Designing Small Gas Turbine Engines for Low Noise and Clean Exhaust

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Design features contributing to the low noise signatures of current JT15D and PT6 engines are outlined. New aircraft for close-in or STOL operation will use low-speed 'quiet' propellers. Some early results from programs to keep noise from advanced PT6 engines below 'quiet' propeller noise are shown. As regards emissions, small gas turbines are clean compared to reciprocating engines but have higher idling emissions than large gas turbines. Exhaust emission levels promulgated by EPA are very challenging but the art of emission evaluation and reduction is developing rapidly. Encouraging results from recent experimental programs at UACL are cited.

Introduction

EXISTING or proposed regulations limiting aircraft noise and exhaust emissions have considerably complicated the engine designer's traditional criteria of safety, performance, and cost. Designing for low noise is a rapidly maturing art with the tradeoffs in performance becoming clearly defined. The techniques of measurement, evaluation, and reduction of exhaust emissions are rather new but developing rapidly.

Designing for Low Noise

The FAA issued regulations in 1969 to control CTOL aircraft noise. Levels were established as a function of aircraft weight on what was considered to be economically feasible and technologically practical grounds. Light business aircraft, although not the major noise source, were included in these restrictions. The Swiss and German governments have since issued regulations limiting permissible noise from light propeller aircraft and recently ICAO has proposed a "Recommended Practice for Light Propeller-Driven Aircraft Noise Certification." The U.S. Environmental Protection Agency, EPA, has just recommended to Congress that current CTOL levels be reduced and that regulations be established for propeller aircraft. The present emphasis on noise reduction is affecting the entire aircraft industry and the need for quieter engines and installations is becoming increasingly more apparent.

Many technical papers have been written about noise of large turbofan engines. Very few papers have been published on smaller turbofan, turboshaft, and turboprop engines and the steps industry is taking to alleviate noise.

JT15D Low Noise Design Features

The JT15D is a 2200 lb thrust turbofan designed and optimized for light twin business executive aircraft. Low noise was a primary design requirement. The cycle was selected on the basis of proven in-house fan and compressor components. Bypass ratio was derived from a cycle study with a conservative turbine inlet temperature and a two-stage fan turbine. This resulted in a moderately high

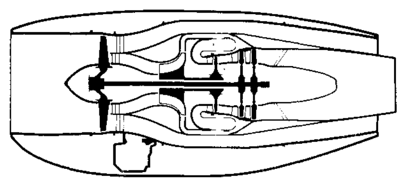

Fig. 1 JT15D engine X-section.

bypass ratio and low jet velocity. Turbofans, like turbojets, derive their thrust from a change in momentum. Since jet noise is proportional to the jet velocity to the eighth power, a small reduction in jet velocity results in a significant reduction in jet noise. The turbofan exploits this principle by moving larger quantities of air at lower velocities; hence the noise due to the exhaust jet velocity is minimal. A single stage 1.5 pressure ratio fan developed by Pratt & Whitney Aircraft in East Hartford was scaled and modified to suit the JT15D's needs. Because of the JT15D's size this resulted in a high shaft design speed with a high blade passing frequency (BPF). This high-frequency tone and many of its subharmonics are readily absorbed by the atmosphere over a relative short distance. At the ICAO ANNEX 16[1] reference atmospheric condition 25°C (77°F) and 70% relative humidity the absorption is of the order of 15 dB per 1,000 ft. No inlet guide vanes (IGV) were needed for the fan, thus eliminating the noise due to vane wake chopping. Fan blade to stator vane number ratio and axial spacing were selected to minimize the wake interaction noise. These design features are listed in Table 1 and described in greater detail in Ref. 2.

Table 1 JT15D Turbofan 'Quiet' design features

Single stage fan	pressure ratio = 1.5
Low fan radius ratio	R_{hub}/R_{tip} = 0.405
Optimum stator/rotor blade number ratio	Ns/Nr = 2.36
No IGV's	...
High blade passing frequency-design N_f	7440 Hz
Large fan gap/chord ratio	s/c = 1.83

Table 2 Comparison of Cessna Citation with FAA CTOL noise regulations

EPNL (EPNdB)	Takeoff 3.5 nm from start	Sideline 0.25 nm from runway ℄	Approach 1.0 nm from threshold
FAA-FAR part 36	93	102	102
Cessna Citation Model 500	78	86	88

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Fig. 2 Cessna Citation series 500.

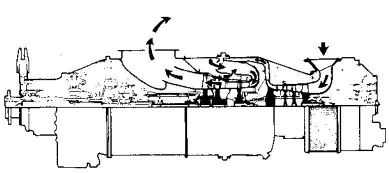
The resultant engine design when installed in the Cessna Citation results in noise levels which are 15 EPNdB lower than the current FAA regulations[3] see Table 2. The Cessna Citation features a long clean fan inlet which minimizes fan flow distortion and the noise associated with it. Also the nacelle is located on the fuselage, with the inlet above the wing which acts as a very effective shield (see Fig. 2). This is believed to effectively reduce the forward radiated fan BPF by 15 and 10 dB at takeoff and approach conditions, respectively. These data were obtained from ground static and flight data and were compared in Figs. 13 and 14 of Ref. 2.

PT6 Low Noise Design Features

The PT6 engine was designed in 1959 and was based on a series of design studies on both fixed-wing aircraft and helicopters. A free turbine configuration was selected to avoid the need for propeller drag-limiting systems on turboprop aircraft, and to eliminate the clutch requirement for helicopter applications. It also allows for selecting propeller speed for optimum efficiency and minimum noise. This flexibility of controlling the noise output is particularly noticeable during cruise and taxi operation. Propeller speeds as low as 400 rpm can be obtained during ground operation. At cruise 70% propeller design speed is not uncommon, whereas a fixed shaft engine cannot substantially reduce rpm for cruise.

The PT6 was designed before many of the engine noise generating mechanisms were fully understood. However, because of its size and the fact that it is a shaft engine, noise from the engine is not considered critical for turboprop aircraft. The PT6 engine cross section is shown in Fig. 3. The first stage axial compressor is the primary noise source (see Fig. 7). Robust large-chord blades were chosen to reduce foreign object damage. The gap/chord ratio is less than that desired for low noise. There are no IGVs, hence noise due to vane wake chopping is eliminated. The PT6 A-50 first-stage tip speed is in the order of 1300 fps with a blade passing frequency of 10,000 Hz. A narrow-band spectrum of the engine inlet is shown on Fig. 4. Combination tones, submultiples of the BPF, span the

Fig. 3 PT6 A-50 engine X-section.



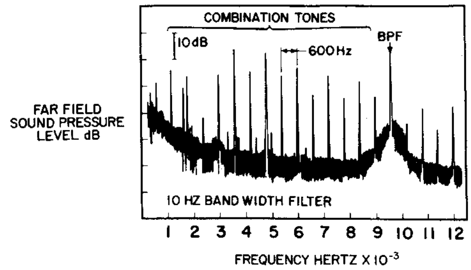


Fig. 4 PT6 intake narrow-band noise spectrum.

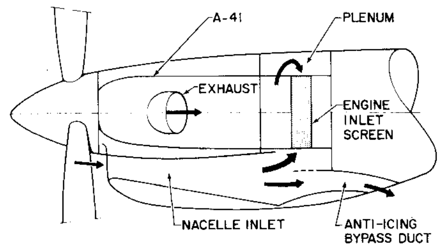


Fig. 5 Typical PT6 installation.

complete spectrum. These tones are produced by geometric nonuniformities in the blading. By rearranging the blade deviations the amplitude of the tones should be altered and this was demonstrated on an engine. Control of these manufacturing tolerances is very much more difficult and expensive for these small engines.

The PT6 engine gas path configuration is very different from the conventional engine in that the inlet is located at the rear. A nacelle inlet duct is required to deliver air to a plenum from which the engine aspirates. The resultant configuration, shown in Fig. 5, is a buried engine inlet with a multiplicity of right angled bends which very effectively impedes noise transmission. Also, placement of noise linears is more effective when coupled with bends. Tests to determine the transmission loss with and without noise treatment in the nacelle inlet were conducted in an anechoic room with a known noise source. Figure 6 illustrates the degree of transmission loss. A vertical section of the engine noise field is shown without propeller noise. The area outlined by equal perceived noise contours is very much reduced when the engine is installed in a nacelle. A further reduction is realized when noise treatment is installed in the nacelle inlet. Liner treatment depth is relatively small because the compressor BPF and its subharmonics are high.

The exhaust noise spectrum (Fig. 7) in full octaves is relatively flat, peaking at about 500 Hz. Most of this noise is internally generated and is believed to result from the turbine flow turbulence interaction with the exhaust duct. The exhaust duct diffuses the flow, collects it, and reaccelerates it through outlet ports with an exit Mach Number of 0.3 and 0.4 for the turboshaft and turboprop respectively. Noise due to the free air jet mixing is not considered significant. A series of tests to determine the variation of exhaust noise with turbine speed and power were conducted. Because the PT6 engine has a free power tur-

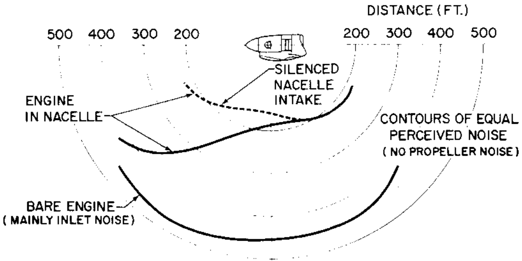


Fig. 6 Effect of installation on PT6 noise.

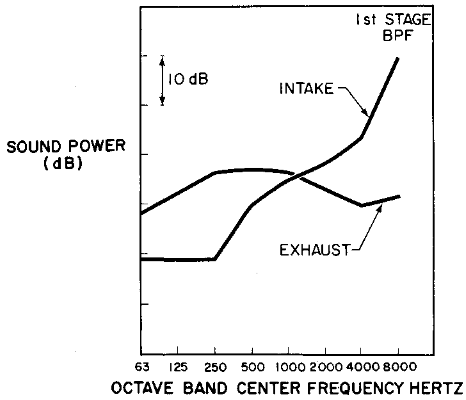


Fig. 7 PT6 Bare engine noise.

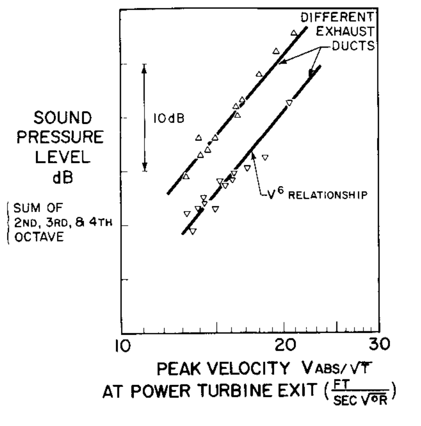


Fig. 8 Exhaust noise correlation.

bine, turbine speed can be changed at fixed power over a wide range of operating conditions. Noise output for a broad range of powers and power turbine speeds is plotted against the absolute velocity at entry to the exhaust ducts in Fig. 8. The correlation yielded a V^6 relationship, i.e., $SPL = 10\,Log\,(V/V_{REF})^6$.

The limited data available to us on exhaust noise levels of different shaft engines are shown on Fig. 9. Engine noise levels appear to fall within a band 4 dB wide and vary proportionately with shaft horsepower. The correlation suggests that doubling the size of the engine also doubles the noise output, which is a 3 PNdB increase in perceived noise level. Individual engine power/noise variation appears less consistent as the PT6 follows a $(SHP)^4$ relationship (i.e., $PNL = 10\,Log\,(SHP/SHP^{REF})^4$ while other free turbine engines vary from $(SHP)^{1.7}$ to $(SHP)^{5.3}$.

Propeller Noise

Propeller noise is produced primarily by the rotation of the propeller blade pressure field and is a function of tip speed. Other sources of noise such as vortices shed from the blade, or blade thickness and blade vibration noise are not generally significant over the range of tip speeds currently used. The propeller is the dominating noise source for light turboprop aircraft. For PT6 installations, the engine noise contribution at most operating conditions is negligible. Only at very low propeller tip speed (700 fps) does engine noise level approach propeller noise.

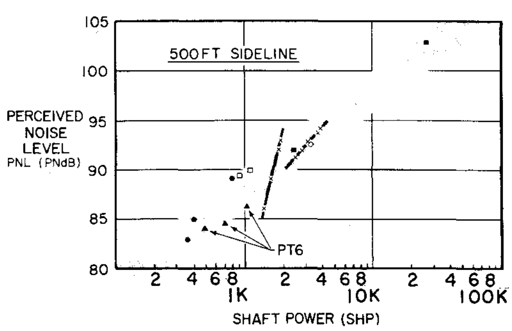


Fig. 9 Shaft engine perceived noise level.

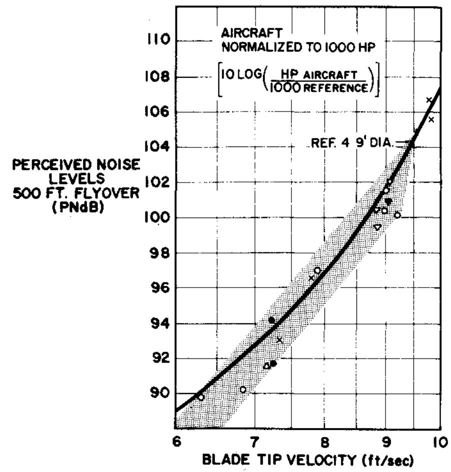


Fig. 10 Propeller noise variation with tip speed.

To show the trend in propeller noise with tip speed a number of aircraft flight noise data are plotted on a log-linear grid vs blade tip speed, Fig. 10. All data obtained from a variety of sources were normalized to an equivalent 1000 SHP using the relationship shown on Fig. 10. The shaded band, which is 4 PNdB wide covers almost all the test data. The resultant gradient follows a V^6 power law; i.e., $PNL - 10\,Log\,(V_{TIP}/V^{REF})^6$. The noise level for a single four bladed 9 ft diam propeller absorbing 1,000 HP predicted using the Hamilton Standard (HSD) method[4] shows excellent agreement. Higher levels than predicted have been measured from aircraft under static conditions. These levels are believed to result from blade stall. This increase was not included in the above method.

The advantages of low tip speed are readily apparent. To achieve these low levels requires large diameter propellers to retain optimum loading and avoid separation. Should the blades be overloaded and separation occur, the levels no longer follow this trend. Figure 11 is a comparison of an aircraft with a fixed power at ground static and flyover for two tip speeds. The static noise gradient followed a 2.3 power law with tip speed, and the level is very much higher.

One example of an aircraft utilizing this low noise technology will be the De Havilland DHC-7, Fig. 12. This is a 48-passenger STOL Airliner capable of operating out of 2,000 ft runways. The aircraft is equipped with lightly loaded Hamilton Standard four-bladed propellers with a tip speed of only 715 fps. The blades are designed for a low aerodynamic disk loading and utilize fiberglass blades with aluminum spars to minimize weight. The aircraft will be powered by four PT6A-50 engines specially de-

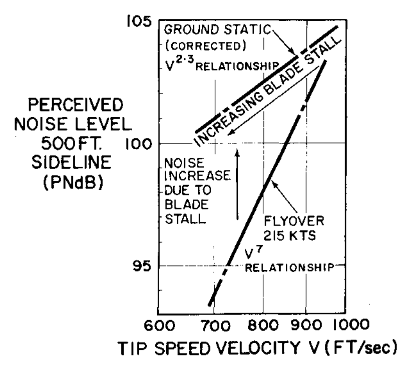


Fig. 11 Effects of blade stall.

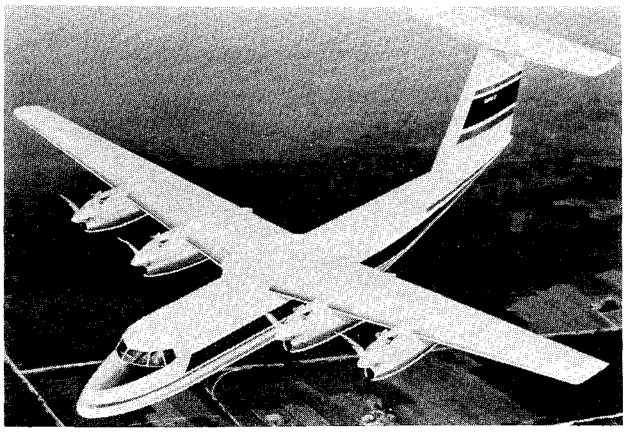


Fig. 12 DHC Dash 7 quiet STOL airliner.

signed to handle the high torque loads imposed by the low-speed propellers. The exhaust stubs are located on top of the engine to direct the exhaust noise away from the ground and to use the wing as a shield similar to the arrangement in the Citation. The DHC-7 external noise objective is 95 PNdB at 500 ft which is considered to be the lowest level of any transport aircraft on record. This level, with suitable corrections for distance and units, is in the order of 20 EPN dB below current FAA limits.

Another newly-designed aircraft is the Shorts SD3-30, Fig. 13, a twin-engined wide-bodied 30 passenger Feederliner designed for commuter and regional carrier service. This aircraft will be powered by the PT6 A-45 engine which incorporates a new intermediate-speed reduction gearbox, and will drive a specially-designed Hartzell 5-bladed propeller. The intermediate tip speed propeller feature ensures low exterior noise levels and a quiet flight for passengers.

Noise Research

UACL is actively engaged in a research program on engine internally generated exhaust noise, part-sponsored by the Canadian National Research Council. With the advent of low tip-speed propellers for medium size transports and the low noise requirements of auxiliary power units for large aircraft, engine exhaust noise becomes significant. Inlet noise, although comparable in level, is very much easier to suppress since a major portion of the energy is contained in the 8th octave. Hence simple thin liners are very effective. Exhaust noise, however, is broadband in nature with a significant amount of low frequency energy. This is more difficult to suppress because of the dominance of low frequencies and the exhaust gas temperature. The exhaust noise of turboshaft engines appear to fall within a band which is proportional to horsepower (Fig. 9) indicating that the current hot-end design principles are relatively similar. Exploration into this area, to determine the nature of the exhaust noise, may derive the knowledge required for reducing it in the design stage without undue sacrifice to engine weight, size and performance. To resolve these problems work is underway on a cold flow rig to establish the nature of the PT6 exhaust noise source. The effect of the exhaust duct geometry on the generation transmission and radiation of the noise is being actively explored. Tests to date have led to a better appreciation of the noise generation mechanisms which enabled us to derive a better understanding of the trends noted on engines.

Fig. 13 Shorts SD3-30 commuter airliner.

Designing for Clean Exhaust

Regulations

The U.S. Environmental Protection Agency (EPA) determined that exhaust emissions from aircraft engines are responsible for less than 1% of the total air pollution problem[5] but do contribute to pollution levels in the vicinity of at least some airports.[6] Only emissions produced below 3000 ft altitude and close to the airport were considered a potential problem. Accordingly, EPA devised a rating procedure based on a landing/takeoff duty cycle to regulate aircraft emissions below this altitude. The cycle chosen for small gas turbine propulsion engines, Class T1, was presumably representative of operation from congested airports with delays imposed on takeoff or landing, as time allocated to the taxi-idle mode comprised more than 77% of the duty cycle.

The initial EPA proposed standards, in Dec. 1972, sought to regulate aircraft emissions as early as 1976 and called for further reductions, by as much as 8.7 times, by 1979. Strong representations were made to EPA that the

Table 3 EPA emission standards for small gas turbine aircraft propulsion engines

Class	Description	Effective date	UHC (as CH_4)	CO	NO_x (as NO_2)	SAE Smoke no.
	Proposed December 1972[a]		Emission Limits			
T_1	All propulsion engines below 6000 lbs thrust or 6000 ESHP (units of lb/1000 lb thrust-hr or lb/1000 HP-hr)	1 Jan. 1976	8.7	11.3	—	35
		1 Jan. 1979	1.0	2.2	3.7	35
	Promulgated July 1973[b]					
T_1	Turbofans/Turbojets below 8000 lb thrust (units of lb/1000 lb thrust-hr)	1 Jan. 1979	1.6	9.4	3.7	50–32 Depends on power
P_2	Turboprops (units of lb/1000 HP-hr)	1 Jan. 1979	4.9	26.8	12.9	50–26 Depends on power

[a]40 CFR Part 87, Federal Register, Vol. 37, No. 239, Dec. 12, 1972.
[b]40 CFR Part 87, Federal Register, Vol. 38, No. 136, July 17, 1973.

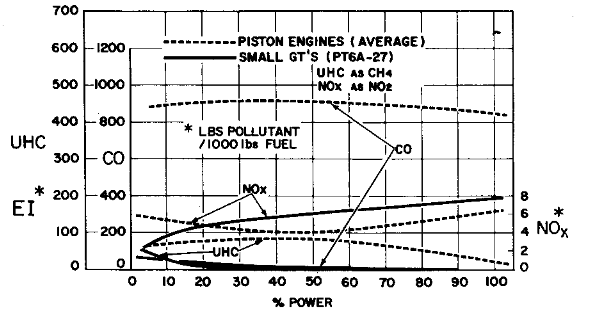


Fig. 14 Emissions from aircraft engines, piston vs small gas turbine.

lead time to the 1976 standards was insufficient to safely implement significant combustor changes. Further, the rating procedure allowed the same emissions from a fan or jet engine of, say, 1000 lb. thrust as from a 1000 HP shaft engine. This regulation was manifestly unfair to turboprop engines since the shaft engine coupled to a propeller would typically produce 2500 or more pounds thrust at takeoff. The 1979 standards proposed had not been demonstrated on rigs. Their technical feasibility, let alone the tradeoffs and associated penalties, had not been assessed.

EPA, in large measure, recognized the validity of these objections. Its regulations were promulgated in July 1973 and the limits set for small aircraft propulsion gas turbines were substantially modified.

The 1976 standards were dropped and the 1979 standards for class T_1 were relaxed by a factor of 2.5 on an equivalent-energy-loss basis. A new P_2 category established for turboprops has limits approximately 3× those for T_1 thus recognizing the propellers conversion of shaft horsepower to thrust.

Engine Comparisons

Figure 14 compares emission indices obtained from a series of aircraft reciprocating engines[6] with a representative small turboprop engine, UACL's PT6A-27. At all power settings the turbine produces markedly lower unburned hydrocarbons (UHC) and particularly carbon monoxide (CO). Above 20% power the piston engines show somewhat lower production of oxides of nitrogen (NO_x). The surprisingly modest levels of NO_x and very high levels of CO emitted by the piston engines is consistent with operating them fuel-rich to provide engine cooling for reliability and life.

Emissions from representative large and small gas turbines are compared in Fig. 15. The small gas turbine has substantially higher emission indices of CO and UHC at low power but lower levels of NO_x at higher power. The comparatively poor performance of the small engine at low power is due primarily to operation at low combustor pressure and temperature, to a high ratio of combustor surface area to volume, and to the use of relatively simple and low-cost combustor and fuel systems. The good NO_x performance at high power is due principally to lower levels of combustor inlet pressure and temperature. These effects are discussed next.

Gas Turbine Combustor Design Requirements

The exigencies of emission reduction necessitate some compromise in established combustor design technique. The traditional approaches have concentrated mainly on design point operation where combustion efficiencies are usually very high. Reliable cold starting and altitude relight capabilities have been a very major concern at the other end of the power scale. Combustor pressure losses have been minimized for maximum engine efficiency while still providing adequate mixing for fuel/air distribution, uniform exit temperature pattern, and low smoke generation. The requirement of long combustor life has been achieved by rather generous wall film cooling, particularly in the primary zone. The choice of fuel systems has been dictated by considerations of durability (low fuel pressures and contamination susceptibility), cold starting, and cost. Not surprisingly, these factors have resulted in low but acceptable combustion efficiencies at idle power operation.

Low Emission Requirements

The formation of NO_x depends on the time spent by combustion products at very high temperatures. Rate of formation increases rapidly as the gas temperature is increased above a threshold value of about 2800°F. High pressures which are characteristic of advanced large gas turbines also increase the rate of NO_x production. CO is usually a result of inadequate oxygen and/or too rapid chilling of the intermediate combustion products to temperatures below about 2200°F which effectively stops the 'burning' of CO to CO_2. High combustor temperatures and pressures promote the conversion of CO to CO_2 and this is the basic cause of the usual inverse relationship between NO_x and CO emissions. High levels of UHC are frequently caused by relatively coarse fuel atomization, particularly if some of the fuel can become entrained in cool air adjacent to the combustor walls and carried almost directly out of the combustor. Cool combustor walls tend to promote UHC, and high combustor temperatures or pressures discourage it.

Some Related Research

In 1971–1972 UACL assisted by United Aircraft Research Labs (UARL), designed and developed two small single-can combustors for EPA's Advanced Automotive Power Systems.[7] Figure 16 summarizes results achieved

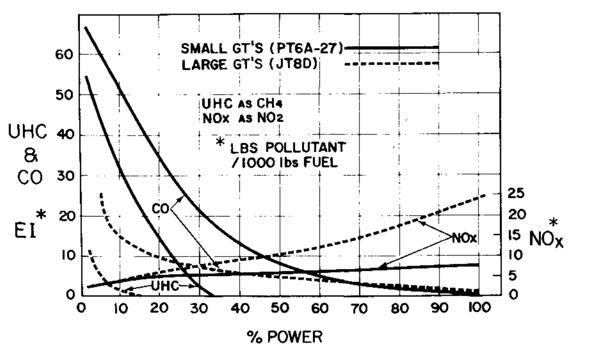


Fig. 15 Emissions from aircraft engines, large vs small gas turbine.

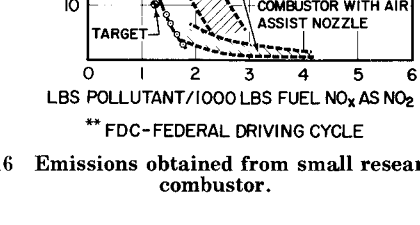


Fig. 16 Emissions obtained from small research can combustor.

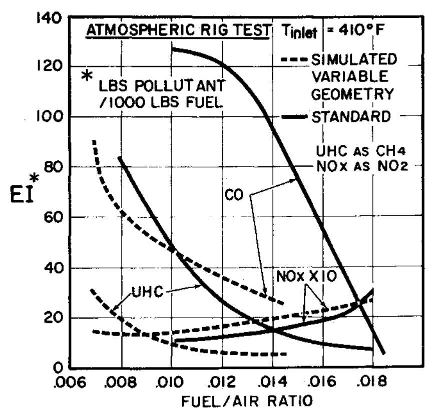


Fig. 17 Variable geometry effect on emissions.

on the 2.5 in. diam can, which was designed for a potential nonregenerative vehicular gas turbine. The broad band covers early test data and shows the anticipated inverse relationship between NO_x and CO emissions. The band at low CO levels shows a major reduction in emissions achieved solely by aerodynamic means within the combustor. The final curve was obtained using an improved "air blast" fuel injector. Although its emissions were commendably close to the very demanding target, the can was not optimized as the results were obtained in the final week of testing. These results indicate that low emissions can be achieved in very compact combustors by aerodynamic-cum-fuel injection techniques.

UACL with partial funding from the Canadian Defense Research Board has undertaken other small programs of combustion research. On one of these the potential for emission reduction of simple variability external to the combustor was demonstrated (Fig. 17). Although the geometry was not optimized, the beneficial effect is quite obvious. As previously noted, variable geometry has drawbacks but its potential for emission reduction is very great and some additional work on it is being undertaken.

Additional Problems

The current state of technology is such that emissions from even the most sophisticated combustion systems are governed to a certain extent by variations in the engine inlet conditions. It is widely recognized that ambient temperature and humidity significantly affect engine emissions, but relatively little is known about the mechanism or magnitude of the effect, and whether a normalizing parameter is possible. EPA has announced programs to investigate the phenomena. Generally, UHC and CO diminish with increasing inlet temperature while NO_x formation is inhibited by increased humidity. The data of Table 4[8] shows that these trends are large and by no means universal.

Current Engine Status

A feature common to many small aircraft turbine engines is the use of centrifugal compressors delivering air to reverse-flow annular combustors, which are relatively large in cross-sectional area and long in path length. This generous volume allows low combustor pressure drop combined with good temperature distribution at turbine inlet. It also provides long residence time which can profitably be used to 'burn-off' CO and smoke but will also tend to produce NO_x. The proportionately large surface area will promote UHC particularly if highly cooled in the interests of long life. Velocity profiles from the centrifugal compressor are relatively stable so the combustor does not have to cater for major changes in external aerodynamic flows.

Table 4 Effects of ambient temperature and humidity on emissions

Ambient Temp. (°F)	Estimated JT9D-7 EPAP[a] EPAP CO	UHC	NO_x
25	9.73	2.65	3.83
59	7.84	1.76	5.46
85	6.50	1.28	7.04
	JT3D Emissions		
Ambient Temp. (°F)[b]	CO at idle	EI lb/10^3 lb fuel UHC at idle	NO_x at take-off
25	265	No effect of ambient tempera-ture	11.4
59	110		12.35
85	65		13.45
Specific humidity[c] lb H_2O / lb air	CO at idle	EI lb/10^3 lb fuel UHC at idle	NO_x at take-off
0.005	140	106	12.8
0.010	110	50	12.35
0.015	90	25	11.80
	70	13	11.35

[a]EPAP = lbs/10^3 lbs thrust-hours. Specific humidity = 0.0058 – 0.0110 lb H_2O/lb air.
[b]Specific humidity = 0.010 lb H_2O/lb air.
[c]Ambient temperature = 59°F.

Differences between UACL combustors likely to influence emissions are as follows:

1) The JT15D combustors are in absolute terms larger than their PT6 counterparts but with combustor loadings in between the PT6A-27 and the A-41. Twelve fuel nozzles of 4.65 flow number, defined as the ratio of the fuel flow rate to the square root of the pressure drop across the nozzle, are located in the flametube dome and arranged to spray axially forward. This arrangement is well suited to accept fuel system changes as a means for emission control.

2) All PT6 engines utilize 14 fuel nozzles located just within the outer periphery of the flametube and arranged to spray tangentially. The A-27/L-73/T400 family uses relatively low flow number nozzles (1.36). Changes to the liner inner wall profile are currently undergoing evaluation.

3) The A-41/A-45/A-50 engines have significantly smaller flametubes, with higher fuel flows (1.55 flow number nozzles) and hence are more highly loaded. The compressor discharge is located closer to the primary zone of the flametube.

Aircraft engine emissions work has been very active at

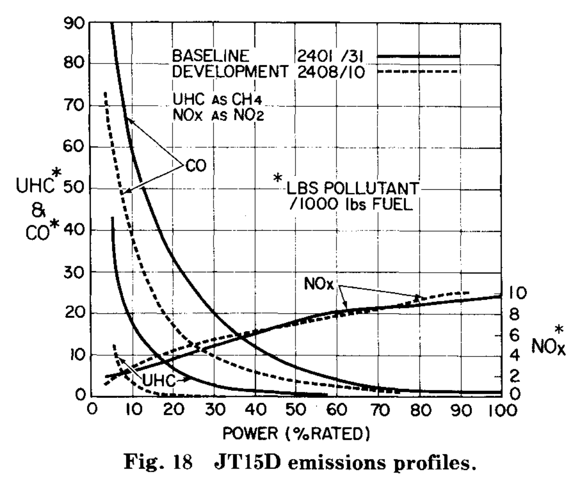


Fig. 18 JT15D emissions profiles.

Table 5 UACL Engine emission reduction progress[a]

JT15D	Date	T_{amb} (°F)	SH	Ng (% @ idle)	EPAP (lbs/10³ lb thrust-hr) UHC	CO	NO_x	Smoke number
JT15D-4 (base line)	May 29, 1973	56	0.010	52.0	8.7	29.7	4.1	25[c]
JT15D-4 (development)[b]	Aug. 20, 1973	79	0.012	52.0	2.2	16.9	4.2	25[c]
EPA 1979 Standard					1.6	9.4	3.7	43

PT6A-41	Date	T_{amb} (°F)	SH	Ng (% @ idle)	EPAP (lbs/10³ Hp-hr) UHC	CO	NO_x	Smoke number
A41 (baseline)	Feb. 5, 1973	53	0.0065	52.0	78	106	6.8	21.5[c]
A41 gas generator (development)[d]	July 24, 1973	97	0.0125	52.0	5.9	24.1	10.1	—
EPA 1979 Standard					4.9	26.8	12.9	45

PT6A-27, L-73, T400	Date	T_{amb} (°F)	SH	Ng (% @ idle)	EPAP (lbs/10³ Hp-hr) UHC	CO	NO_x	Smoke number
A27 (baseline)	Aug. 8, 1973	100	0.0163	50.0	37.8	53.5	5.9	15
A27 King Air[e]	Nov. 1968	—	—	61.7	12.0	27.7	4.9	24
T400 (development)[f]	June 26, 1973	95	0.0140	48.6	13.6	26.9	7.2	18
EPA 1979 Standard					4.9	26.8	12.9	45

[a]*Note:* UHC as CH_4; NO_X as NO_2; SH = specific humidity (lb H_2O)/lb air); Smoke number to SAE-ARP-1179; N_g = gas generator speed.
[b]Development flametube: improved recirculation, delayed quench, modified fuel injection.
[c]Estimated maximum from closely related test results.
[d]Development flametube: longer, larger primary zone; marginal carbon formation.
[e]King Air data: earlier flametube geometry, hotter dome, very high idle, single-point sampling on aircraft installation, subject to major sampling errors.
[f]Development flametube: delayed quench.

UACL since December 1972. Base line data from each engine model was obtained first, followed by development to reduce emissions. The approaches currently showing the most favorable results with the smallest penalties include: a) Delayed introduction of dilution (quenching) air, b) High combustor inlet swirl, c) High head-end swirl, d) Controlled head-end wall temperature, and e) Revised internal flow patterns.

Baseline and some early development data are compared in Table 5 and Figs. 18–20. The JT5D engines are quite clean but the 1979 standards are very demanding. The development test shown is encouraging but does not represent a proven viable combustor; in this case, there was some carbon deposition and the fuel nozzle modifications would need additional development to allow acceptable engine handling.

Baseline A-41 data shows relatively high emissions attributable to higher combustor loadings combined with a large amount of wall cooling for long combustor life. The gas generator test shows very major reductions, to close to 1979 standards, achieved with a longer flametube (which fits into existing engine geometry) with modified internal air flows and hotter combustor walls. Again this is not a viable combustor as known problems include carbon deposition and potential durability.

Baseline A-27 data shows that combustor to have intermediate emission levels. Data measured on a Beech King Air aircraft in November 1968 are shown in the table as these early results have been fairly widely reported. The low indicated levels may be attributed to hardware changes (hotter combustor walls), to the very high idle used on that test and to the extreme sampling difficulties. A single point probe was used on a tethered aircraft and the indicated exhaust very possibly was 'vitiated' by ambient air. The development engine results tabled and shown on Fig. 20 were achieved by delayed quench at the apparent cost of a small worsening of turbine inlet temperature distribution.

The early development data are very encouraging as they indicate that major reductions in CO and UHC can be achieved with only small increases in NO_x by means that do not imply appreciable changes in the size, weight, or complexity of this engine type. It should be emphasized that these development combustors have not been through the necessarily long and expensive certification required to ensure their safe use in aircraft engines.

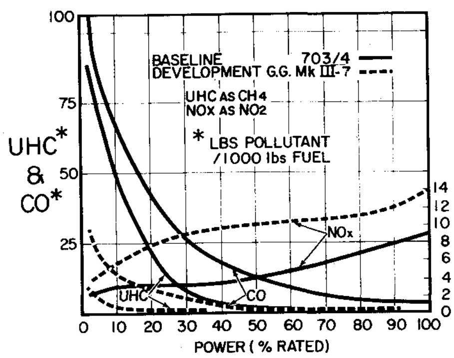


Fig. 19 PT6A-41 emissions profiles.

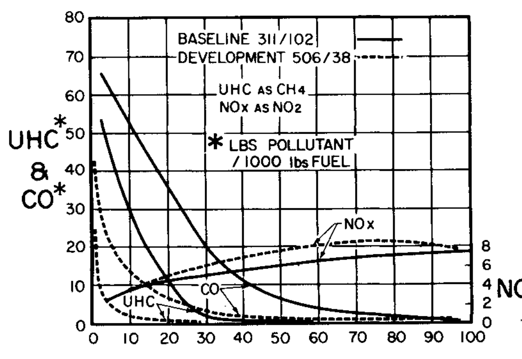


Fig. 20 PT6-A27/L73/T400 emissions profiles.

Summary

Noise

UACL has considered noise as a major design criterion for both its fan engines and more recent versions of the PT6. The Cessna Citation, powered by the JT15D turbofan, is the quietest jet aircraft in existence. The PT6 free-turbine has also established a reputation for quietness in the turboprop field. Development of lower output shaft speed versions of the engine will continue in order to exploit the noise benefits of low propeller tip speed. Continued effort will be devoted to improve our understanding of the nature of the noise sources and the effects of the installation.

Emissions

Designing for low exhaust emissions is under intense study and the mechanisms of pollutant formation are generally understood. Some techniques for reducing emissions are identified as well as test results showing that significant improvements can be effected although the necessary tradeoffs are not fully established. The time required for safe introduction of such improvements is necessarily rather long. The emission levels originally proposed for 1979 were extremely low and might not be achievable by even very radical changes. The levels promulgated by EPA in July 1973 are still very challenging but appear more realistic.

Current emission levels from UACL engines are shown along with encouraging early results from intensive development efforts presently underway. These results are not from fully developed viable combustors. They do indicate, however, that the principal penalty exacted by the new regulations is likely to be in engine development cost rather than major changes in engine volume, weight, or complexity.

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