Jet Engines: Technology, Supply Chain and Ecosystem

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A comprehensive primer on jet engine technology covering design, manufacturing, supply chains, and India's indigenous development efforts including the Kaveri engine program.

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1 Executive Summary

The development of jet engines is one of the most ambitious and technologically advanced areas in aerospace engineering worldwide. Countries that have successfully developed this technology have secured strategic military superiority on the one hand and are leaders in commercial aviation, innovation, and economic fronts.

Currently, India depends on imports for jet engines. However, developing a domestic jet engine is critical for achieving strategic and technological self-reliance in aerospace and defence.

This document provides an understanding of jet engine technology. It emphasises its impact on modern aviation and examines design, development, manufacturing, and maintenance processes. This document will also cover India's effort to build an indigenous jet engine.

By understanding the intricacies of jet engine technology and the global supply chain from this primer, we hope policymakers can make informed decisions to strengthen India's aerospace industry and position the country as a major player in the global aviation market.

2 Introduction

Modern aviation has changed the way we fly. Today's jetliners fly as high as fifty to sixty thousand feet above sea level and as fast as the speed of sound. Military fighter aircraft, on the other hand, have broken the sonic barrier and fly even faster than the speed of sound. Air travel has become more affordable and accessible to the common populace. And all this has been made possible by the jet engine that powers the modern aircraft. This primer provides an introduction to the world of jet engines.

2.1 Why this document for jet engine technology?

This document is meant to act as a comprehensive compilation to help understand the technology, supply chain, and global and Indian ecosystems for jet engines. Only a handful of countries possess complete lifecycle capability to design, develop, test, manufacture, and maintain commercial and military jet engines. Despite the perceived "mature" status of jet engine technology, developing this technology for countries lacking one remains a challenging task.[1]

The inventors—Frank Whittle and Hans von Ohain—developed the jet engine in order to eliminate various drawbacks of the conventional engine used to power aircraft during that period, namely the Piston Internal Combustion Engine (or just the Piston Engine). Piston engines are the same as used in current gasoline automobiles. Their structural flaws are enlisted in Figure 1.[2] [3]

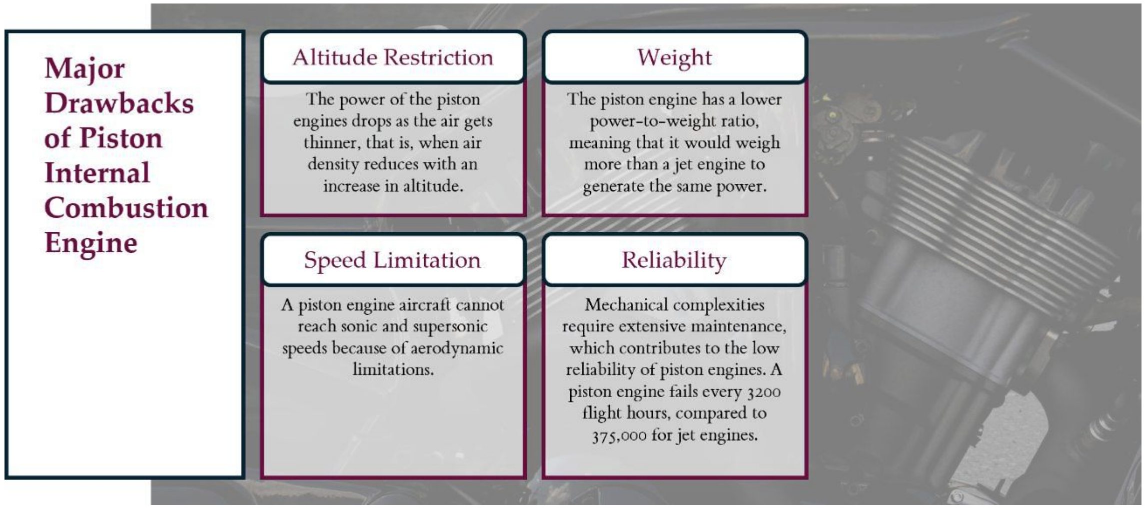

Figure 1: Figure 1: Drawbacks of a piston engine. (Collated/ Created by Author)

Major Drawbacks of Piston Internal Combustion Engine:

- **Altitude Restriction**: The power of the piston engine drops as the air gets thinner, that is, when air density reduces with an increase in altitude.
- **Weight**: The piston engine has a lower power-to-weight ratio, meaning that it would weigh more than a jet engine to generate the same power.
- **Speed Limitation**: A piston engine aircraft cannot reach sonic and supersonic speeds because of aerodynamic limitations.
- **Reliability**: Mechanical complexities require extensive maintenance, which contributes to the low reliability of piston engines. A piston engine fails every 3200 flight hours, compared to 175,000 for jet engines.

In addition to the jet engine, there are other propulsion systems such as the rocket, ramjet, scramjet, pulsejet, electric, and nuclear engines. Rocket engines are designed to operate in space and carry fuel and oxidiser separately, hence increasing the weight. Engines like ramjet and scramjet only operate at supersonic speed. Electric and nuclear engines are still futuristic as the technology is not developed for use in aviation. As a result, none of these engine technologies are currently suitable for aircraft flights.

3 Engine Fundamentals and Anatomy

This section explores the anatomy and operational principles of the jet engine, the commonly used term for a gas turbine engine used in an aircraft. This section will facilitate familiarity with the technology, aiding in comprehension of technological issues surrounding it.

3.1 Jet Propulsion Principle

An engine works on the third law of motion, propounded by Isaac Newton. The law states that when two bodies interact, they apply forces to one another that are equal in magnitude and opposite in direction. In simple terms, it states that for every action, there is an equal and opposite reaction. This can be understood with a few examples, such as rowing a boat, where pushing water backwards creates a motion of the boat forward. This same concept is used to propel a jet engine.

A family of engines uses this principle of generating jets to propel itself forward. The engines under this family comprise all types of rocket engines, ramjet, scramjet, pulsejet, and gas turbine engines. That is how an aircraft equipped with a jet engine moves.

3.2 The Jet Engine Anatomy

The primary elements of a jet engine are the compressor, combustion chamber, and turbine.

3.2.1 Compressor

The first engine component, the compressor, breathes in air and prepares it for efficient fuel burning.

Compressor has two essential functions: - Increase Efficiency - Create Air Flow

The thermal efficiency of an engine increases when the fuel is burnt at higher pressure. Thermal efficiency measures how efficiently the engine converts heat energy from fuel into work or mechanical energy. This means the more air is pressurised until the combustion process, the more efficient the engine will be.[4] Improved efficiency results in reduction in fuel consumption to produce a certain amount of forward force, also called thrust.[5]

The compressor has two elements that handle compression and propel the air: rotors and stators. As the name suggests, rotors rotate and push the air rear of the compressor, and the stator increases the airflow pressure by diffusing the flow. A commercial engine like the Rolls-Royce Trent 700, which powers the Airbus A330, has 14 stages of compressors. Meanwhile, in a military engine like the GE-404, which powers India's LCA Tejas, there are 7 stages of compressors.[6]

The extent of compression by the compressor is measured by the pressure ratio, which is defined by the number of times the pressure is increased. For example, the Rolls-Royce Trent 700 increases air pressure 35 times, hence the pressure ratio of 35. Similarly, the pressure ratio of GE 404 is 26.[7]

Two configurations achieve the essential function of a compressor: centrifugal and axial. Both configurations have rotors and stators. The two mechanisms of the compressor differ based on how the rotor and stator work to create flow and increase pressure.

In an axial compressor, the rotor pushes the air, and the stator increases the pressure. In many cases, the rotor and stator increase pressure. The setup of rotors and stators resembles a series of stages. Rotors are connected to the shaft, and the stators are attached to the casing.

A centrifugal compressor is robust and easier to manufacture, whereas an axial compressor draws in more air for the same frontal area and can be designed to achieve higher pressure and higher thrust. That is why a centrifugal compressor is used in smaller engines, whereas axial compressors are universally used for all modern aircraft jet engines.

3.2.2 Combustion Chamber

The combustion chamber's role is to facilitate fuel burning at optimum conditions. The fuel is sprayed through the nozzles and burnt in air-rich conditions. The fuel burnt depends on the thermal efficiency, which in turn depends on the temperature the turbine blades (the next stage) can bear. The maximum temperature is limited to 850 to 1700 degrees Celsius.[8]

The combustion chamber is designed strategically to keep the combustion chamber walls and other components cool using the incoming air. Only 40% of the air is used for combustion, and the remaining 60% is progressively used to cool down the chamber walls.[9] The energy from the energised high-temperature airflow is extracted from the next section of the engine, called the turbine.

3.2.3 Turbine

The purpose of a turbine in a jet engine is to extract the energy from the energised fluid. Just like a compressor, a turbine also has two essential functions:

Turbine has two essential functions: - Extract Energy - Accelerate Airflow

The energy extracted from the energised air is used to power the compressor and other engine accessories. The mechanism is simple. The turbines are connected to the compressor by a common shaft. Consequently, the rotation speed attained by the turbine is transferred to the compressor. To produce the required rotational force, also called torque, the turbine consists of multiple stages, each with a stator and a rotor.

Rotors and stators of the turbine aerodynamically expand the gases to lower temperature and pressure, and accelerate gases to high speed. These high-speed gases are then used to create a jet via the nozzles of the engine to create thrust.

The turbine operates in extreme conditions. The temperature entering the turbine can reach up to 1700 degrees Celsius, the pressure will be twenty to thirty times atmospheric pressure, and it rotates at 10000 - 15000 rotations per minute.[10] This imparts both thermal effects and mechanical force on the turbine rotor blades. This has challenged every jet engine manufacturer to design and manufacture such blades since the invention of the jet engine, including India. Operating engines at higher temperatures at the turbine inlet is important, as this makes them thermally efficient and boasting a better thrust-to-weight ratio. The higher the temperature the turbine blades can withstand, the higher the thrust for a given engine weight.

3.3 Working of Jet Engines

The air flows through the inlet of the engine, where the compressor is sucking-in air via its rotors. The rotors of the compressor ensure the air always has enough momentum to move rearward. As the air moves across the compressor's rotor and stator, the pressure gradually increases at every stage. The high-pressure air burns at constant pressure and undergoes isobaric (constant pressure) combustion. After burning, the high-pressure and high-temperature gases will be guided towards the turbine. The energised airflow then rotates the turbine rotors. Turbine blades expand the gases at the stator and rotor, increasing the velocity of the gases and decreasing the pressure. As the gases reach the nozzle, they are accelerated to create a jet. Thrust is generated depending on the jet velocity and airflow rate. This is the working principle of the thermodynamic cycle called the Brayton cycle.

3.4 Configuration of Jet Engines

Over the years, the jet engine has taken various forms and shapes. Modification and upgradation have been done either to increase efficiency or to operate in specific conditions.

3.4.1 Turboprop

The first variation of the jet engine was to introduce a propeller in the front or back. An additional turbine is fitted in the engine to power the propeller. In this version, the aircraft's thrust is generated by rotation of the propeller rather than a jet. This engine is called a turboprop engine. Although it is used for higher efficiency generated from propellers, it has a speed disadvantage and cannot attain transonic speed. These engines are used for smaller aircrafts and large long-distance cargo aircrafts.

3.4.2 Turbofan

This is the most commonly used jet engine configuration in modern commercial and military aircrafts. It preserves the propeller's efficiency and improves turboprops' speed limitation. Turbofans have the potential to operate in transonic and supersonic speed regimes. A turbofan engine has a fan with a larger diameter than the inlet of the engine's core.

The bypass airflow provides different benefits for commercial and military turbofan engines. The extent of bypass flow is measured using the bypass ratio, which is the amount of air bypassed to the amount of air going inside the engine. Commercial turbofan engines have large bypass ratios. For example, Pratt and Whitney PW1000G, which powers Airbus 320neo, has a bypass ratio of 15:1, which means for every unit of air flowing inside the engine's core, fifteen units of air are flowing outside. This high bypass ratio helps make the engine more efficient than the turbojet variant. The fan is used in military fighter aircrafts to get extra airflow to support the cooling of the aircraft. The bypass ratio for a fighter aircraft turbofan engine like GE 404 is around 0.34:1.[11]

The rotational speed of the fan is lower than the compressor. Hence, to drive the fan at different speeds, an additional turbine stage is attached to the rear of the turbine. Gears and concentric shafts are used to facilitate the different rotational speeds. This configuration is called a twin-spool.

3.4.3 Turboshaft

A turboshaft engine is similar to a turboprop engine. Instead of driving a propeller in a turboprop, this shaft in a turboshaft engine is connected to a gearbox that powers a rotor system in a helicopter or other machinery like generators or pumps. This setup is for applications where direct jet thrust is not the primary means of propulsion. The turboshaft engine relies entirely on the shaft power to generate lift and thrust through the rotor system. This distinction makes turboshaft engines particularly well-suited for helicopters.

4 Jet Engine Life Cycle

The life cycle begins with designing a jet engine based on the needs of the aircraft which it is supposed to power. After designing, a prototype of the engine is developed. The prototype will undergo multiple levels of testing. Once the design and testing of the engine is successfully completed, the engine is certified by the relevant agencies and approved for manufacturing. The final process includes getting certification for its airworthiness. These approved engines will be fit for integrating with the specific aircrafts. Like any other machine, an engine will undergo multiple maintenance, repair, and overhaul cycles in its lifetime.

4.1 Design

The life cycle of a jet engine starts with defining its requirements, which establish what the engine must be capable of. These requirements are primarily defined by the target weight, thrust (force), and fuel used. The aircraft and its operating conditions also define these primary requirements.

Designing aerospace machinery is an iterative process. This is because weight and drag are crucial factors. The iterative nature of designing is based on performance assumptions, thrust calculations, engine design, and performance calculations that cycle until satisfactory results are achieved.

Designing a jet engine is a complex process. It involves designing the core components of the engine, such as the compressor, combustion chamber, and turbines, as well as various subsystems, such as accessory drives, internal air systems, and fuel systems.

Compressor Design: Compressor design involves designing blades, casing, disk, and shaft. A compressor is a set of rotors and stators called a stage, where the rotor pushes the air, and the stator increases the pressure. These blades take an aerofoil shape for a smooth, efficient airflow. The distance between the blades increases for air to diffuse and increase the pressure. The compressor blades have a twist for an efficient performance by keeping the velocity (speed) of the airflow constant along the cross-section. Hence, the blades twist from their root to tip.

The compressor is designed to work at an optimum aircraft speed and altitude. However, it must work at a range of speeds and altitudes. If the operating speed is far from the designed speed, it can induce flow separation or surge, leading to blade vibrations, which in turn can damage the compressor setup. Flow separation occurs when the airflow around the compressor blades is no longer smooth, reducing the compressor's efficiency. The compressor is usually designed to avoid flow instability.

Compressor Materials: Steel and nickel alloys are used for the compressor blades. This is because they have good fatigue strength, which is the ability to bear repeated loads. Recently, the use of lightweight titanium in the compressor's initial stages has become prevalent. The blades and the rotor setup, including disks and drums, are made of titanium in the early stages and nickel alloys in the high-pressure and temperature stages. The compressor casing is made of titanium owing to its high rigidity.[12]

Combustion Chamber Design: The design of a combustion chamber focuses on its fuel supply, combustion efficiency, combustion stability and cooling. The airflow inside the combustion chamber is critical for efficiently burning fuel and maintaining temperature. As mentioned earlier, only 40% of airflow is involved with burning the fuel. In contrast, the remaining airflow is used for cooling purposes to protect the combustion chamber and turbine blades from high temperatures.

The most popular type of combustion chamber setup is an annular chamber. This layout reduces the length and weight of the engine compared to the other two types of chambers used in older designs.

Combustion chamber performance is determined by combustion intensity, efficiency, stability, and emissions. Combustion intensity is what determines engine power. Intensity depends on the size of the chamber and the rate of fuel burning. Combustion efficiency measures the complete burning of the fuel. Combustion efficiency is reduced with altitude. Combustion stability is the ability of the flame to burn smoothly, which depends on the air-to-fuel ratio at combustion. The flame may be extinguished if the air-to-fuel ratio reduces or exceeds the design value.

Combustion Chamber Materials: The materials used in the combustion chamber must resist high temperature, corrosion (phenomena like rusting for iron) and creep (material failure due to prolonged load exposure). Nickel-based alloys are used to construct the combustion chamber. Few components use cobalt-based alloys, which have better creep strength. Designers must balance creep strength and corrosion resistance at high-temperature regions while selecting a material. A thermal barrier coating is used to tackle this. These barrier coatings are ceramic in nature. Material like Yttria-stabilized zirconia (ZrO2 – Y2O3) is used for insulation, and McSally (M – metal like Cobalt or Nickel, Cr – Chromium, Al – Aluminium, Y – Yttrium) is used for corrosion resistance.[13]

Turbine Design: Designing a turbine is a complex process. Unlike compressors, turbine blades face high pressure, mechanical force, and temperature. Turbines have two tasks to achieve; one is to extract energy from hot-flowing gas and convert it to mechanical energy to rotate compressors, and the second is to increase the flow speed, hence reducing the pressure. The blades are designed to be aerofoil-shaped for smooth flow and efficient energy transfer. They are also spaced so that the pressure decreases and gas speed increases. Unlike in the compressor, where blade spacing diffuses flow, in a turbine the spacing expands flow with increased flow speed and decreased pressure. Just like in compressor blades, the turbine blades are also twisted along the root to the tip of the blades.

The maximum temperature a turbine can bear is limited by the turbine blades' ability to withstand such thermal and centrifugal (due to its rotation) loads. Therefore, it is crucial to have cooling mechanisms to cool turbine blades so the temperature is below the blade's melting point. Cooling is done by routing cool air inside these blades. The cool air transfers the heat from the blades through convection. This cool air is then flushed out of pores on the turbine blades.

Usually, the number of turbine stages is less than that of the compressor stages. For example, the Rolls-Royce Trent 700 Engine has 6 turbine stages compared to 14 compressor stages. The turbine is designed to drive the compressor at its design speed. A reduction in turbine rotational speed results in a surge in the compressor, and an increase will result in the compressor choking.

Turbine Materials: Turbine blades are evolving to sustain higher temperatures. Nickel-based superalloys are used in current engines. Materials are being developed based on the manufacturing method. For example, various nickel superalloys are developed based on manufacturing methods like equiaxed casting, directionally solidified casting or single crystal casting. There has also been an attempt to develop non-metal-based reinforced ceramic turbine blades. A nickel-based superalloy is also used in the turbine discs, which hold the turbine's rotor blades.[14]

Other Engine Systems: The exhaust system collects air from the turbine and expels it into the atmosphere. The converging shape of the exhaust accelerates the airflow to create a jet. Accessory drives transfer power from the rotating engine shaft to power essential aircraft systems. The internal air system refers to airflow used for engine operations and safety, cooling the combustor and turbine. The fuel system is a complex network that delivers fuel to the engine for combustion and controls fuel flow.

4.1.1 Design Agency Supply Chain

The design of jet engine components and subcomponents is usually done by the Original Equipment Manufacturer (OEM) themselves. Major aircraft jet engine OEMs from four countries capable of developing jet engines include:

United States: - Pratt and Whitney (PW) - General Electric (GE) - Honeywell

United Kingdom: - Rolls Royce (RR)

France: - Safran

Russia: - United Engine Corporation (UEC)

International Joint Ventures: Many major jet engine companies come together to create joint ventures to build engines, including: - CFM International: JV between GE and Safran - Engine Alliance: JV between GE and Pratt & Whitney - International Aero Engines: JV between Pratt & Whitney, MTU Aero Engines and Japanese Aero Engine Corporation - Powerjet: JV between Safran and NPO Saturn

4.2 Materials

In most sectors, the materials are chosen to keep cost in mind, but in aerospace, the materials are chosen by keeping weight in mind. Design usually requires materials to be as light as technology allows.

Titanium alloys are used for many low-pressure areas such as compressor blades, discs, casings, fans, and low-temperature exhaust systems. Examples of Titanium alloys used in jet engines are 6al/4V, Ti-8Al-1Mo-1V, Ti6242S, and Titanium Alloy 834.[15]

Nickel alloys are used for high-pressure and high-temperature systems like turbine discs and blades, high-pressure compressor blades, discs and casings, combustors, and high-temperature exhaust. A few examples of Nickel alloys used in jet engines are Nickel alloy 617, 230, 718, CM247LC, PWA1422, DMD4, TMD-103, Rene 95, Udimet 720LI, MERL-76 and IN 100. **Magnesium** is used for the gearbox.[16]

Ceramic coating and **thermal barrier coating** are used in the combustion chamber to protect it from high temperatures. **Cobalt alloys** are used for the nozzles and combustion chambers.

4.2.1 Materials in Research

With many limitations in achieving the best possible engine performance, ongoing research is exploring various materials which can help overcome such limitations. **Ceramic**, **Intermetallic**, **Composites**, **Chromium-Based Alloys**, **Molybdenum-Based Alloys**, and **Platinum-Based Alloys** are a few materials that can potentially replace contemporary materials.

Ceramic materials have high-temperature tolerance, which increases engine efficiency. **Intermetallic** materials like Titanium Aluminides, particularly TiAl-based alloys, show promise in high-temperature performance and weight reduction.

Composites are widely used in aircraft structures, but they have found limited uses in jet engines. Ceramic matrix composites (CMCs), specifically Silicon Carbide-matrix composites, are promising candidates for hot section components due to their high-temperature tolerance properties.

Chromium-based alloys offer potential advantages like high melting point, low density, and high thermal conductivity, and **Molybdenum-based alloys** possess excellent high-temperature tolerance properties. Research work is going on extensively to overcome their drawbacks.

While expensive, **Platinum-based alloys** offer exceptional high-temperature properties like oxidation and thermal shock resistance. They are being explored for non-rotating components in gas turbines.[17]

In spite of all the advantages mentioned above, challenges like brittleness, reliability, low toughness, and manufacturing difficulties hinder their adoption.

4.2.2 Materials Supply Chain

The widespread use of Nickel, Titanium and Cobalt alloys in jet engines requires understanding their global availability.

Cobalt: 74% of the world's cobalt is mined in Congo, whereas Indonesia produces only 10% of what Congo produces. India has cobalt reserves in Jharkhand, Nagaland, and Odisha, but no cobalt production exists. The material is usually imported and later refined here. Leading Indian industries which refine metal and produce cobalt superalloys are Nicomet Industries Ltd (bought by Vedanta Ltd) and Rubamin Ltd.[18]

Nickel: Indonesia is a major nickel producer, contributing 50% to the global production. Hindustan Copper Limited produces Nickel sulphate as a byproduct from its Ghatsila facility in Jharkhand. They have a capacity of 390 million tonnes per annum. Another private player in the space is Nicomet Industries Ltd (now owned by Vedanta Ltd). The Goan enterprise produces nickel metal and its derivatives with a capacity of 5400 million tonnes per annum.[19][20]

Titanium: Titanium is usually extracted from a titanium sponge. This raw form of titanium is produced in China. India has a rich titanium reserve on the shores of Kerala, Tamil Nadu, Andhra Pradesh, and Odisha. In 2011, India became the seventh country in the world to extract titanium out of titanium sponges successfully. Kerala Minerals and Metals Ltd produces titanium in Kerala.[21]

4.3 Manufacturing

The engine's design must complement the manufacturing capability of selected materials. Most of the engine components need innovative and high-precision manufacturing techniques.

Most steel, nickel, and cobalt alloys are produced by forging. Meanwhile, the remaining components, like turbine blades, are casted. Most components are finished using various fabrication and machining techniques and joined using welding techniques. In addition to this, techniques like heat treatment, electro-plating, chromate sealing, chemical treatments, and anodising are used to stop corrosion.

4.3.1 Forging

Forging is a method of shaping the metal to the required size and shape using compressive force. The compressive force can be applied using hammering, pressing, or rolling the metal. For jet engines, forging is used to create engine drive shafts, compressor discs, turbine discs, and gear trains. High-precision forging techniques are employed for manufacturing blades. This includes accurately producing aerofoil shapes with variable thickness and twist. Annular combustion rings and high-pressure compressor casings are also forged.

4.3.2 Casting

Casting is a manufacturing method that involves pouring liquid metal or plastics into a component-shaped mould. The liquid solidifies and takes the shape of the mould cavity. There are various casting methods: sand casting, die casting and investment casting. Investment casting is used extensively for engine component manufacturing, as the final product out of casting needs no further machining.

Turbine blades are produced using investment casting with high-temperature nickel alloys. This casting method has evolved over time to address the issue of extending the blades' life. The latest casting technique, called single crystal casting, has increased the blade's life even further. Recently, in India, DMRL (Defence Metallurgical Research Laboratory), a DRDO laboratory (Defence Research and Development Organisation), has successfully demonstrated the manufacturing of single crystal turbine blades.

4.3.3 Additive Manufacturing

Additive manufacturing, or 3D printing, builds components from a digital design layer by layer. This fairly new method resolves many constraints posed by traditional manufacturing methods like forging and casting. This manufacturing process adds material layer by layer, unlike conventional methods where the material is removed to obtain a component. This technique saves materials, making it very relevant for components of precious metals.

With technological advancements in additive manufacturing techniques, it is estimated that more than 75% of jet engine parts will be suitable for additive manufacturing owing to their complex shape and structure.[22] It is currently used to create components like turbine blades, fuel and turbine nozzles.[23] These parts often have intricate internal channels and optimised geometries that are difficult or impossible to produce using traditional manufacturing methods.

4.3.4 Fabrication

Major engine components like bearing housings, combustion and turbine casings, exhaust units, jet pipes, by-pass mixer units, and low-pressure compressor casings are produced as fabricated assemblies. This uses sheet materials like stainless steel, titanium, and various nickel alloys. These components undergo various machining processes, including Electrical Discharge Machining (EDM), to achieve the desired precision and intricacy of shape.

4.3.5 Inspection

The precision of the manufacturing must be remarkably high for a jet engine. Once the manufacturing is complete, it is important to inspect the accuracy of the final product for a defect-free engine. Techniques, such as ultrasonic, radiological, magnetic particle and penetrant inspection, and electrolyte and acid etching, are used to check precision.

4.3.6 Manufacturing Supply Chain

All the major OEMs who design the aircraft engine also manufacture most of the engine components. In most cases, OEMs manufacture critical and core components. Critical components include compressor blades, discs, combustion chamber, turbine blades and discs, whereas the engine's core includes the compressor, combustion chamber and turbine setup.

OEMs outsource the manufacturing of various components to Tier-1 manufacturers, such as MTU Aero Engines, Avio Aero (now bought by GE Aerospace), GKN Aerospace, and Motor Sich.

Many companies like Hindustan Aeronautics Limited (HAL) license the manufacturing process. HAL makes engines like Adour MK811/ 804E, TurbomecaTM333 2B2 /TM333 2M2, Artouste IIIB/B1, Saturn AL-31FP, and Klimov RD-33.[24]

As noticed earlier, only limited countries like the U.S., UK, France, and Russia have the capability to design and manufacture jet engines. Most of the other nations manufacture by obtaining a licence from the OEMs. Notable companies that manufacture jet engines under licence include Aerostar (Romania), Atlas (Italy), Bet Shemesh Engines Ltd (Israel), Hindustan Aeronautics Limited (India), Xi'an Aero Engine Corporation and Liming Engine Manufacturing Corporation (China), Mitsubishi (Japan), and Aerospace Industrial Development Corporation (Taiwan).

4.4 Certification

An engine goes through rigorous testing once its design and development are finalised. This is essential in order to evaluate the engine and its subsystem's satisfactory performance.

Every country has a certification and regulation authority that provides guidelines for the testing requirements, and certifies the engine for its airworthiness. This certificate helps ensure that the engine meets safety and operational standards before use, thus building confidence in safety for aircraft OEMs, airlines, and countries operating the unit.

In several countries, multiple authorities handle commercial and military certification separately. Civil or commercial aircrafts and their engine certifications are regulated by the aviation authorities, while military aircrafts and their engines are governed by Defence departments. In India, the Directorate General of Civil Aviation (DGCA) regulates civil aviation, which is under the Ministry of Civil Aviation. In contrast, the Centre for Military Airworthiness & Certification (CEMILAC) regulates military aircrafts and engines. CEMILAC is a DRDO entity under the Ministry of Defence.

Major regulating bodies worldwide include: - **Commercial and Military Federal Aviation Administration (FAA)** - United States - **European Union Aviation Safety Agency (EASA)** - Europe - **Commercial Transport Canada, Military Airworthiness Authority (AA)** - Canada - **Commercial Civil Aviation Authority (CAA), Military Aviation Authority (MAA)** - United Kingdom - **Commercial European Defence Agency (EDA)** - Europe - **Commercial**

and Military Federal Agency for Air Transport (Rosaviatsia) - Russia - **Commercial and Military Civil Aviation Administration of China (CAAC)** - China - **Commercial Directorate General of Civil Aviation (DGCA), Military Centre for Military Airworthiness & Certification (CEMILAC)** - India

4.5 Maintenance

As an engine is made operational and fitted to the aircraft, it must go through regular maintenance and repair. The OEM (Original Equipment Manufacturer) provides detailed maintenance and repair manuals for each type of engine. These manuals must be strictly followed for optimal engine performance. Engine maintenance constitutes 60% of the overall aircraft maintenance. There are two kinds of engine maintenance:

1. **On-wing or line maintenance**
2. **Overhaul or shop maintenance**

On-wing maintenance: These maintenances are either scheduled or unscheduled. Scheduled maintenance is a regular engine checkup, as per the manufacturer's suggestion. It is usually done within 12-18 months or 5000 service hours.[25] Unscheduled maintenance is carried out during abnormal occurrences, like bird strikes, lighting, crash, hard landing, or malfunction.

Overhaul maintenance: The maximum time a jet engine is integrated into the aircraft is determined by the engine manufacturer and certification agency/authority. This time is called the Time Between Overhauls (TBO). When it reaches this time, the engine must be removed from the aircraft and sent to a shop for overhaul. The overhaul process involves disassembly, cleaning, inspection, repair, testing, balancing, and assembly.

Engine health is monitored using flight deck indicators like, thrust, engine RPM (rotation per minute), turbine inlet gas temperature, oil pressure and vibrations. In-flight recorders like Aircraft Integrated Data Systems (AIDS) continuously record engine parameters. In recent years, a new advanced system called Health Usage Monitoring Systems (HUMS) has been designed to monitor the health and usage of critical components by continuously collecting and analysing data from various sensors. HUMS can detect potential issues early, enabling proactive maintenance and reducing the risk of unexpected failures. This technology significantly improves the reliability and safety of jet engines, optimising their performance and extending their lifespan.[26]

Apart from the on-flight indicators, many inspections can be done on the ground to assess the engine's health. These facilities are called MRO (Maintenance, Repair and Overhaul). MRO ensures the safety and reliability of aircraft engines. It involves a comprehensive range of services, including inspections, repairs, component replacements, and engine overhauls. MRO facilities utilise advanced technologies and specialised tools to diagnose and rectify engine issues, consequently extending their lifespan and optimising performance.

4.5.1 Engine Maintenance Supply Chain

India has one engine MRO, which is established by Air India called Air India Engineering Services (AIESL). AIESL is approved by the FAA (Federal Aviation Administration, U.S.), EASA (European Union Aviation Safety Agency) and DGCA (Directorate General of Civil Aviation, India). Recently, Safran announced an MRO for leap engines in Hyderabad.

Globally, engine MROs are present in many countries, with most of them being in developed economies.

5 Indian Jet Engine Ecosystem

India has long been developing indigenous aircraft ever since its independence, the first of them being the HF-24 Marut which was designed, manufactured, and deployed by Hindustan Aeronautics Limited (HAL). India has successfully developed aircraft design, avionics, flight dynamics, and control laws to build an aircraft. We still aspire to build an Indigenous jet engine, even though the program to build an indigenous Kaveri Engine began parallelly to the LCA Tejas, India's indigenous fighter plane.

5.1 History

The indigenous engine program was sanctioned by the Ministry of Defence in 1989 for the Gas Turbine Research Establishment (GTRE), a DRDO laboratory, to design and develop turbofan engines for Light Combat Aircraft (LCA), also known as Tejas. The engine has been in development for the past three and half decades and is yet to achieve its expected performance. High weight and low thrust (72kN compared to the expected 81kN)[27] are the key reasons why the engine is not qualified to power HAL Light Combat Aircraft.[28]

5.2 Ecosystem

5.2.1 Design Agencies

GTRE is the key entity responsible for developing an indigenous turbofan engine. It has 35 years of experience in developing the jet engine. Another DRDO lab, **Aeronautical Development Establishment (ADE)**, is developing 1kN turbojet engines for drones and 2.7kN and 4.4kN engines for missiles. **National Aerospace Laboratories (NAL)** and **Research Centre Imarat (RCI)**, a DRDO lab, are developing a 2.7kN engine for the NAL Rustom-II UAV.

HAL's Aero Engines Research and Design Centre (AERDC) is developing a 25kN turbofan engine and a 1200kN turboshaft engine to replace the Shakti Engine, which powers HAL's ALH and LUH helicopters.[29]

Bharat Forge, an Indian private industry, is developing multiple miniature and small turbojet engines. Startups have ventured into building micro gas turbine engines. Companies like **Poeir Jets** and **Raghu Vamsi** have working micro gas turbines. These micro engines are developed to propel small UAVs.

Indian Jet Engine Design EcosystemPublic Sector - Defence R&D Organisation:Gas Turbine Research Establishment (Kaveri Engine)Aeronautical Development Establishment (Drone and Missile Engine)Research Centre Imarat (NAL Rustom-II UAV Engine)National Aerospace LaboratoriesHindustan Aeronautics Limited (Helicopter Engine)Private Sector:Industry: Bharat Forge (Miniature Engines)Startups: Poeir (Micro engines for UAV), Raghu Vamsi (Micro engines for UAV)

5.2.2 Manufacturers

HAL is a major manufacturer of aircraft engines in India. It manufactures engines of Russian, U.S., and British origin under licence. They co-developed a turboshaft engine called Shakti with Safran on Ardiden 1 engine. HAL manufactures dozens of engines with licences from OEMs like Safran, Rolls Royce, Honeywell, Saturn-NPO, Klimov, and Tumansky. It has two engine manufacturing units, one in Bangalore, Karnataka and another in Koraput, Odisha.

Many private companies manufacture jet engine components, including **Tata Advanced Systems Limited**, **Reliance Defence**, **Bharat Forge**, **International Aerospace Manufacturing Pvt. Ltd (IAMPL)**, **Godrej Aerospace**, **Mishra Dhatu Nigam Limited (MIDHANI)**, and other MSMEs.

Top Manufacturer of Engines in IndiaHindustan Aeronautics Limited dominates engine production with:Engine Produced Under Licence:Rolls-Royce Turbomeca Adour Mk 811Rolls-Royce Turbomeca Adour Mk 871Honeywell Garrett TPE331-5Saturn AL-31FPKlimov RD-33MKTumansky R-25Turbomeca TM 333Indigenous or co-developed Engine Produced:ShaktiPTAE-7GTX-35VS KaveriTier I/II manufacturers in India:Tata Advanced Systems LimitedReliance DefenceBharat ForgeInternational Aerospace Manufacturing Pvt. LtdGodrej AerospaceMishra Dhatu Nigam LimitedMSMEs

5.2.3 Regulators

As mentioned earlier, DGCA regulates civil aviation, and CEMILAC regulates military aircrafts and engines.

5.2.4 Testing Facilities

Until 2023, India had no dedicated Turbojet Engine test facilities. Most of the GTRE's Kaveri Engine tests were done in Russia.[30] Efforts have been made by GTRE, DRDO, and HAL to establish engine testing facilities like a 'flying test bed' and a 'high altitude test' in India.[31]

5.2.5 Collaborations

The Indian government in 2022 declared that the Defence R&D will be opened for industry, startup and academia. In this regard, DRDO has zeroed in on 75 technology-priority areas and 403 technology categories for open innovation. Under these 75 priority areas, jet engines are prioritised under propulsion technologies and other technology priority areas.[32]

DRDO has also established 15 DRDO Industry Academia Centres of Excellence (DIA-CoEs), of which the seven CoEs focus on jet engine technology development. The progress made in this initiative has yet to be accessed.[33]

5.3 Kaveri Engine

The GTRE Kaveri engine is a significant endeavour in building self-reliance in jet engine technology. The program to build an indigenous engine started in 1989, spearheaded by the Ministry of Defence and assigned to the DRDO lab, GTRE. Kaveri is a turbofan engine expected to produce 81kN and weighs around 1000 kg. This engine program was started parallel to the LCA Tejas program so that the Kaveri Engine could power LCA Tejas aircraft, resulting in a fully indigenous aircraft.

It was estimated that the development of the Kaveri Engine would be completed in 93 months, that is, by 1996. But thirty years later, today, the engine that was developed is falling short of various expectations. Firstly, the thrust Kaveri Engine produces 70-74kN, 12% less than the expected 81kN. Secondly, the weight is overshooting by 18%, with a current weight of 1180 kg. Various other problems regarding its reliability and noise issues are reported from various sources.[34]

Many factors resulted in the delay and underperformance of the Kaveri Engine. The programme began with an overambitious goal of developing the engine in 7 years using the existing technological and industrial base, while not accounting for the complexity of building it from scratch. Lack of expertise in advanced materials also played a role in delaying the process. India also lacks the testing facilities needed for the development of the engine.

India has long relied on Russian facilities to test newly developed engines. The problem with foreign testing facilities is the high cost and long wait time.

Even with such drawbacks, DRDO is pushing for the success of this indigenous engine. DRDO will be using the dry Kaveri Engine, without the afterburner, to power the DRDO UAV named Ghatak. It will also be used in the Tejas Trainer aircraft, acting as a flying test bed for the engine.[35] These engine prototypes will be manufactured by Godrej Aerospace, which will promote India's private manufacturing ecosystem.

It is a miracle that the engine program has survived such adversities in its lifetime. This is an example for policymakers and other stakeholders to understand that research and development of new technology is a cost-intensive process. Factors like expertise, manufacturing capability, and testing infrastructure play an important role in designing a program which aims to develop frontier technology.

5.4 Prospects

The Kaveri Engine program paves the way for India's jet engine capabilities. HAL has already been manufacturing licensed foreign engines for decades. The technology transfer to HAL only provides information on how to manufacture the engine, without sharing the technical know-how for critical technologies like turbine blades.

This might still be true with the upcoming deal to manufacture the GE-414 engine for the upcoming Advanced Medium Combat Aircraft (AMCA) with HAL, which talks about 80% Transfer of Technology (ToT). Interestingly, Safran has offered 100% technology transfer to co-develop the engine for the AMCA. More can be commented on this as further details come to light.

6 Conclusion

Even though jet engine technology is over seventy years old, it is still considered state-of-the-art, and only a few nations can manufacture it. India is moving in this direction owing to the Kaveri Engine program being pursued for the LCA Tejas aircraft, through which India aims to become self-reliant in jet engine technology. Despite the current status of the Kaveri program, it has been a promising ground for the formation of the Indian jet engine ecosystem.

This primer hopes to serve as a foundational resource for understanding the technology, supply chain, and engine lifecycle, while exploring the Indian ecosystem around this technology. We hope policy-makers can make informed decisions to strengthen India's aerospace industry and position the country as a major player in the global aviation market.

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