ICAS-92-0.2

ADVANCEMENTS IN AIRCRAFT GAS TURBINE ENGINES: PAST AND FUTURE

W. L. Webb
Pratt & Whitney
East Hartford, Connecticut

This paper will primarily address the use of gas turbine engines in commercial transport service with brief references to military engines as it relates to state of the art technology advancements. The commercial gas turbine era was initiated in the early 1950's with the DeHavilland Ghost 50 engine, Figure 1, powering the DeHavilland Comet DH106 Airliner. This engine and other early commercial gas turbines were minor derivatives of military fighter jet engines. At Pratt & Whitney it was the J57 and J75, and at General Electric it was the J79. However, in Europe and the United States work started almost simultaneously with the introduction of these straight turbojets to increase the propulsive efficiency and thereby reduce the specific fuel consumption by adding compression stages where air discharged directly into the atmosphere without going through the gas generator. The Pratt & Whitney and Rolls Royce companies chose to mount these additional compression stages in the front of the gas generator where the inner portion acted as the early compression stages for the gas generator, while the General Electric Company chose to mount this feature aft of the gas generator. These engines became known as the early turbofans and set the trend we are still on today, decreasing specific fuel consumption with increased propulsive efficiency coming from increased bypass ratio.

The late 1960's saw the emergence of the "high bypass" ratio engine. This era was ushered in when the General Electric Company was awarded a contract to develop the TF39 engine for the Lockheed C–5A transport. This was followed shortly by the JT9D engine developed for the Boeing 747. The Boeing 747 entered service less than 20 years after the dawn of pure jet powered commercial aviation. Our ability to provide fuel efficient commercial service had progressed from about 20 seat miles per gallon to over 60 seat miles per gallon as shown in Figure 2.

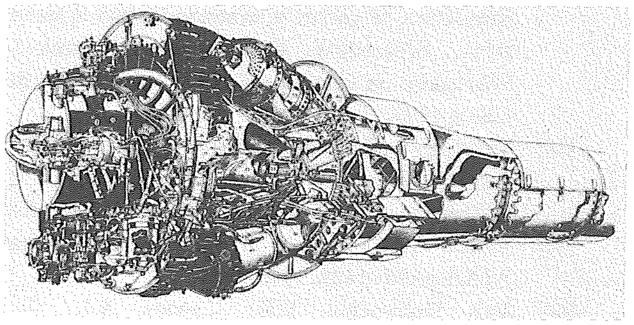
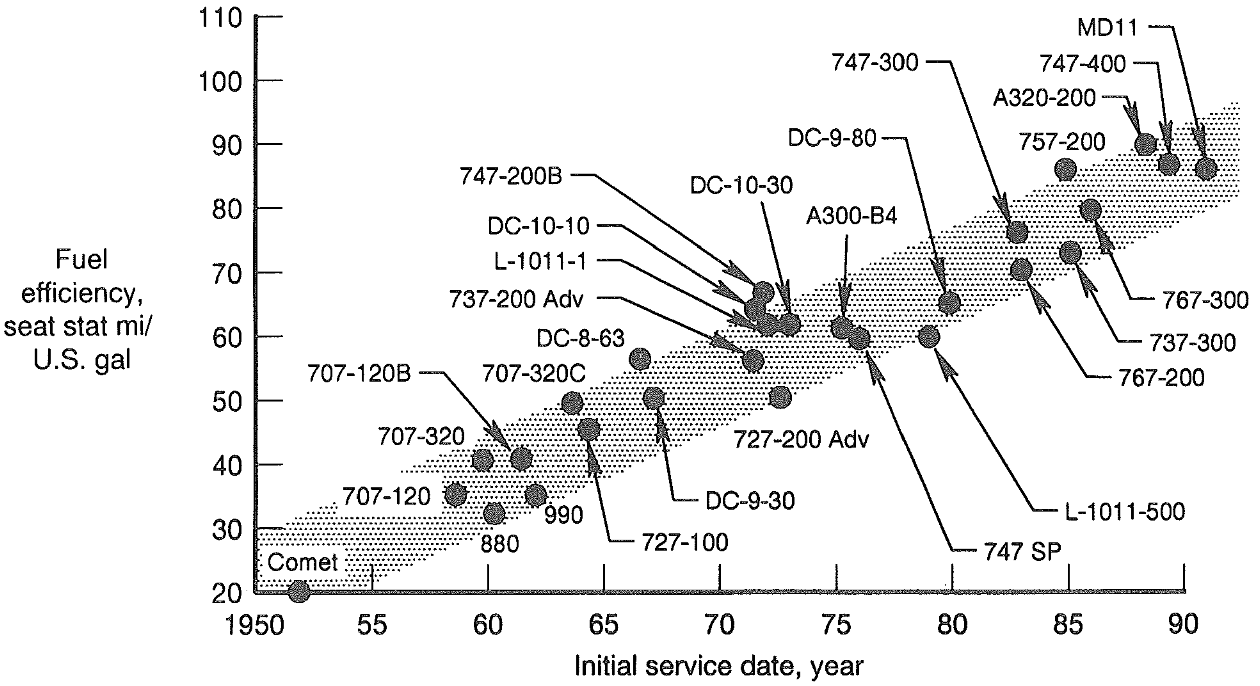


Figure 1. The World's First Commercial Engine – DeHavilland Ghost 50

ENGINE CYCLE EVOLUTION

Figure 2 illustrates the improvement in fuel efficiency spanning 40 years of jet powered aircraft. The early engines like the Ghost were low pressure ratio turbojets with uncooled turbine blades. It was soon realized that the staged axial compressor offered both higher pressure ratio and efficiency with lower frontal area than the single stage centrifugal. The axial design provided a "straight through" compressor flowpath eliminating 90 degree flowpath bends and facilitating the adaptation of a short annular (rather than a can type or cannular) combustor. To achieve operability margin at higher compression ratios, engine turbomachinery designs became polarized by company and featured either two rotor spools with fixed geometry compressors or a single rotor using variable compressor stator vanes. The introduction of titanium alloy front fan rotors reduced weight 45% while the midspan shrouded rotor blade design

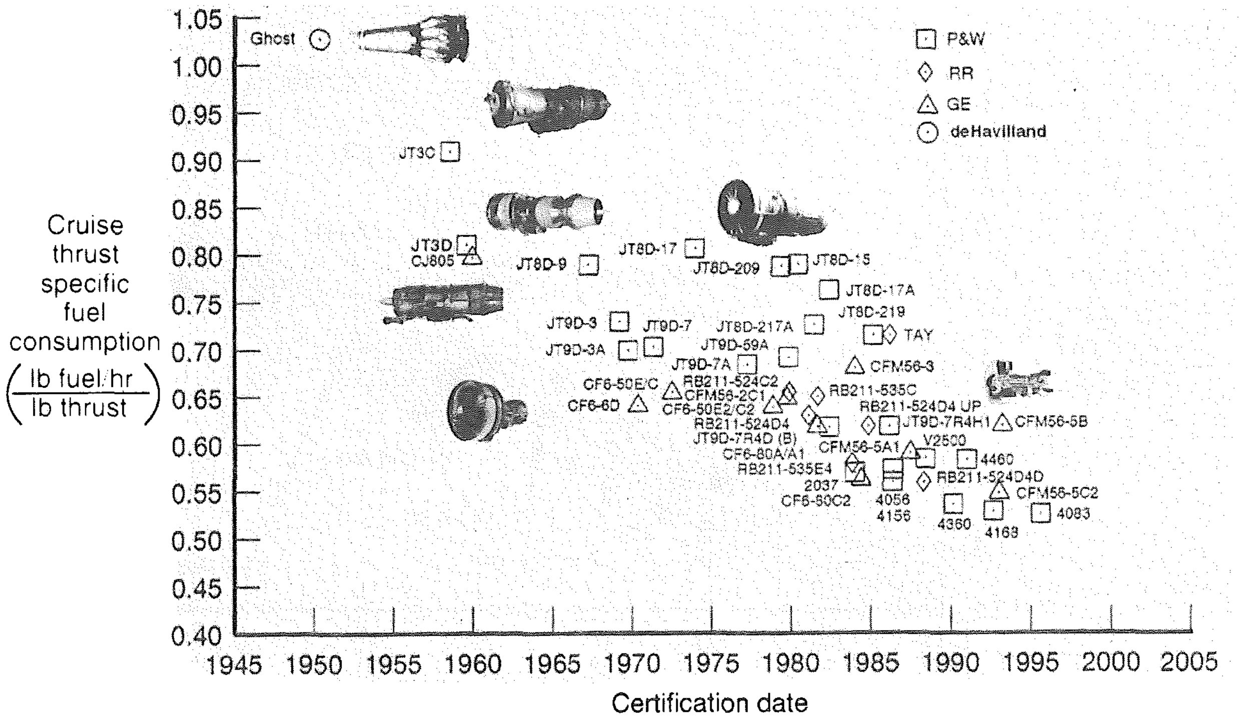


AVP385327 912603

Figure 2. Fuel Efficiency Trends

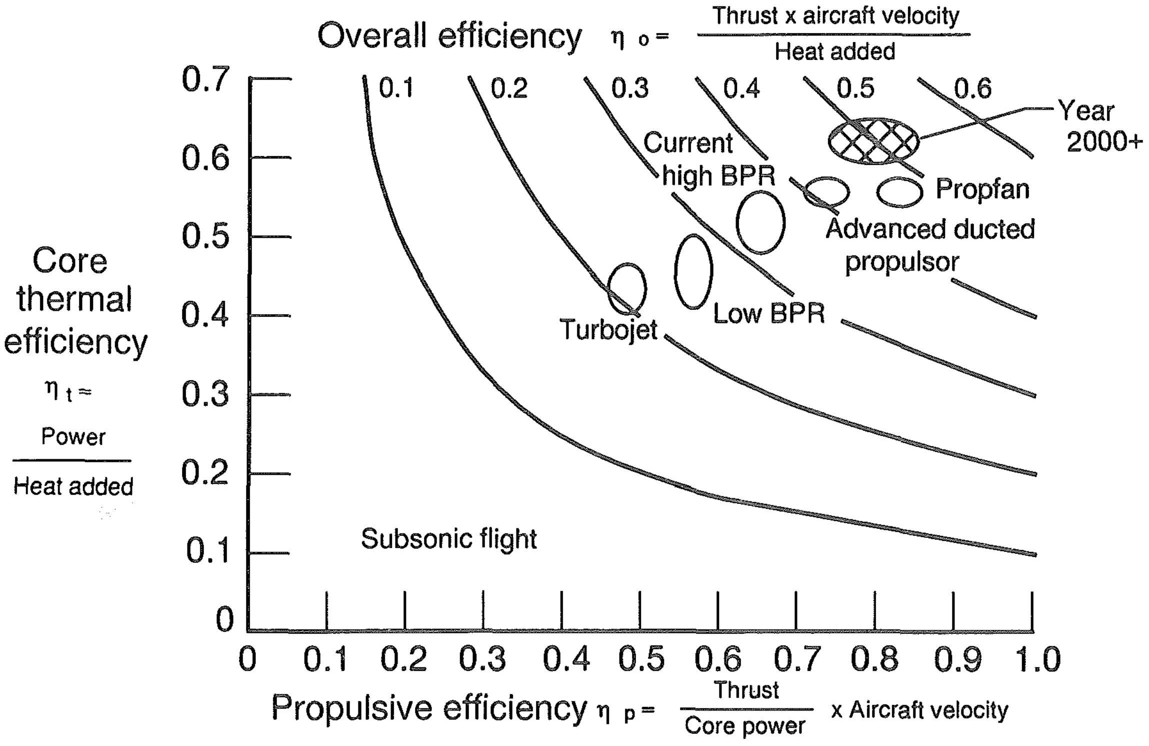
provided a means of controlling resonant and flutter vibration. These advances in materials and design made larger engines practical and paved the way for higher bypass cycles. Many of these early engines are still in use and are being retrofitted with noise reduction kits to meet FAA stage 3 requirements.

Engine cycle, including fan bypass ratio (fan duct/core airflow) and overall pressure ratio, turbine temperature and cooling air, materials and aerodynamics are key technologies that have resulted in the seat mile efficiency shown in Figure 2 that is generated by reductions in fuel consumption. Figure 3 shows the history of various engine configurations and technologies that have impacted engine thrust specific fuel consumption during the past 40 years. A comparison of fuel efficiency (Figure 2) with the engine alone (Figure 3) shows that about half of the improvement is due to the engine. Technologies providing both higher cycle pressure ratios and turbine rotor inlet gas temperatures provided increased power by the core gas generator and paved the way for the more efficient high bypass turbofans for subsonic flight. Increasing the engine bypass ratio while reducing the jet velocity to closer match the aircraft flight speed has produced about 2/3 of the engine performance improvements illustrated in Figure 3. Increasing thermal efficiency through improved components, materials and processing and innovative design has provided the other 1/3 of the performance improvement. The theoretical thermal efficiency of an Air Brayton Cycle gas turbine is a function only of the pressure ratio. For actual gas turbine engines, the thermal efficiency is additionally dependent on a combination of turbomachinery component losses and heat of compression limits.



AVE385289 910205

Figure 3. Engine Performance History



AVP385269 910904

Figure 4. Increasing Overall Efficiency

Figure 4 shows the subsonic flight relationship between the thermal, propulsive and overall efficiency for the engine cycles represented. The thermal efficiency is represented as the ratio of the core engine power to the heat added (fuel flow x lower heating value of the fuel). Efficiently achieving high power in the core engine exhaust gases is a key to increasing thermal efficiency.

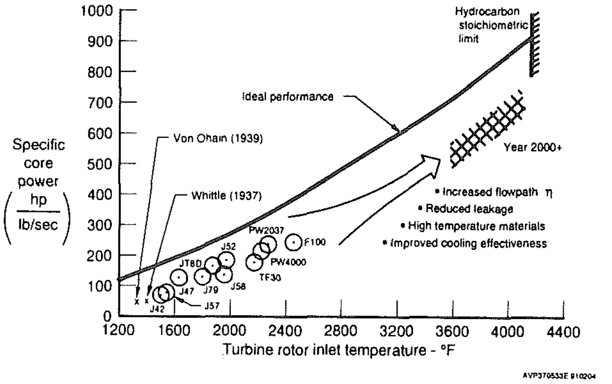


Figure 5. Improving The Core Performance

The propulsive efficiency is the ratio of the propulsive power produced (thrust x velocity) to the core engine power output. For a turbojet, the propulsive efficiency simplifies to:

$$\text{Propulsive Efficiency} = \frac{2}{1 + \frac{\text{jet velocity}}{\text{aircraft velocity}}}$$

Propulsive efficiency reaches 100% when the jet velocity is equal to the flight speed. Matching the jet velocity closer to the flight speed is essential in providing the aircraft with the optimum propulsion system. Therefore, high bypass, low pressure ratio fans having lower exhaust velocities are ideally suited for subsonic flight and high exhaust velocity turbojet engines are more suited for supersonic flight.

Figure 4 also shows that the current high bypass (5:1) fan engines have both higher propulsive and thermal efficiencies relative to the early turbojets. The overall efficiency, the product of thermal and propulsive efficiencies, is the ratio of the propulsive power produced (thrust x velocity) to the heat added. The overall efficiency of the high bypass engine has increased by 75% over the turbojets explaining how the improved fuel economy was achieved over the early aircraft.

IMPROVING THE CORE ENGINE

The energy extracted from the high pressure, high temperature exhaust gas developed by the core engine (compressor, combustor and turbine) is key to overall engine capability and performance. After the turbine extracts energy from the combustion gases to drive the compressor, the exhaust gases must contain enough energy for producing work. Increasing core engine power provides the energy to drive higher bypass fan propulsors leading to higher propulsive efficiency. In the early days, the gas power developed by the core engine was limited by the low levels of compressor pressure ratio, component efficiencies and turbine temperature. Improved materials and manufacturing processes, higher efficiency in turbomachinery components, higher turbine temperatures and design configuration innovations significantly improved core engine power.

Figure 6 shows the relationship between specific core gas power and turbine rotor inlet temperature illustrating that improved performance is indeed possible. The core power is normalized by dividing by the mass flow so that both large and small engines can be represented. During the past 50 years, the core power has steadily increased with turbine temperature by a factor of 5 over the early jet engines of Whittle and von Ohain. Demonstrator engines have been operating successfully at eight times the power of these early engines. The ideal Brayton cycle performance is shown representing 100% component efficiencies and no cooling air. As expected, the actual engines produce less power than the ideal but the progress moves in the same direction. The theoretical performance is truncated at the stoichiometric limit (fuel/air ratio = 0.068) where all the oxygen and fuel are burned. The core power theoretical limit is almost 20 times higher than the early turbojets and 4 times higher than current engines in production. Realizing that actual engines will be lower than the ideal, we can expect a concentrated technology effort to achieve an increase in core power of 2.5 over current production engines within the next twenty years.

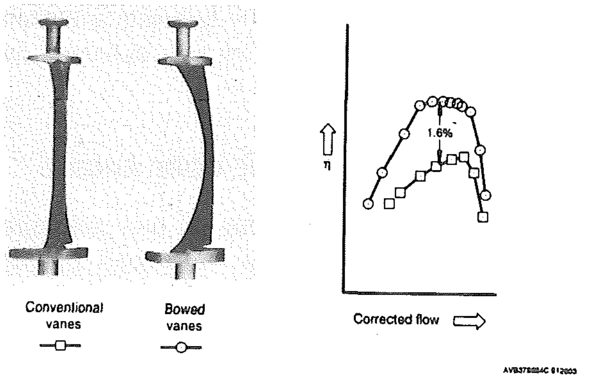


Figure 6. 3D Aerodynamic Modeling

It's important to recognize that current engines are using between 20–30% of the core flow to cool the turbine. This air bypasses the combustor leaving only 75% for combustion. If the turbine cooling air is increased further with turbine temperature, there will be less air to burn in the combustor and the core power could actually decrease. To achieve higher power with increased turbine temperature, technology improvements must be incorporated to hold or reduce the turbine chargeable cooling air.

A combination of increased turbine blade, vane and shroud cooling effectiveness, improved materials and processes, higher component efficiencies and reduced leakages must be achieved to realize greater core power with higher turbine temperatures. The projection for further core improvements is excellent and is the basis for both increased thermal and propulsive efficiencies. The gas turbine jet engine has a bright future! There is nothing on the horizon to replace it!

Significantly improved computer modeling techniques have opened a new era in developing improved aerodynamic configurations. Figure 6 illustrates the use of "bowed" compressor stators to reduce end wall diffusion losses resulting in converting total to static pressure. The reduction in losses results in higher stage compression efficiency. The curved or bowed shape is the result of improved three–dimensional aerodynamic modelling made practical by large computational capacity and improved codes.

Titanium has been one of the most significant material advances for jet engines in having reduced weight and cost with good machining and joining qualities and a low coefficient of thermal expansion for reduced radial clearances. Its major limitation has been its creep resistance and pyrophoric characteristics at higher pressures and temperatures. Titanium fires have resulted in configuration compromises for safety by carefully isolating the titanium airfoils in the flowpath with adjacent steel alloy vanes and shrouds to reduce heat generated rubs. The use of steel alloy stator vanes has increased both weight and cost. Materials research over the past eight years has resulted in producing a superior non–burning titanium alloy exhibiting high strength and capable of operating at 1200 degrees Fahrenheit. The ultimate strength and durability characteristics of this new "Alloy C" are shown in Figure 7 and its future looks bright in safely replacing nickel superalloys used within the compressor. The application of this higher strength non–burning titanium alloy to compression system blades and vanes offer a safe, lighter weight configuration than nickel alloys. This improvement is again attributable to advances in materials and manufacturing processes.

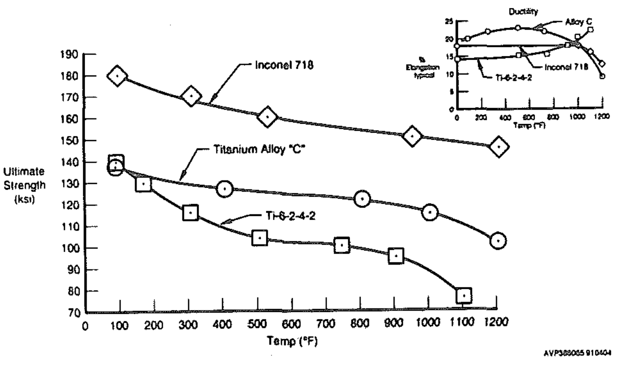


Figure 7. High Strength – Non Burning Titanium Alloys

In the early days, as shown in Figure 8, gaseous and particulate emissions from turbojet engines were not a consideration. In the late 50's and 60's however, we were motivated to eliminate visible smoke particulates. By 1970 work began to eliminate carbon monoxide (CO) and unburned hydrocarbons (HC) and within the next ten years achieved a threefold reduction by improving combustion efficiency at or near idle power. Combustion efficiency at cruise power and above has always been near 100%.

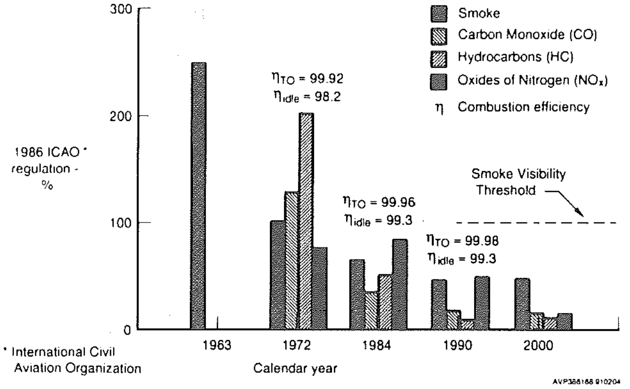


Figure 8. Progress In Emission Reductions

Additional significant progress was made during the decade of the 80's in developing technology to reduce oxides of nitrogen (NOx) combustion emissions. Since gas turbine combustion efficiencies are already in the 99+% range, there is little opportunity to further reduce CO and HC emissions. It is generally agreed that the issue of NOx emissions will be the heavy focus in the 90's because of its contribution to ground level ozone and smog, acid rain and stratospheric ozone depletion. Combustion system engineers are working toward a 3:1 reduction in NOx by the year 2000.

Despite the fact that aircraft contribute only 1–2% NOx to the atmosphere on a global basis, they are a significant entity on a local airport basis and a main contributor at high altitudes where the High Speed Civil Transport (HSCT) would fly. NOx is a combination of oxygen and nitrogen formed at elevated temperatures in the combustor. Its formation is heavily dependent on local gas temperatures within the combustor and to the time spent at these elevated temperatures. Higher gas temperatures, and resultant high NOx formation rates, are produced from combustion near stoichiometric fuel/air ratio occurring at high combustor air inlet (compressor discharge) temperatures. Figure 9 shows that burning either fuel rich or fuel lean can significantly reduce combustion temperatures and NOx production rates and is the fundamental approach to controlling NOx emission.

One way to control combusting fuel/air ratios and reduce NOx is to use a staged combustion concept shown in Figure 10. Sharing the fuel loading among several fuel and air stages controls the local fuel–to–air ratio to minimize NOx formation rates as power is increased. These fixed geometry systems offer more than a 30% reduction in NOx relative to current production combustors.

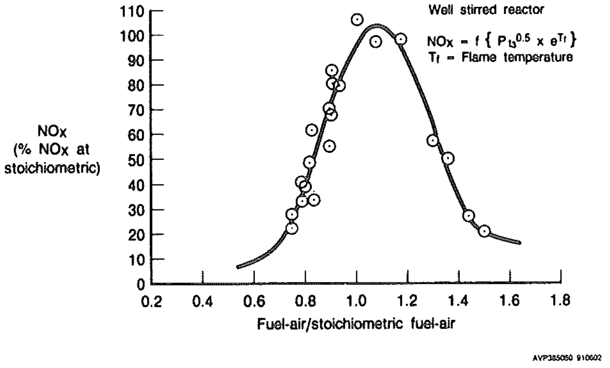


Figure 9. NOx Generation

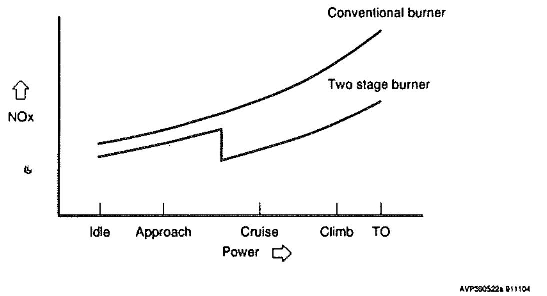


Figure 10. NOx Emissions Reduction

Figure 11 shows a candidate two zone (staged) combustor. At low power only the pilot zone is fueled providing a high stability zone with fuel/air ratios above the lean combustion blowout limit. This is necessary to provide satisfactory altitude windmill airstarting. As the engine power is advanced and the primary fuel flow increases, the local fuel/air ratio is increased producing a higher level of NOx (also shown in Figure 10). Before NOx production exceeds limits, the combustor is "staged" by initiating combustion in the secondary or main zone. The combined primary and secondary zones operating together maintains a lean local fuel/air ratio which controls NOx emission at higher power levels, including cruise. At takeoff and climb power and for higher combustor inlet temperatures, the fuel/air ratio increases again suggesting additional fuel zone staging might be effective. Fortunately, the introduction of the electronic engine control capable of "threading a needle", makes the combustion staging concept practical.

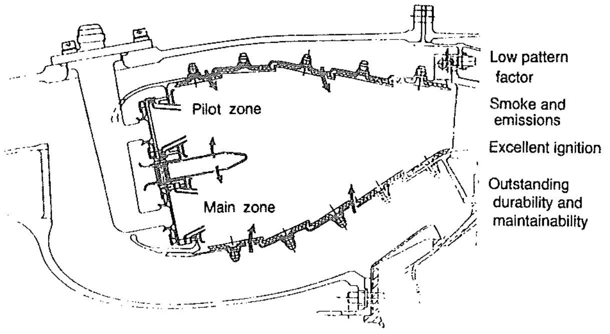


Figure 11. Improving Combustion Performance

NOx emission is a barrier problem of special concern for the High Speed Civil Transport (HSCT) since it will fly in the stratosphere where the ozone layer is concentrated between 50–90,000 ft. This ozone layer which protects earth from harmful ultraviolet radiation is converted to oxygen by the NOx which becomes trapped in the stratosphere by the tropopause, the region separating the troposphere from the stratosphere. Because of the importance of high altitude NOx emissions, General Electric, Pratt & Whitney and NASA are working on a joint program to reduce NOx emissions in preparation for a launch of the HSCT program.

The early high pressure ratio turbines had solid undamped high aspect ratio blading. Forged nickel base superalloys were used for blades primarily because of their high fatigue strength. It was soon realized that castings like X–40, a cobalt base alloy still being used, offered a high melt temperature and superior resistance to oxidation and corrosion for vanes. Higher strength nickel base coatings followed. The development of turbine blade and vane cast nickel base superalloys has paced the progress in achieving higher turbine gas temperatures. Figure 12 shows 45 years of progress in turbine airfoil materials development representing a 500 degree Fahrenheit increase in metal temperature capability.

Early jet engines were severely limited by hot section materials motivating a few research scientists to invent improved alloys. The concept of developing superalloys was discovered in the 40's but the alloying of key strengthening elements such as aluminum and titanium was limited by the air melting process. This resulted in very high strength alloys with unacceptably low ductility. The breakthrough came in 1953 with the implementation of Vacuum Induction Melting (VIM), a process touted as "having made the jet engine what is is today". This innovative process boosted superalloy temperature capability by 200 degrees Fahrenheit for turbine blades as shown (Figure 12) in the 1955 time period. The Vacuum Arc Remelting (VAR) process followed in 1958 to produce large forgings for disks. These innovative manufacturing processes launched the development of today's generation of superalloys for disks, shafts, bolts, and structures.

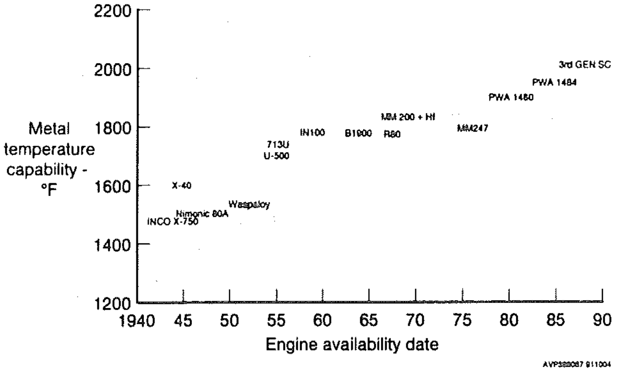


Figure 12. Turbine Materials Progress

The combustor hot streak gas temperatures into the turbine made it necessary to air cool the vanes even on the early engines. This is a very small penalty to the cycle since most of the cooling air still passed through the nozzle vane throat into the turbine rotor to produce work. Since rotor blades pass through the peak hot streaks, they "see" a considerably lower average gas temperature. The use of forged alloys for blades prevailed until cycle advances demanded higher gas temperatures than the uncooled blades could withstand and required the introduction of air cooling more readily provided with castings. The air cooled blades also required longer chords for the internal heat exchanger resulting in lower aspect ratio airfoils with improved resistance to lower mode vibratory bending and torsion excitation. However, blade damper devices to suppress vibratory forces became standard features because of the inherent lower properties of castings and protective coatings with stress concentrations caused by the cooling features.

The introduction of directional solidification and then single crystal superalloys produced a breakthrough representing a 200 degree increase in metal temperature. The lower Youngs Modulus of the single crystal alloys can be used to achieve a lower stress for the same strain range. The result is an alloy that is more resistant to thermal fatigue. This allows the designer to improve the local cooling by passing relatively cold air up the hot leading edge airfoil passage without introducing thermal fatigue cracks.

Figure 13 shows the spectacular progress in achieving higher turbine rotor inlet gas temperatures (RIT) as a function of the cooling effectiveness using single crystal materials. The cooling effectiveness is a measure of how well the airfoil is cooled (between the limits of the hot–gas and cooling air temperatures) and is a function of the airfoil heat load to cooling flow. The RIT base for the solid uncooled blade is 1800 degrees Fahrenheit representing mid–50's technology. Progressing to convection cooled blades with a cooling effectiveness of 0.4 allows a 400 degree Fahrenheit increase in RIT. The payoff for increased material temperature capability is amplified as cooling effectiveness level increases. The family of film/convection blades with a cooling effectiveness of 0.6+ have RIT capabilities to 3000 degrees Fahrenheit using single crystal materials. This temperature is 1200 degrees Fahrenheit above the solid cooled airfoils and some 600 degrees Fahrenheit above the melting point of the nickel based materials.

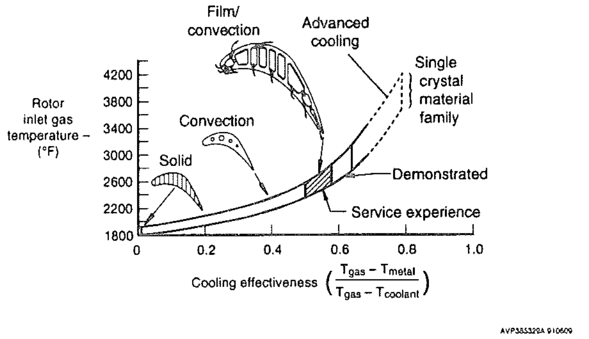


Figure 13. Improving Performance With Improved Turbine Cooling and Materials

Most commercial engines have extremely efficient two stage high pressure turbines to drive the compressor when the pressure ratio is more than 7:1. At the higher temperatures and moderate pressure ratios, a high speed single stage turbine uses less cooling air and offers the opportunity to reduce the number of stages for both the turbine and compressor. The CFM56 turbofan core engine has been successfully derived from the GEF101 military engine and uses a high speed single stage turbine. Higher temperature single stage turbines are expected to play an increasingly important role in future core engine gas generators.

While the above described advances were being made in performance, equally impressive improvements were being made in durability. There are today engines in service that have not been removed from the original aircraft in over five years. That is equivalent to operating an automobile for over one–half million miles with an occasional spark plug and filter change – a truly remarkable achievement considering that gas path temperatures exceed the melting point of nickel for much of the operating time. Significant to this increase in durability and performance has been the advances made in rotor disk materials.

Figure 14 shows the varying material requirements for the different locations on the disk. The progress made in gas turbine material superalloy stress capability, as required for modern engines, is shown in Figure 15 while the crack growth (DA/DN) characteristics for three disk materials of choice versus ΔK for three high strength materials is shown in Figure 16. It is important to note that the higher strength materials also have less desirable crack growth characteristics.

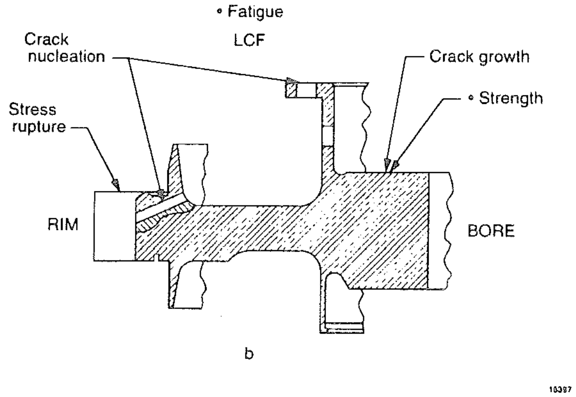


Figure 14. Gas Turbine Disk Material Demants

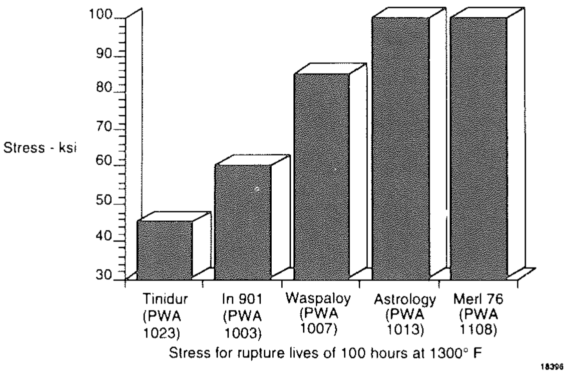


Figure 15. Superalloy Properties

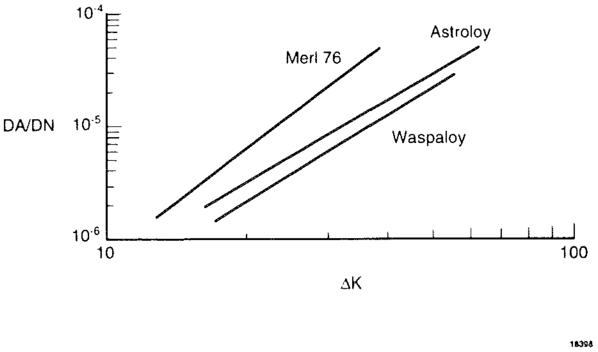


Figure 16. Crack Growth Of Superalloys

ENGINE SYSTEMS

Over the years, the aircraft gas turbine design and development process has reached a high level of discipline based on a "lessons learned" approach. Figure 17 represents how the integration of key technologies is used to meet the "big four" requirement categories based on a balanced trade–off. With few exceptions, the "big four" requirements: Performance (including noise, emissions and safety), Reliability/Durability/ Maintainability, Weight and Cost, apply for both military and commercial engines. The "lessons learned" recognize that the engine configuration must be based on a balanced trade–off of these requirements. Successful integration of the core engine gas generator into the complete engine involving the controls propulsor, drive turbine, externals and nacelle, requires that this disciplined approach be used.

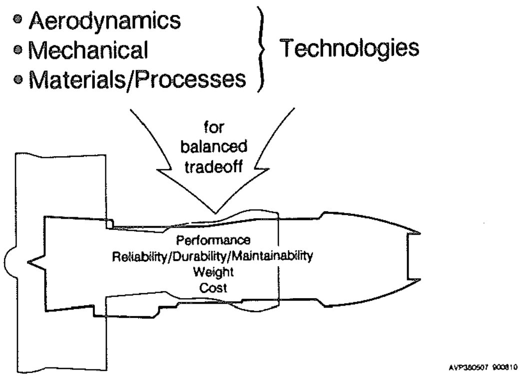


Figure 17. Engine System Design

The control is the "brain" of the engine translating the throttle signal request to specific commands involving fuel flow, compressor stator vane angle, low compressor bleed valve setting, turbine cooling valve position, rotor speed feedback signals, and nacelle thrust reverser operation.

During the past 40 years, control system capability has increased 20:1 to meet ever expending functional requirements. Figure 18 illustrates the evolution of simple hydromechanical control systems to highly capable and reliable multi–function electronic controls.

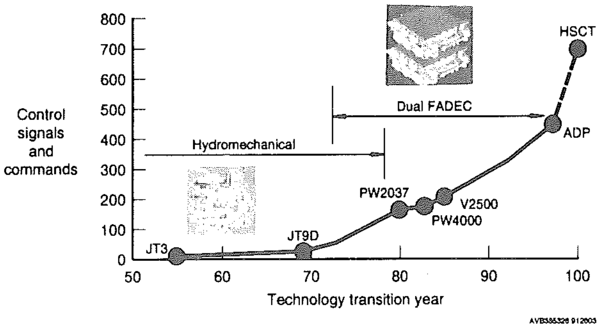


Figure 18. Hydromechanical To Electronic Controls

Mounting an electronic control on the engine in a hostile environment proved to be an enormous structural and mechanical design challenge. The circuit boards and connectors are bolted down. The control housing is mounted to the engine with isolators to attenuate vibratory response. Both air and fuel cooling are used to accommodate the wide range of temperature variations within the nacelle. Engine nacelle heat during soak down must also be accommodated. A by–product of the electronic control was the addition of comprehensive diagnostic systems utilizing the computer and sensors to improve maintainability.

Looking to the future we can envision the use of increased portable computing capability that can be referred to as Expert System diagnostics. Artificial Intelligence (Expert System) based diagnostic systems are considered a significant future enhancement to jet engine support and maintenance. With this approach, the engine mounted electronic controls can be interrogated with a portable computer that provides maintenance personnel access to the reasoning and knowledge base of experts. Step–by–step troubleshooting procedures are displayed that are responsive to any system faults. Support information, like wiring diagrams, assembly details, or tool identification can also be displayed. This approach can eliminate dependence on multiple field support manuals and can allow relatively unskilled maintenance personnel to perform like 'experts'.

Experimental evaluations underway using the device shown in Figure 19 has proven to meet all pretest expectations. Even though it is the first generation system, it could result in elimination of the maintenance manuals shown in Figure 20, significantly reducing troubleshooting time and maintenance training.

Figure 19. Expert Diagnostic System

The current reliability levels achieved in commercial aviation are unprecedented in the field of transportation and still improving. Figure 21 shows the trend in engine shop visit rate as a function of the years in service. More than a 4 to 1 reduction in initial shop visit rate has been achieved for modern turbofans. This represents a considerable cost savings to the airlines during the first several years of service.

Figure 20. Engine Maintenance Shop

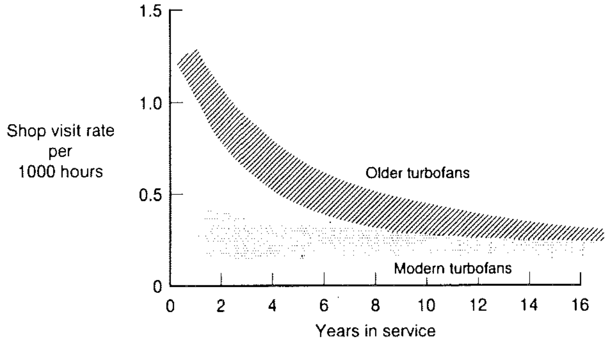


Figure 21. Reliability

The system design concept described in Figure 17 is becoming effective in producing a disciplined "lessons learned" approach in the design and development process. However, there is much work yet to be done.

Reliability problems with modern high bypass engines are caused primarily by shortcomings with engine external systems. These include oil, fuel, hydraulic, pneumatic, and electrical systems. Statistically 65% of engine "In Flight Shut Downs" and 90% of "Delays and Cancellations" are caused by these external systems.

The first production turbojet and low bypass engines were unreliable despite their inherent simplicity. Reliability was dramatically improved for low bypass engines after intensive development programs. The externals systems for these engines are simple and robust.

Figure 22 shows that the complexity of external systems for modern high bypass engines has increased dramatically introducing a serious reliability challenge.

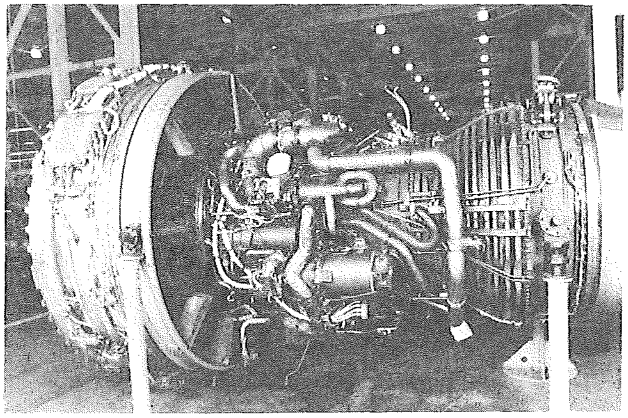


Figure 22. Modern High Bypass Engine External Complexity

The need for improved engine performance has been the primary driver for complex control systems. Variable stator vanes, active clearance control, start and stability bleeds, precise fuel flow control, and heat rejection management are systems that support enhanced engine performance. Additional customer requirements have also driven complexity. Greater electrical, cabin bleed, and hydraulic needs have evolved. The trend toward large twin engine aircraft have expanded the single engine's service output to meet the one engine out criteria. This rapid expansion of secondary systems has not been without problems. The inherently harsh environment within the engine nacelle is subject to severe thermal gradients, strong vibrational drivers, caustic hydraulic fluid, and a maintenance environment where engine manuals may not always be available. It is a challenge to package intricate and voluminous systems within a limited space and still preserve a reasonable "take it apart and put it together" capability. The engine externals also represent a major design challenge as we move in the direction of adding further complexity to the external fuel system to meet emissions requirements. These challenges are being met by applying the same dedication of engineering resources as we have used in developing our turbomachinery. We are responding to our "lessons learned" with improved design practices, technologies, materials, analytical techniques and substantiation testing. This will lead to achieving the performance advances with improved reliability.

Figure 23 shows that the application of technology has made significant progress in noise reduction during the past 25 years. The cumulative effective perceived noise (EPN) as measured in decibels at approach, sideline and takeoff locations is represented. The zero level is FAA regulation 36.

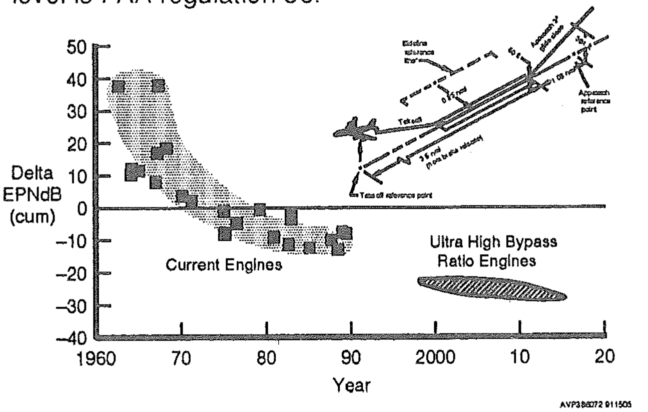


Figure 23. Noise Reduction Progress After The Turn Of The Century

Reductions in noise were achieved by optimizing the blade vane relationships in numbers and spacing, adding acoustic treatment in the nacelle and increasing the bypass ratio to reduce the jet velocity. Sound suppressors are also being added to reduce the noise level in lower bypass engines. With the introduction of the ultra high bypass engine after the turn of the century, we can expect to see noise levels even lower than that of today's engines. This will allow the increase in takeoff gross weight of airplanes without violating noise regulations.

A VISION OF THE FUTURE

Predicting the future is not always a scientific art. The Buck Rogers cartoons of the 1930's made some fantastic predictions which were realized 40 years later when we put men on the moon. Of course, no one's perfect. Not one writer in that era predicted the whole world would be watching on television.

History shows that great achievements generally start with a vision. Both Whittle and von Ohain had independent visions that "there had to be a better way" for aircraft propulsion. Innovation, development and application followed during the next 50 years. The jet engine is now heralded as the greatest achievement during the past quarter century in having made the world smaller.

Visions of airplanes for the future include: 1) efficient very large subsonic commercial transports carrying 1000 people at a seat mile cost about 1/2 today's baseline; 2) a High Speed Civil Transport carrying 300 people over long range in about 1/2 the time of subsonic transports at fares equivalent to today's baseline; 3) an emerging hypersonic transport carrying 100 to 200 passengers over very long routes in 1/3 to 1/4 today's subsonic transport; 4) commercial sub–space travel that take off and land on conventional runways; and 5) a vertical takeoff and landing vehicle for mid–city to mid–city or mid–city to airport travel.

One propulsion system that could provide accelerator power for a hypersonic transport is shown in Figure 24. The Mach 6 hydrogen fueled accelerator engine (Figure 24) incorporates both liquid rocket and air breathing engine technologies into a unique hybrid engine concept. This engine features a lightweight inlet pre–cooler to reduce the thermal environment of the 2–stage counter–rotating fan. The fan blade design would incorporate hydrogen cooled advanced berryllium or titanium alloys or uncooled ceramic matrix composites to allow operation up to Mach 6 where blade stagnation temperatures will approach 2800 degrees Fahrenheit. Power to drive the counter–rotating multi–stage uncooled turbines is provided by energy addition to the high pressure hydrogen fuel. Fuel rich combustion products leaving the gas generator are mixed with fan discharge air and burned at stoichiometric temperatures upstream of the exhaust nozzle.

This propulsion concept exploits the high energy high heat sink characteristics of hydrogen fuel, IHPTET technologies, and advanced lightweight heat exchangers to provide both a high thrust to weight ratio and fuel efficient propulsion system to enhance range and payload. Other embodiments of the concept could have the compression system bypassed as Mach No exceeds the uncooled capability of the compressor material and continue to accelerate and cruise as a pure ramjet. It is also possible to envision variations of this cycle operating on methane or other fuels capable of high heat absorption.

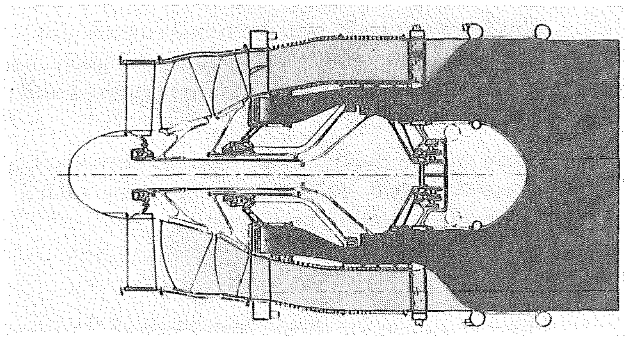


Figure 24. Hydrogen Fueled Penetrator Engine

CONCLUSION

The past 50 years have been exciting in the realization of Whittle's and von Ohain's vision for the jet engine. But, we in the jet engine industry can agree with Whittle's prediction that the next 50 years will be even more exciting. Today's technology barriers will be pushed back significantly to achieve the substantial specific power increases available in gas turbine engines. And undoubtedly, some of the advanced concepts now only being discussed or explained in the scientific community will be applied to revolutionize jet propulsion in the 21st Century. It is essential that the research and development that has brought us from the early days of the DeHavilland Ghost engine powering the DeHavilland Comet airplane to the High Bypass Ratio engines like the PW4084 powering the Boeing 777 airplane continue unabated for these advances to be realized. Only through painstaking advances in aerodynamics, thermodynamics, materials, computational sciences, and the aggressive use of electronic–based computation will we achieve the advances in aircraft propulsion that are possible.