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Progress in Aeroengine Technology (1939–2003)

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Second only to the invention of an airplane by the Wright Brothers 100 years ago, the jet engine has revolutionized both military and civil aviation. We present a survey of the key aeroengine technology trends. Since 1939, engine thrust has increased over 100-fold and the (thrust/weight) ratio to 7. Whereas the early jet engines barely lasted for less than 10 hours, today's civil engines can stay on wings for up to 10,000 hours, and high-performance military engines can last several hundred hours. Advances in blade cooling technologies and high-temperature materials have permitted an increase in turbine inlet temperature from 1280 to 3200°F. Today, engine thermal efficiency is approaching 50%. Also, today's most powerful aeroengines already meet the International Civil Aviation Organization ultra-low gaseous and smoke requirements. Finally, civil and military technology is moving along the direction set by the versatile affordable advanced turbine engines (VAATE) propulsion capability goals. The spectacular achievements of the last century truly provide an outstanding start for many future achievements to come in the field of aeroengine technology, along the lines of the VAATE goals.

Nomenclature

D_p	=	pollutant mass emitted during LTO cycle
F_{oo}	=	maximum thrust, kN
PC	=	propulsion capability (T/W/T-O TSFC)
Q_{in}	=	rate of heat release
T	=	takeoff thrust (224.8 lbf = 1 kN)
T_t	=	turbine inlet temperature, °F
V_o	=	aircraft velocity
W_{out}	=	engine output power
π_{oo}	=	engine pressure ratio at maximum thrust
η	=	efficiency

Introduction

SECOND only to the invention of the airplane by the Wright Brothers 100 years ago, the jet engine has truly revolutionized both military and civil aviation. At the turn of the century, members of the U.S. National Academy of Engineering (NAE) voted power generation, automobile, and airplane as the three top inventions of the 20th century. Today, gas turbine is the engine of choice for power generation and airplanes. Indeed, the NAE citation for the prestigious 1991 Charles Stark Draper Prize to von Ohain and Whittle reads: "the development of turbojet engines revolutionized the world's transportation system, thus improving the world's economy and transforming the relationship between nations and their people."

In 2003, the "Centennial of Powered Flight," 64 years will have elapsed since the near-simultaneous development of jet engines by von Ohain in Germany and Whittle in England. Today, the market for both aero and industrial gas-turbine engines remains as strong as ever. In the 10-year period 2002–2011, Opdyke and Franus of Forecast International[1] project the global production of 160,325 gas-turbine engines of all types, valued at $414.5 billion (in 2002 U.S. dollars). Figure 1 shows the unit production by application. Further, the value of this global production is estimated to be aeroengines $208.5 billion; industrial and marine engines $197.5 billion; and Auxillary Power Unit (APU), Ground Power Unit (GPU), and microturbines the rest. Finally, over the life of each gas-turbine engine sold it is estimated that the revenue generated in parts and services can amount to as much as two to three times the original sale price.[1] Thus, it is clear that aeroengines alone will produce revenues in excess of $500 billion in this decade.

In this paper, we present a survey of the key aeroengine technology trends. We begin by quoting Glenn Martin,[2] "The airplane, from its inception, has grown in capacity and performance only at the pace permitted by the aircraft engine, and we have historically selected the engine first and designed the airplane around it. The search for high power has never relaxed for an instant."

Data Sources

There are many data sources on aeroengines in the literature. Some key sources are: manufacturers' websites, *Jane's Aero Engines*,[3] *Jane's World Aircraft*, *Aviation Week and Space Technology*, *Gas Turbine World*, the Federal Aviation Administration website,* the International Civil Aviation Organization (ICAO) Web site,† and unclassified literature produced by the U.S. Department of Defense (DoD)/NASA/DARPA/Industry Integrated High Performance Turbine Engine Technology (IHPTET) and the DoD/DoE/NASA/Industry Versatile Affordable Advanced Turbine Engine Technology (VAATE) programs.[4] Also, in 1979 Quinn[5] presented a brief survey of aeroengines in service with the U.S. Air Force. However, much progress has been made in the last 24 years. Now, the celebration of the Centennial of Powered Flight presents a historic opportunity to revisit the achievements made in aeroengine technology. Finally, Curran[6] has conducted an excellent survey of advanced propulsion systems such as ramjets, scramjets, pulse detonation engines, and turborockets.

Data Accuracy

The civil aviation business is extremely competitive. Therefore, there is no doubt that the aeroengine manufacturers highlight the best attributes of their products and continuously upgrade and repackage their engine offerings. In contrast, and as would be expected, data on military engines remain classified. Thus, we cannot guarantee or refute the accuracy of the public-domain data. Further, we do not

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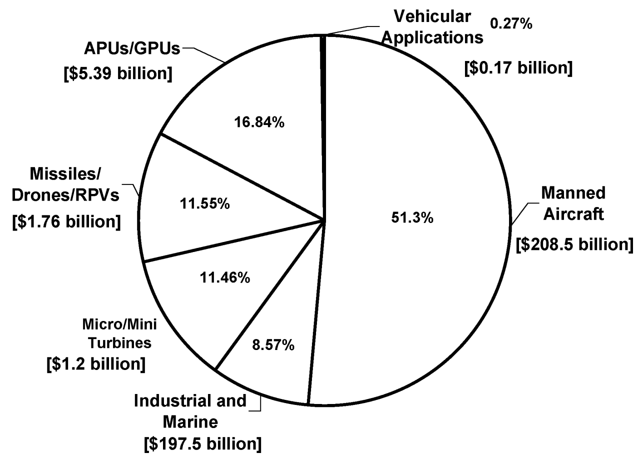

Fig. 1 Unit market share (percent) and value (2002 U.S. dollars) for gas turbines in (2002–2011).

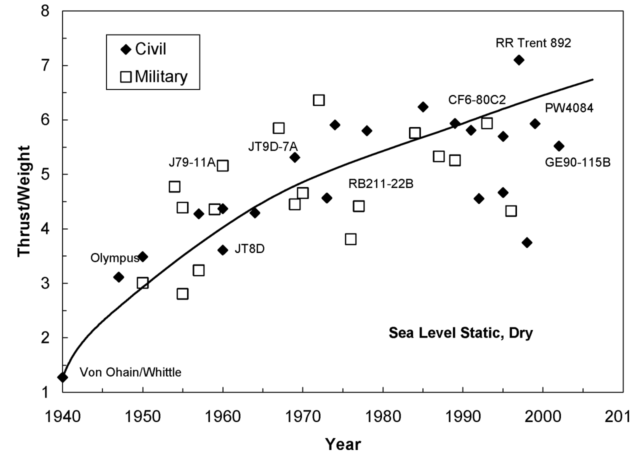

Fig. 3 T/W advancements for aeroengines.

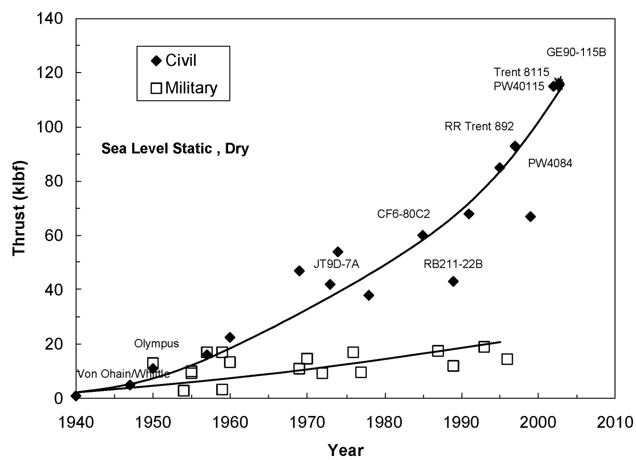

Fig. 2 Thrust improvement for aeroengines.

endorse or dismiss any particular design, manufacturer, or product claim. Rather, our objective is to analyze the public-domain data and demonstrate general trends and conclusions. Finally, the views expressed in this paper are our own and not necessarily those of our employers, especially the U.S. Air Force.

Scope

This paper covers the following gas-turbine engine parameters and describes progress in each category during the 1939–2003 period. Engine parameters are presented in British units because these units are familiar to gas-turbine engine designers. A total of 50 aeroengines (one-half military and the rest civil) were analyzed.

Engine Parameters

Thrust

This is a measure of engine power. The data are available for both takeoff and cruise conditions. We chose to compare takeoff thrust [sea-level static condition (SLS), dry] for this survey because data are available for this operating condition.

Figure 2 shows the progress of engine takeoff thrust (SLS dry condition) to date. In 1903, Charlie Taylor built a 12-hp aluminum engine weighing 200 lb for the Wright Brothers.[7] In August 1939, a von Ohain-designed He.S3B engine produced a thrust of approximately 1000 lbf, and soon thereafter, in March 1942, the Whittle W2B engine produced a thrust of 1250 lbf. On 20 November 2001, during ground tests the GE90-115B engine achieved an unprecedented thrust of 120,316 lbf. Now, the GE90-115B, Rolls Royce Trent 8115, and Pratt and Whitney PW40115 engines are all scheduled for Federal Aviation Regulation (FAR) 33-type certification rated at 115,000 lbf of thrust (equivalent to some 34,500 shp) and entry into service. Thus, aeroengine power has grown an incredible 2875-fold since the first flight by the Wright Brothers and an equally impressive 115-fold since the pioneering works of von Ohain and Whittle.

Many military engines use afterburners to boost the takeoff thrust level as much as 80%. However, Fig. 2 shows takeoff thrust levels for military engines with an afterburner turned off. These data show that today's military engines are at least 20 times more powerful.

Figure 2 also shows a dramatic enhancement in thrust since the mid-1980s as a result of many factors. For example, in the civil sector the worldwide boom in air travel created a market need for super-large aircraft and high thrust engines to propel them. The civil aeroengine sector is intensely competitive, and competition is the prime driver of technological innovation. Also, in the United States, the IHPTET program initiated in October 1987 led to a coordinated effort between government and industry to significantly enhance military turbopropulsion capability. Advances in lightweight, high-temperature composite materials and the computer revolution also made possible the optimization of many aerodynamic and structural design parameters.

Thrust/Weight and Specific Thrust

Weight is the enemy of aircraft performance and fuel economy, and a lighter engine improves both. Therefore, engine (takeoff thrust/dry weight) ratio is a key design parameter.

Figure 3 shows improvements in thrust-to-weight ratio (T/W). In 1940, the von Ohain and Whittle engines had a T/W of 1.2. Today, and in spite of its 123-in-diam (largest ever) fan, the GE90-115B engine still recorded an impressive T/W of 5.5 and the other lower-thrust rated civil engines produced numbers approaching seven. Military engines (thrust without an afterburner) recorded similar gains. Such impressive achievements result from the extensive use of lightweight composite materials, computer-assisted structural design, and improved aerodynamics leading to lighter turbo machinery.

Specific thrust is a measure of engine thrust produced per unit mass of the airflow that the engine accelerates. This parameter is important because it affects aircraft size and drag. Turbojet engines accelerate a small airflow mass to a very high jet velocity. Therefore, they produce a high specific thrust, but low propulsive efficiency and fuel economy. In contrast, the turbofan engines use a large fan to accelerate a huge quantity of airflow to a jet velocity just above the aircraft speed. These engines produce lower specific thrust but higher propulsive efficiency and better fuel economy.

Figure 4 illustrates two aeroengine trends: civil and military. For turbo-fan type civil engines, the increasing use of fans with high by pass ratio (BPR) has kept the specific thrust approximately constant around a value of 30 but produced significant reductions in thrust specific fuel consumption (TSFC) and noise. In contrast, the specific thrust of (low BPR) military engines has increased over three-fold, as compared to civil engines, reaching values over 100.

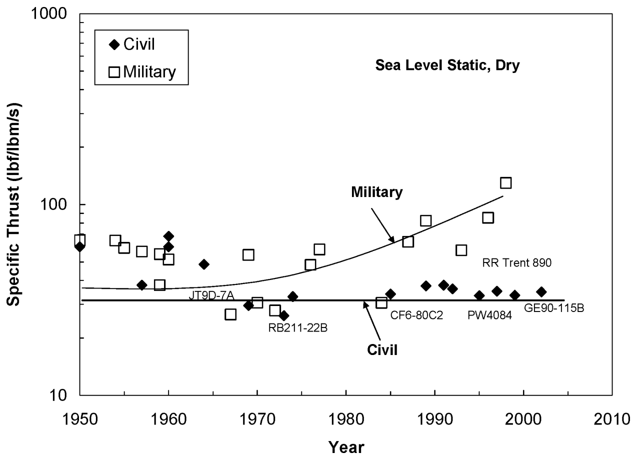

Fig. 4 Specific thrust for aeroengines.

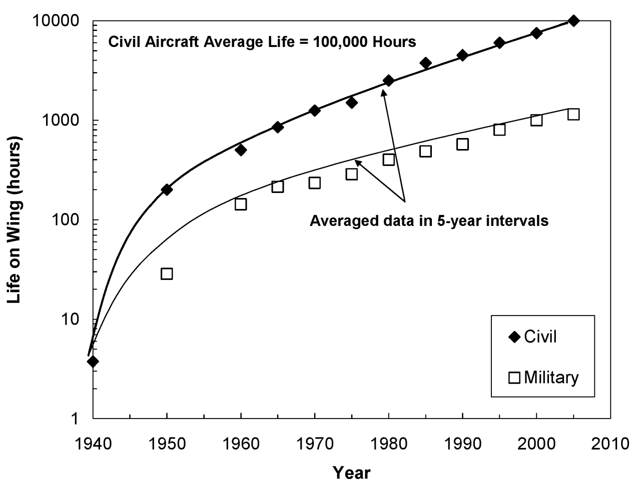

Fig. 5 Life on wing improvements for aeroengines.

Life and Reliability

Typically, a civil aircraft life of 25 years equates to 100,000 flying hours The aeroengine life is defined in terms of “life on wing” This is the average time (in flying hours) that an engine will stay on the aircraft before it is replaced or removed for full maintenance service. However, as is often the case, the engine is given routine maintenance while it is still on the wing. The engine reliability is measured in terms of in-flight shutdown rate (IFSD). The whole topic of aeroengine life and maintenance is very complex and subject to interpretation. Also, data are very difficult to obtain, scattered, and/or highly proprietary. Thus, it is the least accurate of all of the data presented.

Singh[8] and Gunston[3] have collected representative and averaged data for civil and military engines through year 2000. These data are averaged for several engines designed in each five-year interval. As such, only broad trends on engine life and reliability can be ascertained.

Figure 5 illustrates both civil and military engine life enhancement trends over the years. These data illustrate that whereas the early jet engines lasted for less than 10 hours, today the civil engines can stay on wings for up to 10,000 hours. The military uses all types of engines: at one end of the spectrum are turbojets or low-BPR turbofans with afterburners for fighter aircraft, and at the other end are high-BPR turbofans for cargo hauling. Although the averaged-data show a life of about 800 hours, it should be obvious that the fighter aircraft engine needs maintenance sooner than the cargo aircraft engine—presumably every couple of hundred hours. Nevertheless, engine life has made significant gains over the years.

Figure 6 shows the civil aeroengine reliability trend. It appears that the aeroengine reliability (IFSD rate) has risen exponentially from one engine failure per 1000 flying hours (1950s) to less than

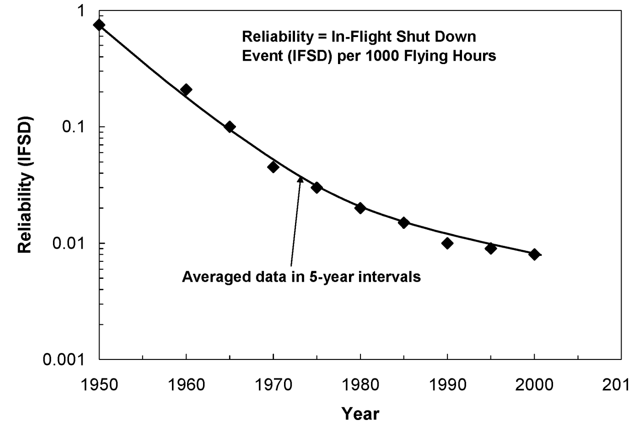

Fig. 6 Reliability improvements for aeroengines.

one failure per 100K flying hours (2000 s). For example, “Jane’s Aero Engines”[3] provide an IFSD value of 0.008 for a CF-6 family of engines. This engine has been in service with over 150 customers and logged 180 million flight hours. General Electric (GE) claims their CF-6 series to be the “the world’s most reliable family of aircraft engines.” This extended engine life on wing and reliability (IFSD) have had two major impacts:

First, the very high reliability of today’s engines is the reason for a move to equip the aircraft with only two engines, even for extended trans-Atlantic and trans-Pacific flights. Aircraft with more than two engines are permitted an unlimited flight planning. However, aircraft with only two engines must have an extended-range, twin-engine operation (ETOPS) certification to fly either 120 or 180 min away, in an emergency (mostly over oceans on one engine alone) from the nearest available runway. Currently, large aircraft such as the Boeing 777 equipped with their GE, Rolls-Royce (RR), or Pratt and Whitney engines are working hard to get certification for an ETOPS level of 240 min. If successful, this means that, in an emergency, 400 or more passengers could be flying on one engine alone over 1740 n miles from the nearest airfield.

Second, the dramatic improvement in civil engine life and reliability threatens the very profitable after-market parts and services business. Now, it appears that few if any new replacement civil engines might ever be required over the life of the aircraft. Rather, routine service can keep the engine on wing for the entire life of the aircraft.

Component Improvements

Fan/Compressor

The combined fan and compressor performance is characterized by an overall pressure ratio (OPR). This value is the product of fan and core compressor pressure ratios. Higher OPR generally produces high thermal efficiency and lower TSFC. Today’s large civil turbofan engines are typically approaching a fan pressure ratio around 1.7 (Ref. 3). Figure 7 shows the takeoff SLS OPR data for both military and civil engines. It is observed that the most powerful civil engines of today are reaching a maximum OPR $= 45$.

Over the years, compressor designers have continued to pursue the strategy of increasing the stage pressure ratio. Clearly, it would save weight and parts if the compressor could develop the same pressure ratio in as few compressor stages as possible. Figure 8 shows the results of these efforts. Since 1950, the compressor single-stage pressure ratio has increased from 1.2 to 1.57. Recently, Benzakein[9] has shown that the airfoil blade count decreased from 1518 to 968 by decreasing the compressor stages from 9 to 6.

Three significant advances have made possible the outstanding performance of today’s fans and compressors: 1) three-dimensional computational fluid-dynamics analysis of blade aerodynamics has yielded high-flow swept fan, wide-chord and forward-swept aerofoil shapes, high-stage loading, and optimization of blade geometry from root to tip and from low- to high-pressure stages; 2) use of advanced materials such as lightweight graphite-epoxy composite materials for the fan, advanced titanium aluminide compressor blades, and

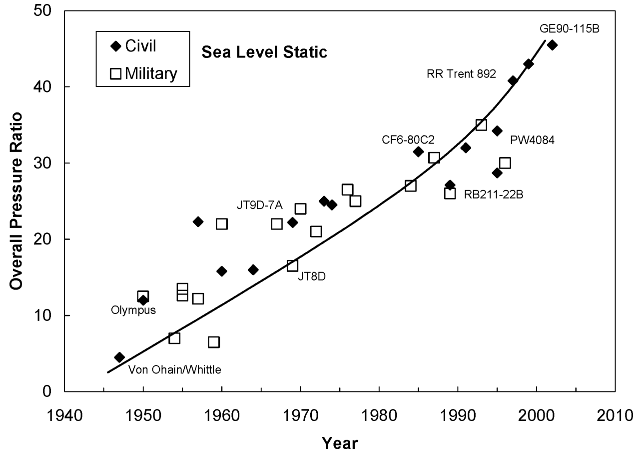

Fig. 7 Overall pressure ratio increases for aeroengines.

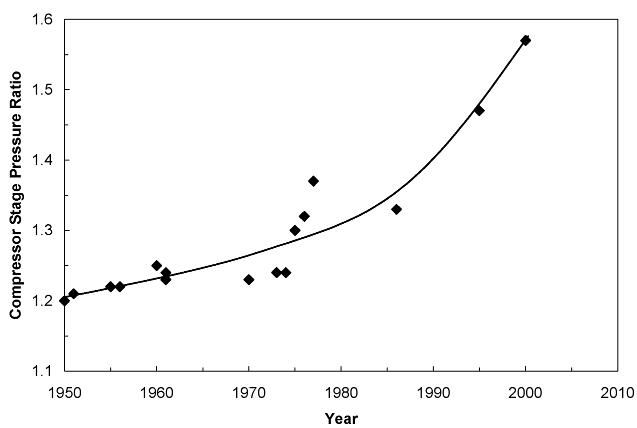

Fig. 8 Compressor single-stage pressure ratio for aeroengines.

high-temperature titanium matrix composite ring construction for the compressor rotor has produced weight reduction and improved durability; and 3) clearance control, assessment of leakage losses, and optimization of stall margin, stage pressure ratio, and efficiency have enhanced compressor performance.

Thus, aerodynamics, structural design and manufacturing technologies have contributed to the novel compressors manufactured today.

Combustor

Three key combustor performance parameters are low cooling requirement leading to low specific fuel consumption (SFC), exit-temperature traverse quality (pattern factor), and low emissions. A discussion of TSFC, thermal efficiency, and emissions follows later.

The impingement-film float wall combustor has demonstrated a low pattern factor with the excellent temperature profile[4] necessary for high-pressure turbine (HPT) durability and reduced maintenance costs at high fuel/air ratios and increased temperature. Benzakein[9] reports that GE's Twin Annular Premixing Swirlers (TAPS) combustor provides for fuel staging within the coannular swirler. This concept produces a compact combustor and permits lean burning at high power with outstanding operability. Also, combustor liners of ceramic matrix composites are being developed that promise to double the liner life. The RR Trent[3] uses a thermal barrier coated combustor liner for increased durability, reduced cooling, and high-temperature capability. Finally, the Air Force is pioneering innovative in-house designs for the future, such as Trapped Vortex Combustor[10] and Inter-Turbine Burner[11] for improved flame stabilization, low pollutant emissions, relight capability, and low lean blowout.

Turbine

To improve overall efficiency, and therefore fuel economy, all modern aeroengines (including military engines) are of the turbofan type. In a turbofan engine the energy extracted from the engine core provides the power to drive the fan and improve propulsive efficiency. The turbofan arrangement allows the engine core to be designed for maximum thermal efficiency, whereas the low-pressure fan can be designed for maximum propulsive efficiency.

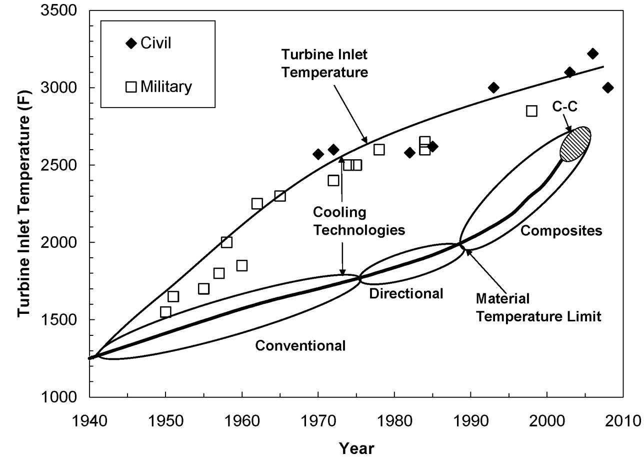

Fig. 9 Comparison between turbine inlet temperature and blade material temperature limits highlighting the importance of cooling technology.

Early pioneers encountered problems producing positive power out of a gas turbine for two reasons. First, the compressor pressure rise was very small and second, no high-temperature turbine blade materials, exceeding 1300°F, were available. An increase in the turbine inlet gas temperature directly increases the thermal efficiency of the engine. Figure 9 shows how advances in turbine blade cooling coupled with development of high-temperature materials have permitted an increase in the turbine inlet gas temperature from 1280°F (von Ohain engine) to today's 3200°F.

Advances in manufacturing techniques have permitted turbine blades to be made with small and intricate air-cooling passages. This has decreased blade cooling air requirements and at the same time has enabled higher turbine inlet temperatures. Today, this advanced cooling technology is making possible greater core thermal efficiency and lower TSFC. The importance of improved cooling technology cannot be overemphasized. For example, today's most resilient material, the carbon-carbon (c-c) composite, can withstand about 2800°F (without sacrificing durability), whereas the stoichiometric turbine inlet gas temperature limit is close to 4200°F. Even if we develop technology to make durable c-c composite turbine blades, still blade-cooling technology will play a significant role, and its improvement will be highly desirable in the future.

Other advances in turbine design include supercooling of turbine airfoils, hollow Ceramic Matrix Composite (CMC) HPT vanes, and bonded dual-web turbine disks.[4] These advances are leading to turbine designs with fewer airfoils, with significant reduction in blade cooling flow, and over 90% stage efficiencies.

Today, turbines are made of exotic materials: For example, GE90 uses cast monocrystal blades, held in powdered-metal (Rene R88DT) discs, military engines use advanced single-crystal blade material with multipass convection and film cooling, and the RR Trent uses single-crystal CMSX-4 blade alloy with internal cooling.[3] Finally, Benzakein[9] refers to the development of a blade material MX4 with improved thermal barrier coating (TBC2). Together with advanced cooling technology, Benzakein[9] proposes to increase turbine inlet gas temperatures to 3500°F in three years and also obtain a four-fold improvement in turbine blade life. Together with the new disk material ME3 (a replacement for INCO718 and R88DT), these high-temperature materials will set new industry standards.

Economy of Operation

Bypass Ratio

As just stated, the turbofan arrangement allows for the low-pressure fan to be designed for maximum propulsive efficiency.

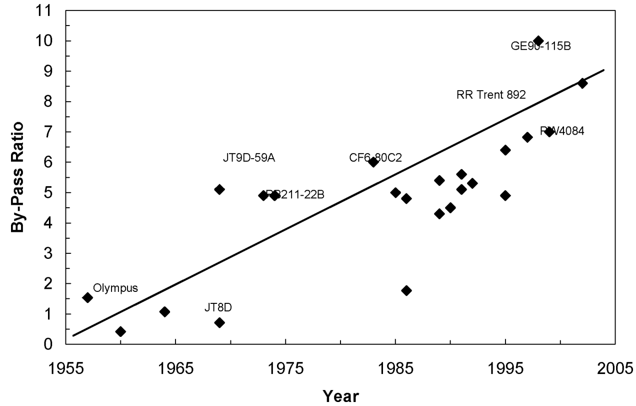

Fig. 10 By pass ratio for aeroengines.

Gunston[3] states that, until 1960, apparently an error in calculating the drag of a complete pod or nacelle forced Rolls Royce (and its competitors) not to offer a large fan with a BPR > 1. Figure 10 shows just how rapidly this has changed, and today civil engines like the GE90-115B engine boasts the highest BPR $= 8.6$. Generally, high-performance military engines need to project a low frontal area for reduced drag; therefore, they are designed for low bypass ratios in range 0.5–1.

An increase in bypass ratio increases fan diameter and hence also engine weight. Also, a large fan might need a complex speed-reduction gear drive. The gear drive adds weight and the possibility of mechanical failure. Finally, hanging a huge nacelle under an aircraft wing increases aircraft drag and can negatively impact aircraft performance. Benzakein[9] has performed an analysis of these various conflicting factors and concluded that for today's large turbofan engines a BPR between 8–10 provides minimum TSFC. Unless the fan aerodynamics is further improved (e.g., variable pitch fan) and newer, lighter-weight fan materials arrive on the scene, we might soon reach an upper limit to BPR and propulsive efficiency, and a corresponding lower limit to TSFC.

Aeroengine designers do not like a gearbox. It is heavy, inefficient, expensive, and a source of unreliability. In contrast, a gearbox can reduce fan peripheral speed, eliminate the need for a large, massive and costly multistage turbine, increase propulsive efficiency and thereby fuel economy, and reduce fan noise (e.g., AlliedSignal LF500 and TFE731 engines). According to Jane's,[3] Pratt and Whitney has been studying how best to design a geared turbofan (or an advanced ducted fan) engine, and a latest example is the PW8000 gearbox for a 25 to 35K lbf thrust class engine. Jane's[3] reports that Pratt and Whitney successfully tested 12 such units in mid-1999, each capable of transmitting 32,000 shp at takeoff, and a PW8000-powered aircraft could enter service in 2005.

Thrust Specific Fuel Consumption

TSFC of an engine is inversely proportional to its overall efficiency (overall efficiency = propulsive efficiency × thermal efficiency). In terms of component parameters, low TSFC is achieved by an optimum combination of BPR, OPR, and turbine inlet temperature. The data for TSFC are available for both takeoff and cruise conditions (Mach 0.8, 35,000 ft). We chose to compare takeoff TSFC (SLS, dry) for this survey.

Figure 11 shows TSFC vs year trend for both military and civil engines. Clearly, with their high BPR, civil engines demonstrate lower TSFC than military engines, reaching a low value of 0.34 for engines such as the GE CF6-80C2. For this engine, the cruise TSFC (Mach $= 0.8$, altitude $= 35{,}000$ ft) is quoted as 0.578. Now, Smith[12] has calculated a theoretical lower limit to cruise TSFC $= 0.19$ for 100% overall engine efficiency. This comparison demonstrates just how far aeroengine technology has progressed, and yet there is always scope for improvement. Clearly, further increases in OPR and turbine inlet temperature, leading to significantly higher thermal efficiency, need to be achieved in the future to improve cruise TSFC.

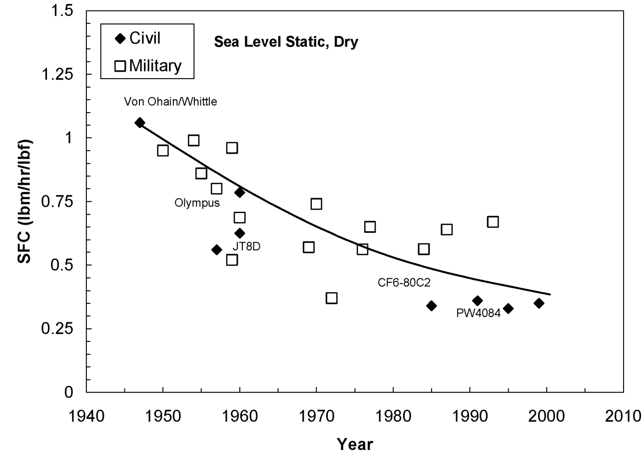

Fig. 11 SFC improvements for aeroengines.

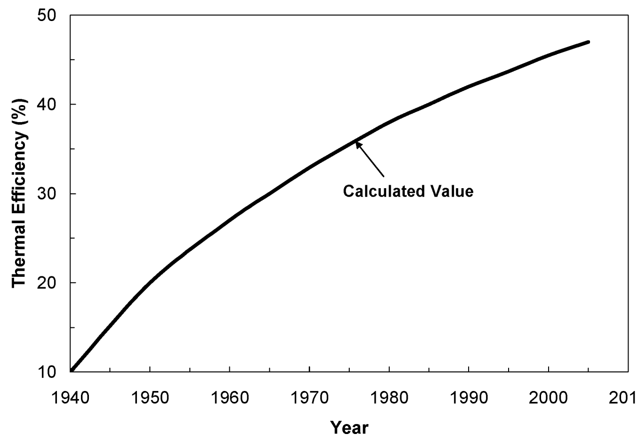

Fig. 12 Thermal efficiency for aeroengines.

Thermal Efficiency

The various efficiencies related to a gas-turbine aeroengine are defined as follows[4]:

Propulsive efficiency:

$$\eta_p = T \cdot V_0 / W_{\text{out}} \tag{1}$$

Thermal efficiency:

$$\eta_t = W_{\text{out}} / Q_{\text{in}} \tag{2}$$

Overall efficiency:

$$\eta_o = T.V_0 / Q_{\text{in}} = \eta_p \times \eta_t \tag{3}$$

The propulsive efficiency is 100% when aircraft speed equals exhaust jet speed. It is estimated that today's high bypass turbofan engines are approaching a propulsive efficiency of around 80%. (Refs. 3 and 8). Moreover, fan size and weight are restricting any further gains in propulsive efficiency.

Figure 12 shows the calculated values of thermal efficiency for selected aeroengines. This result illustrates that the core-engine thermal efficiency has increased 4.7-fold since 1940 to about 47% at the turn of the century. Thus, the overall efficiency of today's turbofan engine has reached $(0.8 \times 0.47) = 38\%$. This calculation demonstrates that there is scope for further improvements to increase the engine core thermal efficiency to enhance TSFC.

Environmental Impact

NOx Emissions

Oxides of nitrogen are comprised mostly of NO and NO_2. These pollutants are typically produced at the high power setting of the engine. As the turbine inlet temperature and engine thermal efficiency

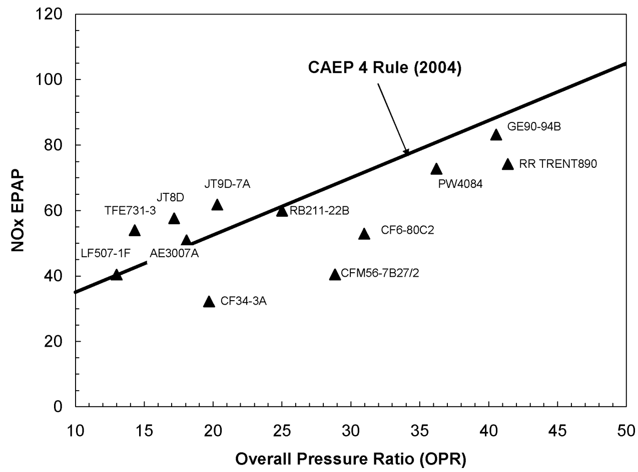

Fig. 13 NOx EPA emissions as a function of OPR (SLS) for aeroengines.

have improved, NOx emissions have increased correspondingly. Today, NOx emissions are the principal constituent (NOx = 86%, CO = 12.4%, unburned hydrocarbons (UHC) = 1.5%, and soot = 0.1% by mass) of the total jet-engine emissions. The ICAO* data show that worldwide NOx emissions from aeroengines are very small (2%) as compared to those produced by power generation (19%), ground transport (70%), and marine engines (9%). Nevertheless, they are of concern because of likely damage to the Earth's upper-atmospheric ozone layer (thereby producing global warming) through the following ozone-depletion reaction.

$$NO + O_3 = NO_2 + O_2 \tag{4}$$

The ICAO Committee on Aviation Environmental Protection (CAEP) examines aircraft emissions and issues various rules.* Although ICAO rules are nonbinding, manufacturers do follow them. The CAEP 4 (2004) rule on NOx emissions is

$$\mathrm{EPAP} = D_p/F_{oo} = 19 + 1.6\,\pi_{oo} \ (\mathrm{OPR} < 30)$$

or

$$= 7 + 2\,\pi_{oo} \ (\mathrm{OPR} > 30) \tag{5}$$

Figure 13 shows a plot of NOx emissions vs OPR for post-1985 engines with OPR > 25 and the CAEP 4 (2004) rule. It can readily be observed that almost all of today's aeroengines already meet the stringent low-NOx-emissions levels suggested for 2004. Advanced annular combustor designs with fuel staging are meeting the future low-emission challenge—a great achievement on the part of the aero engine manufacturers.

Smoke Emissions

Exhaust smoke is caused by the production of finely divided soot particles in the fuel-rich region of the combustor flame. The problems of smoke and soot are always most severe at takeoff when high combustor pressure, coupled with rich fuel-air mixture, produces smoke. ICAO* estimates that as much as 200 tons of carbon can fall on a large busy airport per year. For military aircraft, a smoke trail provides visibility and radar signature. Because the smoke trail is visible during takeoff, both engine manufacturers and airlines have an obvious interest in eliminating it.

Currently, ICAO 1989* standards apply to smoke emissions from all civil aircraft engines above a sea-level takeoff thrust of 6000 lb. These standards use the Society of Automotive Engineers ARP 1179-stained filter paper method to define the smoke number (SN).[13]

$$\mathrm{SN} = \text{Lower of } 50 \text{ or } 83.6/(F_{oo})^{0,274} \tag{6}$$

*Data available online at www.icao.org.

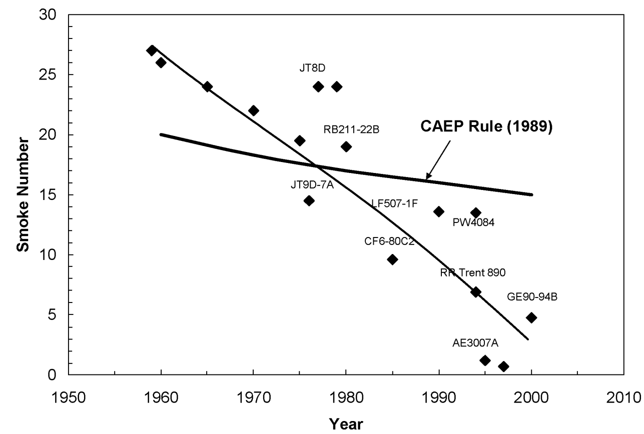

Fig. 14 Smoke number improvements for aeroengines.

Figure 14 shows an ICAO 1989 standard plot of smoke number vs years and exhaust smoke numbers for several high-thrust aeroengines. It can be seen that for today's most powerful aeroengines SN = 7, a value that is 50% lower than the ICAO 1989 rule. However, tougher new regulations are expected in the near future.

Most particulate matter from aircraft engine exhaust is less than 2.5 μ in diameter ($PM_{2.5}$), and studies have linked these airborne particles to both health and environmental concerns.* Accordingly, the National Ambient Air Quality Standards have health-based regulations for particulate matter with diameters less than 10 μ (PM_{10}) and 2.5 μ ($PM_{2.5}$) (also see Environmental Protection Agency Fact Sheet dated 16 July 1997). Soot particulate formation within the combustor causes clogging of fuel injectors, erosion of combustor and turbine blade thermal barrier coating, and production of condensation trails. High particulate loading increases radiative heat flux to the combustor wall, thereby increasing the film-cooling air requirement and hence also engine TSFC.[13]

To mitigate particulate emissions, the Fuels Branch of the U.S. Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio, is developing and evaluating alternate fuel formulations (e.g., varying aromatic and sulfur content) and fuel additives that will significantly decrease soot particulate size, number density and mass emissions.[14,15] Clearly, this is an area of considerable future development.

Other Gaseous Emissions

CO and UHC form the other gaseous emissions. Current ICAO rules* call for following emissions limits for new engines with rated takeoff thrust greater than 6000 lbf (26.7 kN).

$$\text{CO Emissions} = 118 \text{ g/kN} \tag{7}$$

$$\text{UHC Emissions} = 19.6 \text{ g/kN} \tag{8}$$

Modern engines meet both of these limits with an enormous margin. For example, CO emissions are typically below 0.5 g/kg of fuel, and UHC emissions are below 0.05 g/kg of fuel burned. Therefore, CO and UHC emissions become a nonissue, at least in the near future.

Noise Abatement

Engine noise level at takeoff is regulated by FAR 36 and ICAO 1978 rules.* These rules require the measurement of effective perceived noise in decibels (EPNdB) that takes into account the ear's response to different frequencies and other corrections. Most aircraft noise is comprised of engine noise that comes from many sources such as discrete fan tones, turbomachinery blades, turbulent jet exhaust, and gearbox.

We analyzed the measured noise data[3,*] on various aircraft and normalized these data to noise emissions level (EPNdB = 0) from

*Data available online at www.icao.org.

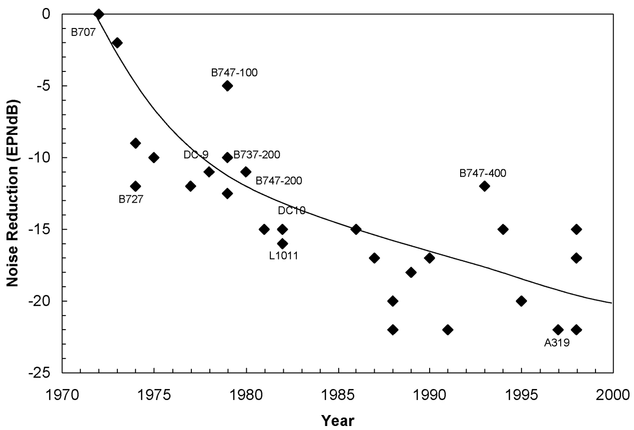

Fig. 15 Noise abatement improvements for aircraft.

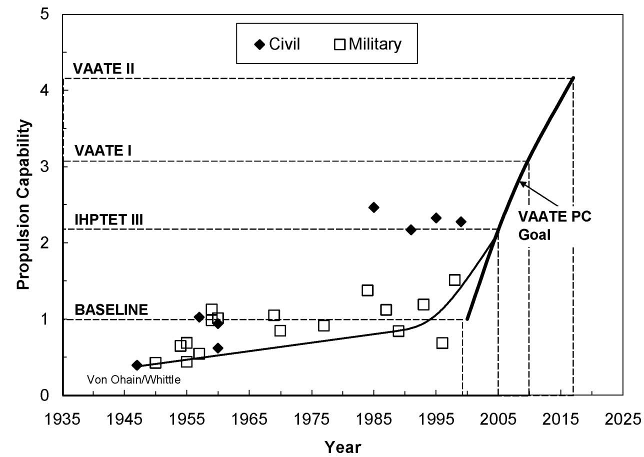

Fig. 16 Propulsion capability of (large turbofan) aeroengines.

a 1971 Boeing 707 (48,000 lbf thrust) aircraft. Figure 15 shows the plot of the normalized noise emissions level. These data illustrate that, for approximately the same thrust, today's Airbus A319 aircraft is quieter by 23 dB. Also, and in spite of a 3.3-fold higher thrust, the Boeing 777-200 is still 17 dB quieter.

However, the forthcoming new rules in FAR 36 Stage IV (Stage III-10) will provide a major challenge to engine manufacturers in the area of fan and jet noise reduction. Benzakein[9] states that by using swept and lean guide vanes on the CF6 fan (−3 EPNdB improvement) and chevron nozzles on the jet exhaust (−3.5 EPNdB benefit) of CF6-80C2 and CF34-8C5 engines have already yielded noise reduction. Nevertheless, the future noise abatement rules will pose significant challenges to the aeroengine designers.

Future

Spectacular gains in aeroengine technology have been made during the years 1939–2003. As the aviation world pauses to celebrate the Centennial of Powered Flight in 2003, yet another challenge is on the horizon for the propulsion engineers of the 21st century. In the United States, this challenge is epitomized by the goals set for the IHPTET III and VAATE programs.

IHPTET and VAATE

The IHPTET program,[4] initiated in October 1987, is a U.S. national collaborative effort to double aeropropulsion capability by 2005 without compromising life, reliability, and maintainability. This three-phase military engine program has yielded enormous improvements in component technologies and also benefited the civil engine sector.

The VAATE program[4] is focused on achieving a 10-fold improvement in turbine engine affordability by 2017. Its mission is to develop a versatility engine (versatile core, intelligent engine, and durability), demonstrate affordability, and transition advanced turbine engine technologies for revolutionary improvements in performance. The VAATE capability/cost index (CCI) is defined as follows: CCI = (propulsion capability/cost Index); where propulsion capability (PC) = (T/W/takeoff TSFC) and Cost Index (CI) = (develop + prod. + maint.) cost.

To quantify the VAATE goals, a baseline value of CCI was calculated using a year 2000 state-of-the-art engine. The program goals, for example, for large turbofan engines, were then defined as

$$\text{IHPTET III(2005)CCI} = 3.1 \times \text{Baseline CCI} \tag{9}$$

$$\text{VAATE I(2010)} = 6 \times \text{Baseline CCI} \tag{10}$$

$$\text{VAATE II(2017)} = 10 \times \text{Baseline CCI} \tag{11}$$

Because engine cost information is highly proprietary and very difficult to obtain, we could not perform CCI calculations. Therefore, we calculated only PC values (numerator of the CCI) for the various engines surveyed, and normalized our calculated values using the VAATE baseline engine value of PC = 7.44 for the year 2000 (for large turbofan engines).

Figure 16 shows a plot of the normalized PC vs years. Also plotted are the IHPTET III and VAATE normalized PC goal lines for a large turbofan jet engine (normalized values of PC = 2.18, 3.13, and 4.17 in years 2005, 2010, and 2017, respectively). It is observed that most state-of-the-art, post-1995 aeroengine technology follows the baseline, while a few large civil turbofan engines are moving along the VAATE PC goal line towards the IHPTET III PC goals of 2005. Thus, it is clear that future aeroengine developments will chart the course set by the IHPTET III and VAATE goals.

Conclusions

We have presented a survey, covering the period 1939–2003, of the key aeroengine technology trends, namely, engine parameters, component improvements, economy of operation, environmental impact, and future development.

1) Since 1939, aeroengine thrust has increased over 100-fold for civil engines and some 20-fold for military engines. Today's engines also recorded (thrust/weight) approaching seven.

2) Whereas the early jet engines barely lasted for less than 10 hours, modern civil engines can stay on wings for up to 10,000 hours and military engines up to 800 hours. However, there is a considerable future scope for increasing aeroengine durability and life and decreasing maintenance and repair costs.

3) For component improvements, the single-stage compressor pressure ratio has increased 30%, and at the same time the number of stages and blade count has decreased. Advances in blade-cooling technologies, even more so than advances in high-temperature materials, have permitted an increase in turbine inlet temperature from 1280 to 3200°F.

4) Aeroengine thermal efficiency is approaching 50%, and takeoff thrust specific fuel consumption is near 0.34.

5) Today's most powerful aeroengines already meet the International Civil Aviation Organization ultralow gaseous and smoke requirements. However, tougher new particulate matter emissions and noise abatement regulations are expected in the near future. These areas will require further improvements.

6) Finally, today's civil and military technology is moving along the direction set by the versatile affordable advanced turbine engine technology (VAATE) propulsion capability goals. Because no alternatives to gas-turbine technology are available, it is incumbent upon us to improve this power plant even further, and the VAATE program lists three broad categories of future developments: versatile core, intelligent engine, and durability. This survey shows that significant enhancements in (thrust/weight) ratio, engine life management, overall pressure ratio turbine inlet temperature, thermal efficiency, thrust specific fuel consumption particulate mitigation, and noise abatement will be required to improve the aero-gas-turbine engine. The spectacular achievements of the last century truly provide an

outstanding start for many future achievements to come in the field of aeroengine technology along the lines of the VAATE goals.

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