stable flight.

### **Thrust vectoring**



MiG-29OVT all-aspect thrust vectoring engine view

Thrust vectoring is a new technology being introduced to further enhance a fighter's turning ability. By redirecting the jet exhaust, it is possible to directly translate the engine's power into directional changes, more efficiently than via the plane's control surfaces. The Sukhoi Su-30 MKI, produced by India under license at Hindustan Aeronautics Limited is in active service with the Indian Air Force, and employs 2D thrust vectoring. The 2D TVC makes the aircraft highly maneuverable, capable of near-zero airspeed at high angles of attack without stalling, and dynamic aerobatics at low speeds. The TVC nozzles of the MKI are mounted 32 degrees outward to longitudinal engine axis (i.e. in the horizontal plane) and can be deflected  $\pm 15$  degrees in the vertical plane. This produces a corkscrew effect, greatly enhancing the turning capability of the aircraft. The MiG-35 with its RD-33OVT engines with the vectored thrust nozzles allows it to be the first twin-engine aircraft with vectoring nozzles that can move in two directions that is 3D TVC. Other existing thrust vectoring aircraft, like the Su-30MKI and the F-22, have nozzles that vector in one direction. The technology has been fitted to the Sukhoi Su-47

Berkut and later derivatives. The U.S. explored fitting the technology to the F-16 and the F-15, but only introduced it on the F-22 Raptor.

## Supercruise



Rafale features supercruise

Supercruise is the ability of aircraft to cruise at supersonic speeds without the afterburner.

Because of parasitic drag effects, fighters carrying external weapons stores encounter a vastly increased drag-divergence near the speed of sound. This can prevent safe acceleration through the transonic regime, or make it too fuel-expensive to be effective on missions. Meanwhile, maintaining supersonic speed without (periodic) afterburner use saves large quantities of fuel too, increasing the range at which an aircraft can in reality still take advantage of its full performance.

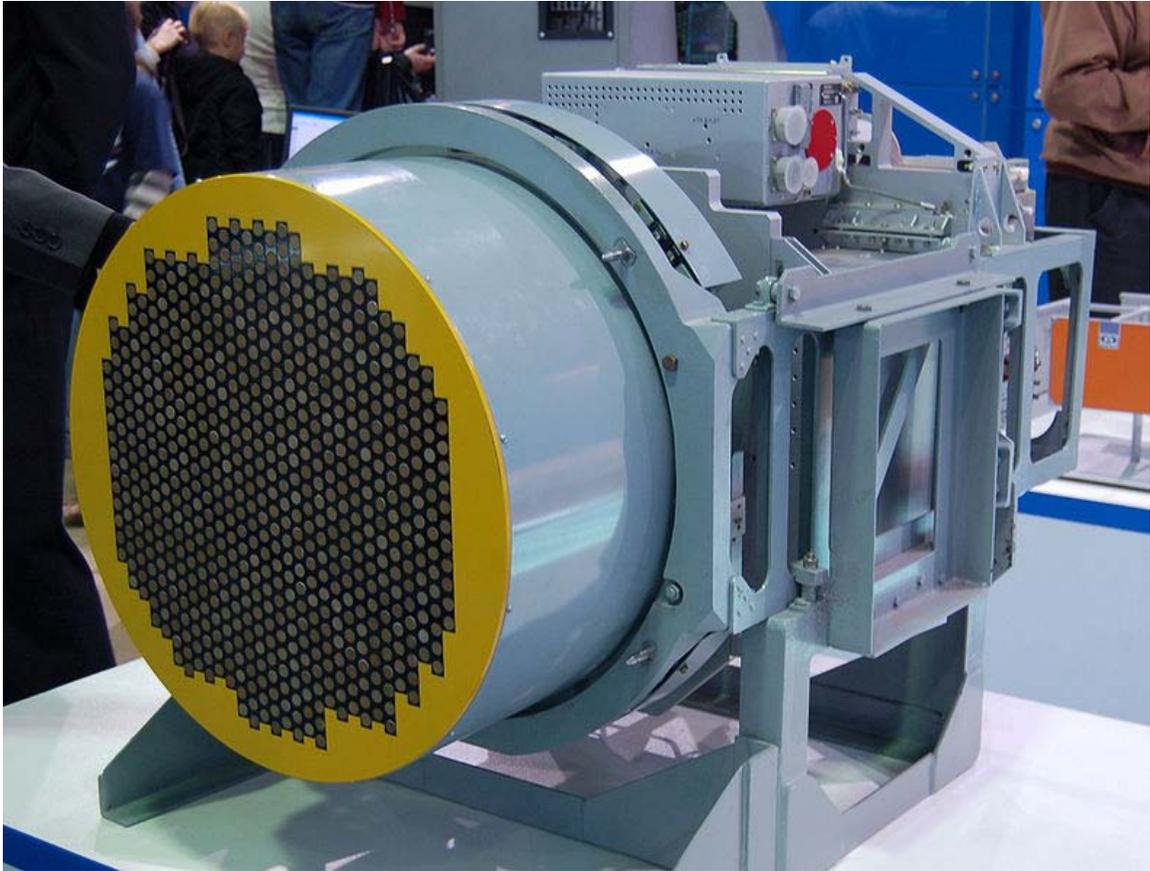
According to the German Luftwaffe the Typhoon can cruise at about Mach 1.2 without afterburner. The manufacturer claims that the maximum level speed possible without reheat is Mach 1.5. A EF T1 DA (Development Aircraft trainer version) demonstrate supercruise (1,21M) with 2 SRAAM, 4 MRAAM and drop tank (plus one tonne flight test equipment, plus 700 kg more weight for the trainer version) during the Singapore evaluation. The Rafale can supercruise, in dry power, even with four missiles and a belly drop tank.

## Avionics



F-15E cockpit

Avionics is a catch-all term for the electronic systems aboard an aircraft, which have been growing in complexity and importance. The main elements of an aircraft's avionics are its communication and navigation systems, sensors (Radar and IR sensors), computers and data bus, and user interface. Because they can be readily swapped out as new technologies become available, they are often upgraded over the lifetime of an aircraft. Details about these systems are highly protected. Since many export aircraft have downgraded avionics, many buyers substitute domestically developed avionics, (sometimes considered superior to the original). For example, the Sukhoi Su-30MKI sold to India, the F-15I and F-16I sold to Israel, and the F-15K sold to South Korea.



Zhuk-AE AESA radar

The primary sensor for all modern fighters is radar. The U.S. fielded its first modified F-15Cs equipped with APG-63(V)2 AESA radars, which have no moving parts and are capable of projecting a much tighter beam and quicker scans. Later on, it was introduced to the F/A-18E/F Super Hornet, and the block 60 (export) F-16 also, and will be used for future American fighters. A European coalition GTDAR is developing an AESA radar for use on the Typhoon and Rafale, Russia has an AESA radar on MIG-35 and the newest Su-27 versions. For the next-generation F-22 and F-35, the U.S. will utilize Low Probability of Intercept (LPI) capacity. This will spread the energy of a radar pulse over several frequencies, so as not to trip the radar warning receivers that all aircraft carry.



The OLS-30 is a combined IRST/LR device

In reaction to the increasing American emphasis on radar-evading stealth designs, the Soviet Union turned to alternate sensors. This drove them to emphasize infra-red search and track (IRST) sensors, first introduced on the American F-101 Voodoo and F-102 Delta Dagger fighters in the 1960s, for detection and tracking of airborne targets. These measure IR radiation from targets. As a passive sensor it has limited range, and contains no inherent data about position and direction of targets - these must be inferred from the images captured. To offset this, IRST systems can incorporate a laser rangefinder in order to provide full fire-control solutions for cannon fire or launching missiles. Using this method, German MiG-29 using helmet-displayed IRST systems were able to acquire a missile lock with greater efficiency than USAF F-16 in wargame exercises. IRST sensors have now become standard on Russian aircraft. With the exception of the F-14D

(officially retired as of September 2006), no 4th-generation Western fighters carry built-inIRST sensors for air-to-air detection, though the similar FLIR is often used to acquire ground targets.

The Eurofighter Typhoon designated '4.5th generation' (beginning with Tranche 1 Block 5 aircraft, while previously build aircraft are being retrofited since spring 2007) and the F-35s will have built-in, PIRATE IRST sensors, a feature adopted early in the design, meanwhile beginning in 2012 the Super Hornet will also have an IRST.

The tactical implications of the computing and data bus capabilities of aircraft are hard to determine. A more sophisticated computer bus would allow more flexible uses of the existing avionics. For example, it is speculated that the F-22 is able to jam or damage enemy electronics with a focused application of its radar. A computing feature of significant tactical importance is the datalink. All of the modern European and American aircraft are capable of sharing targeting data with allied fighters and from AWACS planes. The Russian MiG-31 interceptor also has some datalink capability, so it is reasonable to assume that other Russian planes can also do so. The sharing of targeting and sensor data allows pilots to put radiating, highly visible sensors further from enemy forces, while using that data to vector silent fighters toward the enemy.

## **Stealth technology**

Stealth technology is an extension of the notion of visual camouflage to modern radar and IR detection sensors. While not rendering an aircraft "invisible" as is popularly conceived, stealth makes an aircraft much more difficult to discern among the sky, clouds, or distant aircraft, conferring a significant tactical advantage. While the basic principles of shaping aircraft to avoid detection were known at least since the 1960s, it was not until the availability of supercomputers that shape computations could be performed from every angle, a complex task. The use of computer-aided shaping, combined with radar-absorbent materials, produced aircraft of drastically reduced radar cross section (RCS) that were much more difficult to detect on radar. Meanwhile advances in digital flight control make potentially destabilizing, or control-complicating effects of shape alterations easier to compensate for.

During the 1970s, the rudimentary level of stealth shaping (as seen in the faceted design of the F-117 Nighthawk) resulted in too severe a performance penalty to be used on fighters. Faster computers enabled smoother designs such as the B-2 Spirit, and thought was given to applying the basic ideas to decrease, if not drastically reduce, the RCS of fighter aircraft. These techniques are also combined with methods of decreasing the IR, visual, and aural signature of the aircraft. While fighters designated 4.5th generation under the US-devised system incorporate some low-observable features, so-called fifth generation fighters have more clearly been designed with this as a very high priority. The inclusion of this as a criterion for the designation of "fifth generation" serves to illustrate the degree to which US manufacturers and their clients appear to assign value to this capability.



Eurofighter Typhoon has a largely conventional configuration, but exhibits a substantially lower radar cross-section

than its predecessors.

There are some reports that the Dassault Rafale's avionics, the Thales Spectra, includes "stealthy" radar jamming technology, and systems for the active cancellation of RADAR analogous to the acoustic noise suppression systems on the De Havilland Canada Dash 8. Conventional jammers make locating an aircraft more difficult, but their operation is itself detectable, with missiles being designed more recently to endeavor to follow the jamming itself. The French system is hypothesized to interfere with detection without revealing that jamming is in operation.

Such a system ought in principle to be able to make an aircraft entirely invisible, were it to be feasible to actively mimic an undisturbed RADAR signature (canceling all reflections, and compensating for any RADAR shadow) however such a system would be incalculably difficult and is not envisaged. Meanwhile the real effectiveness of systems that allegedly exist is unknown.

Research continues into other ways of decreasing observability by radar. There are claims that Russian researchers are working on "plasma stealth". Obviously, such techniques might well remove some of the envisaged advantages held by fifth generation aircraft, adding to skepticism over the real value of the "generation" label, which seems to assume the superiority and uniqueness of particular design philosophies. An aircraft with no stealth features, but some advanced ability to detect "stealth" for example, may not "qualify" and yet hold equal advantages to current US aircraft. As yet no such capability has been demonstrated however.

There are in any case ways to detect fighters other than radar. For instance, passive infra-red sensors can detect the heat of engines, and even the sound of a sonic boom (which any supersonic aircraft will make) can be tracked with a network of sensors and computers. However, using these to provide precise targeting information for a long-range missile is considerably less straightforward than radar.

## Combat performance

The F-15 and F-16 have the first and second best known overall combat records of modern jet fighters. F-15s have a claimed combat record of 101 victories and zero losses in actual air to air combat. Naturally such statistics take no account of the quality of the opposition, and are of limited use in comparing aircraft that have not been sent on identical missions, much less against one another.

- 1982 Lebanon War, during the latter, Israeli Air Force credited their F-15s and F-16s with 86 air-to-air kills, mostly of MiG-21s and MiG-23s, while suffering no air-to-air losses of their own.
- Iran–Iraq War, saw the first instance of employing 4th generation jet fighters open war. Iran used F-14s and Iraq deployed MiG-29s, although there are no reports of the two aircraft types actually engaging each other.
- 1991 Gulf War
  - On 17 January 1991, the first night of the Gulf War, an Iraqi MiG-25PD shot down a U.S. Navy F/A-18C (piloted by Lt Cdr Scott Speicher), which was lost 29 nautical miles (54 km) southeast of Baghdad.
  - During the 1991 Gulf War, USAF F-15 pilots shot down five Iraqi MiG-29s.
- On 8 October 1996, after the escalation over Imia/Kardak a Greek Mirage 2000 fired an R550 Magic and shot down a Turkish F-16D over the Aegean Sea. The Turkish pilot died, while the co-pilot ejected and was rescued by Greek forces.
- 1999 Kosovo War,
  - a Dutch F-16 pilot shot down a Yugoslavian MiG-29 and a USAF F-16 pilot also shot down a MiG-29.
  - USAF F-15 pilots shot down four MiG-29s.
- Eritrean-Ethiopian War. In February 1999, according to some reports, Ethiopian Su-27 pilots shot down four Eritrean MiG-29s. Some of these sources claim that the Ethiopian planes were flown by Russian pilots, and the Eritrean planes by Ukrainians. (It is certainly true that local pilots were trained by instructors from those nations.)

## Exercise reports

Different air forces regularly practice against each other in exercises, and when they fly different aircraft some indication of the relative capabilities of the aircraft can be gained.



An Indian air force Su-30MKI Flanker lands here following a simulated combat mission with U.S. Air Force F-15 Eagles during Cope India '04.

During the "Cope India '04" exercise (2004), USAF F-15 Eagles were pitted against Indian Air Force Su-30MKs, Mirage 2000s, MiG-29s and elderly MiG-21s. The results have been widely publicized, with the Indians winning "90% of the mock combat missions". The "Cope India 2005" exercise was conducted with teams that used a combination of United States and Russian-designed aircraft. The *Christian Science Monitor* (CSM) reported that "both the Americans and the Indians won, and lost." However, it also noted "that in a surprising number of encounters — particularly between the American F-16s and the Indian Sukhoi-30 MKIs — the Indian pilots came out the winners.

According to the same article the Indian air force designed Cope 2005 in that the rules of engagement be that the forces fight within visual range, and both forces could not take advantage of their long range sensors or weapons.

In July 2007, the Indian Air Force fielded the MKI (Sukhoi Su-30MKI) during the *Indra-Dhanush* exercise with Royal Air Force's Eurofighter Typhoon. This was the first time that the two jets had taken part in such a exercise. The IAF did not allow their pilots to

use the radar of the MKIs during the exercise so as to protect the highly-classified N011M Bars. During the exercise, the RAF pilots candidly admitted that the MKI displayed maneuvering superior to that of the Typhoon.

In June 2005, a Royal Air Force Eurofighter trainer two seater was reportedly able, in a mock confrontation, to avoid two pursuing F-15E fighter-bombers and outmaneuver them, to get into a shooting position. It is to be noted that despite the nomenclature that seems designed to lump these aircraft together, the RAF Typhoon aircraft has been designed in principle to supersede aircraft such as the F-15 which has been in service for some decades.

## Chapter- 9

# Example of Fourth Generation Jet Fighter Aircraft

## General Dynamics F-16 Fighting Falcon

### F-16 Fighting Falcon



A USAF F-16C over Iraq in 2008

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<b>Role</b>	Multirole Fighter
<b>National origin</b>	United States
<b>Manufacturer</b>	General Dynamics Lockheed Martin
<b>First flight</b>	2 February 1974
<b>Introduction</b>	17 August 1978
<b>Status</b>	Active, in production
<b>Primary users</b>	United States Air Force 25 other users
<b>Number built</b>	4,450+
<b>Unit cost</b>	F-16A/B: US\$14.6 million (1998 dollars) F-16C/D: US\$18.8 million (1998 dollars)
<b>Variants</b>	General Dynamics F-16 VISTA
<b>Developed into</b>	General Dynamics F-16XL Mitsubishi F-2

The **General Dynamics F-16 Fighting Falcon** is a multirole jet fighter aircraft originally developed by General Dynamics for the United States Air Force. Designed as a lightweight, daytime fighter, it evolved into a successful multirole aircraft. Over 4,400 aircraft have been built since production was approved in 1976. Though no longer being

purchased by the U.S. Air Force, improved versions are still being built for export customers. In 1993, General Dynamics sold its aircraft manufacturing business to the Lockheed Corporation, which in turn became part of Lockheed Martin after a 1995 merger with Martin Marietta.

The Fighting Falcon is a dogfighter with numerous innovations including a frameless bubble canopy for better visibility, side-mounted control stick to ease control while maneuvering, a seat reclined 30 degrees to reduce the effect of g-forces on the pilot, and the first use of a relaxed static stability/fly-by-wire flight control system that makes it a highly nimble aircraft. The F-16 has an internal M61 Vulcan cannon and has 11 hardpoints for mounting weapons, and other mission equipment. Although the F-16's official name is "Fighting Falcon", it is known to its pilots as the "Viper", due to it resembling a viper snake and after the *Battlestar Galactica* Colonial Viper starfighter.

In addition to USAF active, reserve, and air national guard units, the aircraft is used by the USAF aerial demonstration team, the U.S. Air Force Thunderbirds, and as an adversary/aggressor aircraft by the United States Navy. The F-16 has also been selected to serve in the air forces of 25 other nations.

## Development

### Lightweight Fighter program

Experience in the Vietnam War revealed the need for air superiority fighters and better air-to-air training for fighter pilots. Based on his experiences in the Korean War and as a fighter tactics instructor in the early 1960s Colonel John Boyd with mathematician Thomas Christie developed the Energy-Maneuverability theory to model a fighter aircraft's performance in combat. Boyd's work called for a small, lightweight aircraft with an increased thrust-to-weight ratio. A 1965 Air Force study suggested equipping its squadrons with a mix of high and low cost fighters as being the most economical. In the late 1960s, Boyd gathered around him a group of like-minded innovators that became known as the "Fighter Mafia". In 1969, the group secured DoD funding for General Dynamics and Northrop to study design concepts based on the Energy-Maneuverability theory.

Although the Air Force's FX proponents remained hostile to the concept because they perceived it as a threat to the F-15 program, the Advanced Day Fighter concept (revamped and renamed "F-XX") gained civilian political support under the reform-minded Deputy Secretary of Defense David Packard, who favored the idea of competitive prototyping. As a result in May 1971, the Air Force Prototype Study Group was established, with Boyd a key member, and two of its six proposals would be funded, one being the Lightweight Fighter (LWF) proposal. The Request for Proposals issued 6 January 1972 called for a 20,000 lb (9,100 kg) class air-to-air day fighter with a good turn rate, acceleration and range, and optimized for combat at speeds of Mach 0.6–1.6 and altitudes of 30,000–40,000 ft (9,100–12,000 m). This was the region where USAF studies predicted most future air combat to occur. The anticipated average flyaway cost of a

production version was \$3 million. This production plan, though, was only notional as the USAF had no firm plans to procure the winner.

### **Finalists selected and flyoff**

Five companies responded and in 1972, the Air Staff selected General Dynamics' Model 401 and Northrop's P-600 for the follow-on prototype development and testing phase. GD and Northrop were awarded contracts worth \$37.9 million and \$39.8 million to produce the YF-16 and YF-17, respectively, with first flights of both prototypes planned for early 1974. To overcome resistance in the Air Force hierarchy, the 'Fighter Mafia' and other LWF proponents successfully advocated the idea of complementary fighters in a high-cost/low-cost force mix (in part, to be able to afford sufficient fighters to sustain overall USAF fighter force structure requirements); this "high/low mix" concept would gain broad acceptance by the time of the flyoff between the prototypes, and would define the relationship of the F-15 and F-16.



A right side view of a YF-16 and a Northrop YF-17, each armed with AIM-9 Sidewinder missiles.

The first YF-16 was rolled out on 13 December 1973, and its 90-minute-long maiden flight was made at the Air Force Flight Test Center (AFFTC) at Edwards AFB,

California, on 2 February 1974. Its *actual* first flight occurred accidentally during a high-speed taxi test on 20 January 1974. While gathering speed, a roll-control oscillation caused a fin of the port-side wingtip-mounted missile and then the starboard stabilator to scrape the ground, and the aircraft then began to veer off the runway. The GD test pilot, Phil Oestricher, decided to lift off to avoid wrecking the machine, and safely landed it six minutes later. The slight damage was quickly repaired and the official first flight occurred on time. The YF-16's first supersonic flight was accomplished on 5 February 1974, and the second YF-16 prototype flew for the first time on 9 May 1974. This was followed by the first flights of the Northrop's YF-17 prototypes, which were achieved on 9 June and 21 August 1974, respectively. The YF-16s completed 330 sorties during the flyoff, accumulating a total of 417 flight hours; the YF-17s flew 268 sorties.

### **Air Combat Fighter competition**

Three factors would converge to turn the LWF into a serious acquisition program. First, four North Atlantic Treaty Organization (NATO) allies of the U.S. – Belgium, Denmark, the Netherlands, and Norway – were looking to replace their F-104G fighter-bombers. In early 1974, they reached an agreement with the U.S. that if the USAF ordered the LWF winner, they would consider ordering it as well. Secondly, while the USAF was not particularly interested in a complementary air superiority fighter, it did need to begin replacing its F-4 and F-105 Thunderchief fighter-bombers. Third, the U.S. Congress sought greater commonality in fighter procurements by the Air Force and Navy, and in August 1974 redirected Navy funds to a new Navy Air Combat Fighter (NACF) program that would be a navalized fighter-bomber variant of the LWF. The four European allies had formed a “Multinational Fighter Program Group” (MFPG) and were pressing for a U.S. decision by December 1974. The U.S. Air Force had planned to announce the LWF winner in May 1975, but this decision was advanced to the beginning of the year, and testing was accelerated.

To reflect this more serious intent to procure a new fighter-bomber design, the LWF program was rolled into a new Air Combat Fighter (ACF) competition in an announcement by U.S. Secretary of Defense James R. Schlesinger in April 1974. Schlesinger also made it clear that any ACF order would be for aircraft in addition to the F-15, which extinguished opposition to the LWF. ACF also raised the stakes for GD and Northrop because it brought in further competitors intent on securing the lucrative order that was touted at the time as “the arms deal of the century”. These were Dassault-Breguet's Mirage F1M-53, the SEPECAT Jaguar, and a proposed derivative of the Saab 37 Viggen named the “Saab 37E Eurofighter”. Northrop offered the P-530 Cobra, which was very similar to its YF-17. The Jaguar and Cobra were dropped by the MFPG early on, leaving two European and the two U.S. candidates. On 11 September 1974, the U.S. Air Force confirmed firm plans to place an order for the winning ACF design sufficient to equip five tactical fighter wings. On 13 January 1975, Secretary of the Air Force John L. McLucas announced that the YF-16 had been selected as the winner of the ACF competition.



YF-16 on display at the Virginia Air and Space Center

The chief reasons given by the Secretary for the decision were the YF-16's lower operating costs, greater range and maneuver performance that was "significantly better" than that of the YF-17, especially at near-supersonic and supersonic speeds. Another advantage was the fact that the YF-16 – unlike the YF-17 – employed the Pratt & Whitney F100 turbofan engine, which was the same powerplant used by the F-15; such commonality would lower the unit costs of the engines for both programs.

Shortly after selection of the YF-16, Secretary McLucas revealed that the USAF planned to order at least 650 and up to 1,400 of the production version of the aircraft. The U.S. Air Force initially ordered 15 "Full-Scale Development" (FSD) aircraft (11 single-seat and four two-seat models) for its flight test program, but this was reduced to eight (six F-16A single-seaters and two F-16B two-seaters). In the Navy Air Combat Fighter (NACF) competition, the Navy announced on 2 May 1975 that it selected the YF-17 as the basis for what would become the McDonnell Douglas F/A-18 Hornet.

## Moving into production



A USAF F-16C of the Colorado Air National Guard (COANG) disengages from a refueling boom (fuel port is still open) over Canada.

Manufacture of the FSD F-16s got underway at General Dynamics' Fort Worth, Texas plant in late 1975, with the first example, an F-16A, being rolled out on 20 October 1976, followed by its first flight on 8 December. The initial two-seat model achieved its first flight on 8 August 1977. The initial production-standard F-16A flew for the first time on 7 August 1978 and its delivery was accepted by the USAF on 6 January 1979. The F-16 was given its formal nickname of "Fighting Falcon" on 21 July 1980, entering USAF operational service with the 388th Tactical Fighter Wing at Hill AFB on 1 October 1980.

On 7 June 1975, the four European partners, now known as the European Participation Group, signed up for 348 aircraft at the Paris Air Show. This was split among the European Participation Air Forces (EPAF) as 116 for Belgium, 58 for Denmark, 102 for the Netherlands, and 72 for Norway. These would be produced on two European production lines, one in the Netherlands at Fokker's Schiphol-Oost facility and the other at SABCA's Gosselies plant in Belgium; production would be divided among them as 184 and 164 units, respectively. Norway's Kongsberg Vaapenfabrikk and Denmark's Terma A/S also manufactured parts and subassemblies for the EPAF aircraft. European co-production was officially launched on 1 July 1977 at the Fokker factory. Beginning in mid-November 1977, Fokker-produced components were shipped to Fort Worth for assembly of fuselages, which were in turn shipped back to Europe (initially to Gosselies starting in January 1978); final assembly of EPAF-bound aircraft began at the Belgian plant on 15 February 1978, with deliveries to the Belgian Air Force beginning in January 1979. The Dutch line started up in April 1978 and delivered its first aircraft to the Royal Netherlands Air Force in June 1979. In 1980 the first aircraft were delivered to the Royal Norwegian Air Force by SABCA and to the Royal Danish Air Force by Fokker.

Since then, a further production line has been established at Ankara, Turkey, where Turkish Aerospace Industries (TAI) has produced 232 Block 30/40/50 F-16s under license for the Turkish Air Force during the late 1980s and 1990s, and has 30 Block 50 Advanced underway for delivery from 2010; TAI also built 46 Block 40s for Egypt in the mid-1990s. Korean Aerospace Industries opened another production line for the KF-16 program, producing 140 Block 52s from the mid-1990s to mid-2000s. If India selects the F-16IN for its Medium Multi-Role Combat Aircraft procurement, a sixth F-16 production line will be established in that nation to produce at least 108 fighters.

## Evolution



F-16 Fighting Falcon

After selection, the YF-16 design was altered for the production F-16. The fuselage was lengthened 10.6 in (0.269 m), a larger nose radome was fitted to house the AN/APG-66 radar, wing area was increased from 280 sq ft (26 m<sup>2</sup>) to 300 sq ft (28 m<sup>2</sup>), the tailfin

height was decreased slightly, the ventral fins were enlarged, two more stores stations were added, and a single side-hinged nosewheel door replaced the original double doors. These modifications increased the F-16's weight approximately 25% over that of the YF-16 prototypes.

One needed change that would originally be discounted was the need for more pitch control to avoid deep stall conditions at high angles of attack. Model tests of the YF-16 conducted by the Langley Research Center revealed a potential problem, but no other laboratory was able to duplicate it. YF-16 flight tests were not sufficiently extensive to resolve the issue, but relevant flight testing on the FSD aircraft demonstrated that it was a real concern. As a result, the horizontal stabilizer areas were increased 25%; this so-called "big tail" was introduced on the Block 15 aircraft in 1981 and retrofitted later on earlier production aircraft. Besides significantly reducing (though not eliminating) the risk of deep stalls, the larger horizontal tails also improved stability and permitted faster takeoff rotation.

In the 1980s, the Multinational Staged Improvement Program (MSIP) was conducted to evolve new capabilities for the F-16, mitigate risks during technology development, and ensure its currency against a changing threat environment. The program upgraded the F-16 in three stages. Altogether, the MSIP process permitted quicker introduction of new capabilities, at lower costs, and with reduced risks compared to traditional stand-alone system enhancement and modernization programs. The F-16 has been involved in other upgrade programs including service life extension programs in the 2000s.

# Design

## Overview



The four-vent cannon port on an F-16A

The F-16 is a single-engined, supersonic, multi-role tactical aircraft. The F-16 was designed to be a cost-effective combat "workhorse" that can perform various kinds of missions and maintain around-the-clock readiness. It is much smaller and lighter than its predecessors, but uses advanced aerodynamics and avionics, including the first use of a relaxed static stability/fly-by-wire (RSS/FBW) flight control system, to achieve enhanced maneuver performance. Highly nimble, the F-16 can pull 9-g maneuvers and can reach a maximum speed of over Mach 2.

The Fighting Falcon includes innovations such as a frameless bubble canopy for better visibility, side-mounted control stick to ease control during combat maneuvers, and reclined seat to reduce the effect of g-forces on the pilot. The F-16 has an internal M61 Vulcan cannon in the left wing root and has 11 hardpoints for mounting various missiles, bombs and pods. It was also the first fighter aircraft purpose built to sustain 9-g turns. It has a thrust-to-weight ratio greater than one, providing power to climb and accelerate vertically.

The F-16A is distinguished by having four vents behind the port for the M61 cannon whereas the subsequent F-16C has only two vents behind the cannon port.

Early models could also be armed with up to six AIM-9 Sidewinder heat-seeking short-range air-to-air missiles (AAM), including a single missile mounted on a dedicated rail launcher on each wingtip. Some variants can also employ the AIM-7 Sparrow medium-range radar-guided AAM, and more recent versions can be equipped with the AIM-120 AMRAAM. It can also carry other AAM; a wide variety of air-to-ground missiles, rockets or bombs; electronic countermeasures (ECM), navigation, targeting or weapons pods; and fuel tanks on eleven hardpoints – six under the wings, two on wingtips and three under the fuselage.

## Chapter- 10

# Fifth Generation and Sixth Generation Jet Fighter Aircraft

## Fifth generation jet fighter Aircraft



USAF F-22 Raptor launching an AIM-120 AMRAAM missile

A **fifth-generation jet fighter** is a fighter aircraft classification used in the United States encompassing the most advanced generation of fighter aircraft. Fifth-generation aircraft are the most advanced as of 2011, designed to incorporate numerous technological advancements over the class similarly dubbed *fourth generation*, including all-aspect stealth even when armed, Low Probability of Intercept Radar (LPIR), high-performance air frames, advanced avionics features, and highly integrated computer systems capable of networking with other elements within the theater of war in order to achieve an advantage in situational awareness. The only currently combat-ready fifth-generation fighter, the Lockheed Martin F-22 Raptor, entered service with the U.S. Air Force in 2005.

## History



F-35 Lightning II, marked AA-1, lands on 23 October 2008 at Edwards Air Force Base.

Previous generation stealth aircraft, such as the B-2 Spirit and F-117 Nighthawk, lacked LPI Active Electronically Scanned Array (AESA) radars, and LPI radio networks, and were thus limited to attacking ground targets, because use of radar to engage other aircraft would have revealed the aircraft's position.

## **Current status**

Currently the only combat ready fifth generation jet fighter is the F-22 Raptor. US fighter manufacturer Lockheed Martin uses "fifth generation fighter" to describe the F-22 and F-35 fighters, with the definition including "advanced stealth", "extreme performance", "information fusion" and "advanced sustainment". Their definition does not include supercruise capability, which has typically been associated with the more advanced modern fighters, but which the F-35 lacks. Lockheed Martin attempted to trademark the term "5th generation fighters" in association with jet aircraft and structural parts thereof, and has a trademark to a logo with the term.

## Critics and alternate definitions



PAK FA during flight testing in 2010.

The use of the term fifth generation fighter has been criticized by companies whose products do not conform to these particular specifications, such as Boeing and Eurofighter as well as by other commentators, such as Bill Sweetman: "...it is misleading to portray the F-22 and F-35 as a linear evolution in fighter design. Rather, they are a closely related pair of outliers, relying on a higher level of stealth as a key element of survivability - as the Lockheed YF-12 and Mikoyan MIG-25, in the 1960s, relied on speed and altitude." The United States Navy and Boeing have placed the Boeing F/A-18E/F Super Hornet in a "next generation" fighter category along with the F-22 and F-35, as the Super Hornet has a "fifth generation" AESA radar, modest radar cross-section (RCS) reductions and sensor fusion. A senior USAF pilot has complained about fifth generation claims for the Super Hornet: "The whole point to fifth generation is the synergy of stealth, fusion and complete situational awareness. The point about fifth generation aircraft is that they can do their mission anywhere - even in sophisticated integrated air defense [IADS] environments. If you fly into heavy IADS with a great radar and sensor fusion, but no stealth, you will have complete situational awareness of the guy that kills you." Michael "Ponch" Garcia of Raytheon has said that the addition of his company's AESA radars to the Super Hornet provides "90 percent of your fifth-generation capability at half the cost."

Apparently in response to the use of the "fifth generation" term, Eurofighter has made a fifth generation checklist placing different weights on the various capabilities, and arguing that the application of the label to strike aircraft such as Lockheed-Martin's F-35 is ill advised, and even inconsistent with the aircraft's specifications. Meanwhile, Eurofighter go on to refer to Link 16 capability, an already well established system, as fulfilling a requirement for 'net-enabled operations' seemingly assigning reduced importance to maintaining low observability of such operations. In the same article

Eurofighter GmbH appear to acknowledge the remarkable performance of Lockheed Martin's F-22 aircraft, while demonstrating that labels as simple as "fifth generation" may easily be devised to serve the interests of the writer.

## **Developments**

In the late 1980s, the Soviet Union outlined a need for a next-generation aircraft to replace 4th generation fighter aircraft: MiG-29 Fulcrum and Su-27 Flanker in frontline service. Two projects were proposed to meet this need, the 4.5th generation fighter aircraft: Su-47 Berkut and the MiG-1.44 Flatpack (although later modernized MiG-35 to 4.5th generation fighter). In 2002, Sukhoi was chosen to lead the design for the new combat aircraft. The 5th generation fighter aircraft - Sukhoi PAK FA (T-50) will incorporate technology from both the Su-47 and the MiG 1.44 and when fully developed is intended to replace the MiG-29 and Su-27 in the Russian inventory and serve as the basis of the Sukhoi/HAL FGFA project being developed with India. A fifth generation jet fighter, it is designed to directly compete with the American F-22 Raptor and American/British F-35 Lightning II. The Sukhoi PAK FA performed its first flight January 29, 2010. Russia is now constructing a new stealth lightweight multirole fighter - MiG-LMFS (aka Projekt 1.27, MiG-1.27) by Mikoyan aircraft manufacturer. This jet fighter is based on the cancelled MiG 1.44.

By late 1990s, several Chinese fifth generation fighter programs, grouped under the program codename J-XX or XXJ, were identified by western intelligence sources. PLAAF officials have confirmed the existence of such a program, which they estimate will enter service between 2017-2019. Nevertheless, the United States has predicted that it may possess as much as 20 times more "advanced stealth fighters" than the Chinese by 2020. By late 2010, it had emerged that two prototypes (#2001 & 2002) of the Chengdu J-20 had been constructed and were undergoing high-speed taxi trials.. The J-20 made its first flight on 11 January 2011.

India is also developing Medium Combat Aircraft, a Twin-engined 5th generation stealth multirole fighter apart from Sukhoi/HAL FGFA project being developed with Russia. The main purpose of this aircraft is to replace the aging SEPECAT Jaguar & Dassault Mirage 2000. Unofficial design work on the MCA has been started.

South Korea has its own project to build a 5th generation fighter, called KAI KF-X, while Japan also has project Mitsubishi ATD-X.

## **Common design elements**

In order to minimize their RCS, all fifth generation fighters use chines instead of standard leading edge extensions and lack canards, though the Sukhoi PAK FA T-50 has engine intake extensions that seem to function somewhat like canards and the Chengdu J-20 designers have chosen the agility enhancements of canards in spite of their poor stealth

characteristics. They all have twin canted vertical tails also to minimize side RCS. Most fifth generation fighters with supermaneuverability achieve it through thrust vectoring.

They all have internal weapon bays in order to avoid high RCS weapon pylons, but they all have external hardpoints on their wings for use on non-stealthy missions, such as the external fuel tanks the F-22 carries when deploying to a new theater.

All fifth generation fighters have a high percentage of composite materials, in order to reduce RCS and weight.

All revealed fifth generation fighters leverage commercial off-the-shelf main processors to directly control all sensors to form a consolidated view of the battlespace with both onboard and networked sensors, while previous generation jet fighters used federated systems where each sensor or pod would present its own readings for the pilot to combine in his own mind a view of the battlespace. This means that while the F-22A was physically delivered without synthetic aperture radar or situational awareness infra-red search and track it will gain these functions later through software upgrades. However any flaw in these huge software systems can knock out supposedly unrelated aircraft systems and the complexity of a software defined aircraft can lead to a software crisis with additional costs and delays.

Sukhoi calls their expert system for sensor fusion the artificial intelligence of the PAK-FA.

## **Situational awareness dominance**

Sensor fusion and automatic target tracking are projected to give the fifth generation jet fighter pilot a view of the battlespace superior to that seen by AWACS aircraft that may be forced back from the front lines by increasing threats. Therefore tactical control could be shifted forwards to the pilots in the fighters.

However, the more powerful sensors, such as AESA radar which is able to operate in multiple modes at the same time, may present too much information for the single pilot in the F-22, F-35 and T-50 to adequately use. The Sukhoi/HAL FGFA offers a return to the two-seat configuration common in fourth generation strike fighters.

## Sixth generation jet fighter

A **sixth generation jet fighter** is a conceptual airplane expected to enter service in the United States Air Force and United States Navy in 2025-2030 timeframe.



This is a concept image of the Boeing F/A-XX sixth generation fighter proposal.

## Next Generation Tactical Aircraft

The United States Air Force is interested in a developing a sixth-generation jet fighter, dubbed the "Next Generation Tactical Aircraft" (Next Gen TACAIR), equipped with: "Enhanced capabilities in areas such as reach, persistence, survivability, net-centricity, situational awareness, human-system integration and weapons effects," a November 4, 2010 presolicitation notice states. "It must be able to operate in the anti-access/area-denial environment that will exist in the 2030–2050 timeframe."

## Chapter- 11

# Example of Fifth Generation Jet Fighter Aircraft

## Sukhoi PAK FA

### PAK FA



PAK FA T-50 prototype on the day of its first flight

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<b>Role</b>	Stealth multirole fighter
<b>National origin</b>	Russia
<b>Manufacturer</b>	Sukhoi
<b>First flight</b>	January 29, 2010
<b>Introduction</b>	2015 (planned)
<b>Status</b>	Test flight / Pre-production
<b>Primary user</b>	Russian Air Force
<b>Number built</b>	3 total, only 1 made for flight
<b>Program cost</b>	US\$8-10 billion (est.)
<b>Unit cost</b>	US\$100 million (est.)
<b>Variants</b>	Sukhoi/HAL FGFA

The **Sukhoi PAK FA** (Russian: Перспективный авиационный комплекс фронтовой авиации, *Perspektivny aviatsionny kompleks frontovoy aviatsii*, literally "Prospective

Airborne Complex - Frontline Aviation") is a fifth-generation jet fighter being developed by Sukhoi OKB for the Russian Air Force.

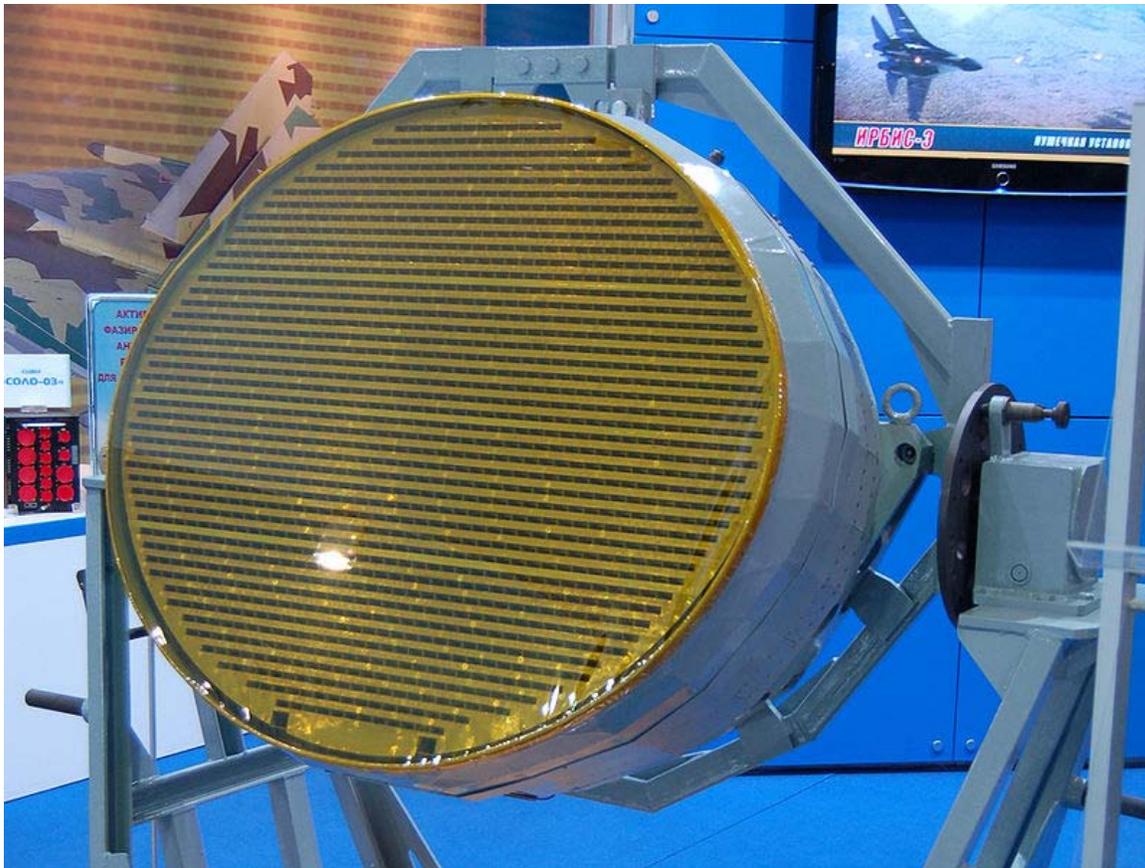
The current prototype is Sukhoi's **T-50**. The PAK FA, when fully developed, is intended to replace the MiG-29 Fulcrum and Su-27 Flanker in the Russian inventory and serve as the basis of the Sukhoi/HAL FGFA project being developed with India. A fifth generation jet fighter, it is designed to directly compete with Lockheed Martin's F-22 Raptor and F-35 Lightning II. The T-50 performed its first flight January 29, 2010. Its second flight was on February 6 and its third on February 12. As of August 31, 2010, it had made 17 flights and by mid November 40 in total. The second prototype was to start its flight test by the end of 2010, but this has been delayed until 2011.

Sukhoi director Mikhail Pogosyan has projected a market for 1,000 aircraft over the next four decades, which will be produced in a joint venture with India, two hundred each for Russia and India and six hundred for other countries. He has also said that the Indian contribution would be in the form of joint work under the current agreement rather than as a joint venture. The Indian Air Force will "acquire 50 single-seater fighters of the Russian version" before the two seat FGFA is developed. The Russian Defense Ministry will purchase the first ten aircraft after 2012 and then 60 after 2016. The first batch of fighters will be delivered without the "Fifth generation" engines. Ruslan Pukhov, director of the Centre for Analysis of Strategies and Technologies, has projected that Vietnam will be the second export customer for the fighter. The PAK-FA is expected to have a service life of about 30–35 years.

## Development



APAA in slat. MAKS-2009



Radar with APAA for the PAK FA is provided by NIIP. MAKS-2009

In the late 1980s, the Soviet Union outlined a need for a next-generation aircraft to replace its MiG-29 and Su-27 in frontline service. Two projects were proposed to meet this need, the Sukhoi Su-47 and the Mikoyan Project 1.44. In 2002, Sukhoi was chosen to lead the design for the new combat aircraft, and in the summer of 2009 the design was approved. The PAK FA will incorporate technology from both the Su-47 and the MiG 1.44.

The Tekhnokompleks Scientific and Production Center, Ramenskoye Instrument Building Design Bureau, the Tikhomirov Scientific Research Institute of Instrument Design, the Ural Optical and Mechanical Plant (Yekaterinburg), the Polet firm (Nizhniy Novgorod) and the Central Scientific Research Radio Engineering Institute (Moscow) were pronounced winners in the competition held in the beginning of 2003 for the development of the avionics suite for the fifth-generation airplane. NPO Saturn has been determined the lead executor for work on the engines for this airplane.

The Novosibirsk Chkalov Aviation Production Association (NAPO Chkalov) has begun construction of the fifth-generation multirole fighter. This work is being performed at Komsomol'sk-on-Amur together with Komsomolsk-on-Amur Aircraft Production Association; the enterprise's general director, Fedor Zhdanov reported during a visit to NAPO by Novosibirsk Oblast's governor Viktor Tolokonkiy on 6 March 2007. "Final

assembly will take place at Komsomol'sk-on-Amur, and we will be carrying out assembly of the fore body of this airplane," Zhdanov specified.

On 8 August 2007, Russian Air Force Commander Alexander Zelin was quoted by Russian news agencies that the development stage of the PAK FA program is now complete and construction of the first aircraft for flight testing will now begin. Alexander Zelin also said that by 2009 there will be three fifth-generation aircraft ready. "All of them are currently undergoing tests and are more or less ready", he said.

On 11 September 2010, the Business Standard of India reported that Indian and Russian negotiators had agreed on a preliminary design contract that would then be subject to Cabinet approval. The joint development deal would have each country invest \$6 billion and take 8 to 10 years to develop the fighter. The agreement on the pre-design of the fighter is scheduled to be signed in December 2010. The preliminary design will cost \$295 million and will be complete within 18 months.

### **Maiden flight**



Optical detection pod for the Su PAK FA. MAKS-2009

On 28 of February 2009 Mikhail Pogosyan announced that the airframe for the aircraft was almost finished and that the first prototype should be ready by August 2009. On 20 August 2009, Sukhoi General Director Mikhail Pogosyan said that the first flight would be by year end. Konstantin Makiyenko, deputy head of the Moscow-based Centre for Analysis of Strategies and Technologies said that "even with delays", the plane would likely make its first flight by January or February, adding that it would take 5 to 10 years for commercial production.

The maiden flight had been repeatedly postponed since early 2007 as the T-50 encountered unspecified technical problems. Air Force chief Alexander Zelin admitted as recently as August 2009 that problems with the engine and in technical research remained unsolved.

On December 8, 2009, Deputy Prime Minister Sergei Ivanov announced that the first trials with the fifth-generation aircraft would begin in 2010. The testing, however, has commenced earlier than stated, with the first successful taxiing test taking place on December 24, 2009.

The aircraft's maiden flight took place on 29 January 2010 at KnAAPO's Komsomolsk-on-Amur Dzemgi Airport; the aircraft was piloted by Sergey Bogdan (Сергей Богдан) and the flight lasted for 47 minutes.

A second airframe is planned to join the flight testing later in fourth quarter of 2010. These first two aircraft will lack radar and weapon control systems, while the third and fourth aircraft, to be added in 2011, will be fully functional test aircraft.

The T-50 is expected to be on display at the 2011 MAKS Airshow.

## **Naval Version**

Navalized Sukhoi T-50 PAK FAs will be deployed on the Russian aircraft carrier Admiral Kuznetsov and future Russian aircraft carriers. There will be a competition between the Sukhoi, Mikoyan and Yakovlev design bureaus to choose the new naval aircraft.

## **Light Fighter**

Alexei Fedorov has said that any decision on applying fifth generation technologies to produce a smaller fighter (in the F-35 range) must wait until after the heavy fighter, based on the T-50, is completed.

## **Design**

Although most of information about the PAK FA is classified, it is believed from interviews with people in the Russian Air Force and Defense Ministry that it will be stealthy, have the ability to supercruise, be outfitted with the next generation of air-to-air,

air-to-surface, and air-to-ship missiles, incorporate a fix-mounted AESA radar with a 1,500-element array and have an "artificial intellect".



The PAK FA on a runway.

According to Sukhoi, the new radar will reduce pilot load and the aircraft will have a new data link to share information between aircraft.

Composites are used extensively on the T-50 and comprise 25% of its weight and almost 70% of the outer surface. It is estimated that titanium alloy content of the fuselage is 75%. Sukhoi's concern for minimizing radar cross-section (RCS) and drag is also shown by the provision of two tandem main weapons bays in the centre fuselage, between the engine nacelles. Each is estimated to be between 4.9-5.1m long. The main bays are augmented by bulged, triangular-section bays at the wing root.

The Moskovsky Komsomolets reported that the T-50 has been designed to be more maneuverable than the F-22 Raptor at the cost of making it less stealthy than the F-22.

## **Avionics**

The PAK-FA SH121 radar complex includes three X-Band AESA radars located on the front and sides of the aircraft. These will be accompanied by L-Band radars on the wing leading edges. L-Band radars are proven to have increased effectiveness against very low observable (VLO) targets which are optimized only against X-Band frequencies, but their longer wavelengths reduce their resolution.

The PAK-FA will feature anIRST optical/IR search and tracking system, based on the OLS-35M which is currently in service with the Su-35S.

Sukhoi recently demonstrated cockpit mock-ups, which may relate to both Su-35 or PAK-FA, suggest two very large multi-function displays (MFDs) and a very wide heads-up display (HUD).

Hindustan Aeronautics Limited will reportedly provide the navigation system and the mission computer.

## **Engines**

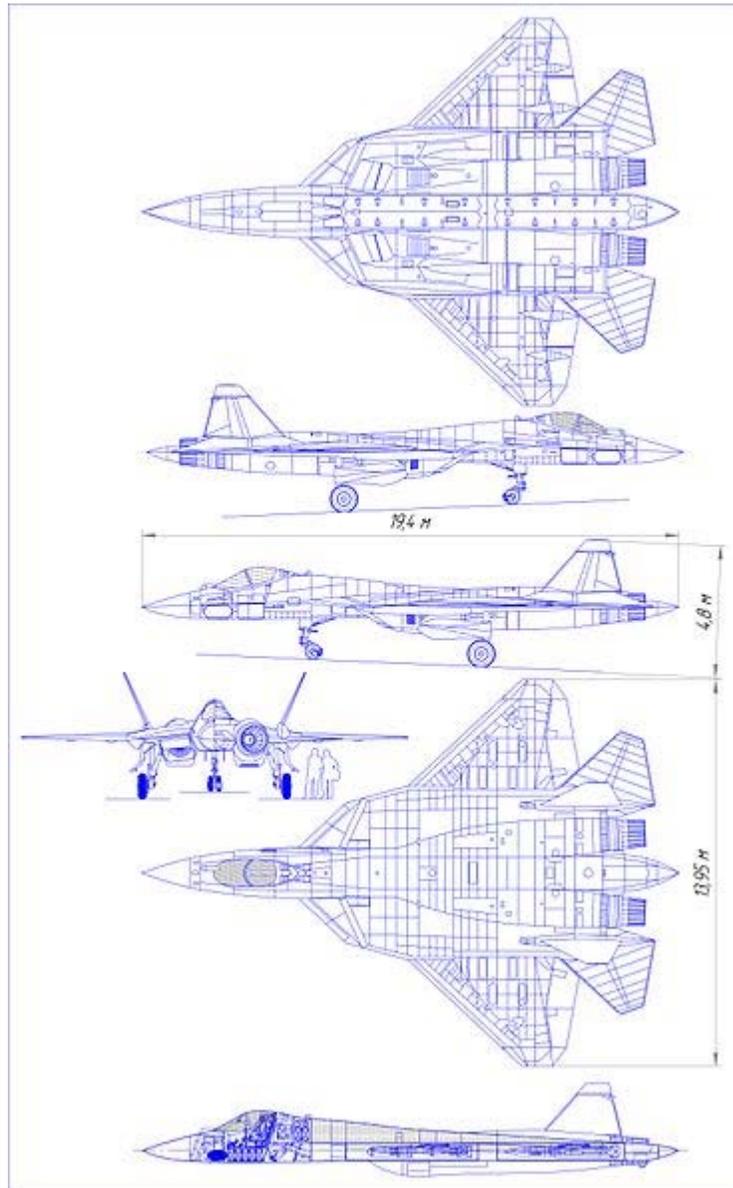
The PAK FA was expected to use a pair of Saturn 117S engines on its first flights. The **117S** (AL-41F1A) is a major upgrade of the AL-31F based on the AL-41F intended to power the Su-35BM, producing 142 kN (32,000 lb) of thrust in afterburner and 86.3 kN (19,400 lb) dry. In fact, PAK FA already used a completely new engine in its first flight, as stated by NPO Saturn. The engine is not based on the Saturn 117S and is rumoured to be called "127 engine". The engine generates a larger thrust and has a complex automation system, to facilitate flight modes such as maneuverability. Exact specifications of the new engine are still secret. It is expected that each engine will be able to independently vector its thrust upwards, downward or side to side. Vectoring one engine up with the other one down can produce a twisting force. Therefore the PAK FA would be the first fifth generation fighter with full 3-D thrust vectoring along all three aircraft axes: pitch, yaw and roll. These engines will incorporate infrared and RCS reduction measures.

## **Operational history**

### **Testing**

The first flight shows that PAK-FA has no conventional rudders, its vertical tails are fully movable. This special tail fin design is mechanically similar to V-tails used by the Northrop YF-23 in 1990s, but is supplemented by dedicated horizontal stabilators (as on the F-22). The T-50 has wing leading-edge devices above the jet engine intakes that have been called a challenge for signature control.

# Specifications



Because the aircraft is in development, these specifications are preliminary and are taken as estimates from the available images.

## General characteristics

- **Crew:** 1
- **Length:** 19.8 m (65.9 ft)
- **Wingspan:** 14 m (46.6 ft)
- **Height:** 6.05 m (19.8 ft)
- **Wing area:** 78.8 m<sup>2</sup> (848.1 ft<sup>2</sup>)

- **Empty weight:** 18,500 kg (40,785 lb)
- **Loaded weight:** 26,000 kg (57,320 lb)
- **Useful load:** 7,500 kg (combat load) (16,534 lb)
- **Max takeoff weight:** 37,000 kg (81,570 lb)
- **Powerplant:** 2× New unnamed engine by NPO Saturn and FNPTS MMPP Salyut of 175 kN each. Prototype with AL-41F1 of 147 kN each, definitive version with new engine >157 kN
- **Maximum Fuel weight:** 10,300 kg (22,711 lb)

## Performance

- **Maximum speed:** 2,100 - 2,500 km/h (Mach 2) (1,300 - 1,560 mph) ; at 17,000 m (45,000 ft) altitude
- **Cruise speed:** 1,850 - 2,100 km/h (1,150 - 1,300 mph)
- **Ferry range:** 5,500 km (3417 miles)
- **Service ceiling:** 20,000 m (65,616 ft)
- **Rate of climb:** 350 m/sec (68,900 ft/min)
- **Wing loading:** 330(normal) - 470(maximum) kg/m<sup>2</sup> (67(normal) - 96(maximum) lb/ft<sup>2</sup>)
- **Thrust/weight:** 1.19
- **Maximum g-load:** 10-11 g

## Armament

- **Guns:** None on prototype. Apparent provision for a cannon (most likely GSh-301). Possible two 30mm cannons
- **Hardpoints:** Two internal bays estimated at 4.6-4.7 metres by 1-1.1 metres. Other sources suggest two auxiliary internal bays for short range AAMS and 6 external hardpoints

## Avionics

N050(?)BRLS AFAR/AESA built by Tikhomirov NIIP and based on Tikhomirov NIIP N035 Irbis-E . It will be the second aircraft based AESA Radar to be built by Russia, the first being the Phazotron NIIR ZHUK-A Radar in the MIG-35.

## Designed armament

Two Izdeliye 810 Extended beyond visual range missiles per weapons bay. Multiple Izdeliye 180 / K77M beyond visual range missiles. K74 and K30 within visual range missiles can also be carried.

Two KH38M or KH58 USHK air-to-ground missiles per weapons bay. Multiple 250–500 kg precision guided bombs per weapons bay, with a maximum of ten bombs in internal bays

Other possible loads include one 1500 kg bomb per weapons bay or two 400 km+ range anti-AWACS weapons on external hard-points. A maximum weapons load of 7500 kg is reported.