OWNER'S & OPERATOR'S GUIDE: CFM56-5A/-5B

CFM56-5A/5B series specifications

The CFM56-5A/-5B series has many variants and sub-variants. A complete description of the family is given, together with their thrust ratings, flat rating temperatures & EGT margins.

The CFM56-5A and -5B series followed the development of the -3 series. The -5A and -5B are one of two engine options available for the A320 family. The CFM56-5A was the original engine on the A320, which gave the CFM56 a market lead over the V.2500 series. The first engines were -5A series powerplants that went into service in 1987, and continued to be manufactured up to 2003. The -5B was developed to provide higher thrust ratings for all A320 family members. The first engines entered service in 1993 and are now the only CFM56-5B series available for the A320 family. To date 3,500 A320 family aircraft have been ordered, and about 2,000 of these have had CFM56-5A/-5B engines specified.

Configuration

The CFM56-5A/-5B have a two-shaft design, and overall have four and eight different thrust ratings between 21,600lbs and 32,000lbs thrust *(see table, page 9)*.

-5A series

The CFM56-5A has a 68.3-inch diameter intake fan, a three-stage low pressure compressor (LPC) booster, a single-stage high pressure turbine (HPT), and four-stage low pressure turbine (LPT). The engine also has a full authority digital engine control (FADEC) as standard. The -5A series engines have red line exhaust gas temperatures (EGT) of 890 and 915 degrees centigrade, depending on modification status. The -5B series have red line EGTs of 950 and 940 degrees centigrade, depending on their sub-variant.

The -5A series has four ratings. The first variant introduced into service was the -5A1, rated at 25,000lbs thrust. This was used to power the A320-100, and also powers the higher gross weight A320-200 model. The -5A1 is flat rated to an outside air temperature (OAT) of 30 degrees centigrade.

This flat rating temperature is significant, because the engine is allowed to operate at maximum thrust for all OATs up to this flat rating temperature. The -5A1's EGT increases by 3.1 degrees for every one degree increase in OAT when operating at maximum thrust. The engine's FADEC and engine control unit then maintain the engine's EGT at a constant level by reducing thrust as OAT increases beyond the flat rating temperature. This reduction in thrust for OATs higher than the flat rating or 'corner point' temperature means that the aircraft may suffer take-off weight and payload penalties.

The other -5A variant for the A320 is the -5A3 rated at 26,500lbs thrust. This also has a flat rating temperature of 30 degrees. The engine's EGT increases at a rate of 3.1 degrees for every one degree increase in OAT below the corner point temperature.

The two variants available for the A319 are the -5A4 rated at 22,000lbs thrust and the -5A5 rated at 23,500lbs thrust. The lower rated -5A4 is flat rated to 45 degrees centigrade, and this higher corner point temperature is beneficial to airlines operating in hot environments. The engine's EGT increases by 2.9 degrees for every one degree increase in OAT. The -5A5 has a corner point temperature of 37 degrees centigrade. EGT increases by 3.0 degrees for every one degree increase in OAT.

A modification programme was developed for three of the -5A series variants, denoted by a /F suffix. This allows the engine to run hotter, via hot section modifications, and so provides it with an increase in EGT certification from 890 to 915 degrees centigrade, thereby increasing the EGT margin by up to 25 degrees centigrade.

-5B series

The -5B series was developed to power all proposed variants of the A320 family, because the -5A series did not have the growth potential that the A321 required. The -5B's configuration is similar to the -5A, but the -5B features a fourth LPC stage which allowed the engine to be developed to provide up to 32,000lbs thrust, and to increase coreflow. The engine could also be de-rated to power all other members of the A320 family.

The -5B series has nine different variants with eight different thrust ratings *(see table, page 9)*. The -5B3 is the highest rated at 32,000lbs thrust, used to power the highest gross weight models of the A321, while the -5B8 is the lowest rated at 21,600lbs thrust for the lighter A318 model. All nine variants share the same hardware for the eight different ratings, and thrust rating is changed by using the data entry plug. The engine can therefore easily and quickly be re-rated, which facilitates its management and can be used to extend removal intervals between shop visits. This means that the engine can first be used on the A321 with one of the highest thrust ratings, and when its EGT margin has been exhausted it can be re-rated to a lower thrust rating as used by the A320 and A319. This process allows it to regain some EGT margin that will enable it to operate for an extended period.

There are three main variant groups of the -5B series. Each one of these has sub-groups. The first of these three main groups comprises the 'classic' -5B engines. This was the first group of -5Bs manufactured between 1993 and 1996, and fewer than 300 were produced. There are only six variants: the -5B1, -5B2, -5B4, -5B5, -5B6 and -5B7. The highest rated -5B3 and lowest rated - 5B8 and -5B9 were not available at the time. These engines are recognisable by the absence of a suffix on their variant name.

The -5B2 powers the A320. It has the highest rating in this group of 31,000lbs thrust, and a corner point temperature of 30 degrees *(see table, page 9)*. The -5B1 also powers the A321, has a rating of 30,000lbs thrust and a corner point temperature of 30 degrees. This relatively low corner point temperature could mean that the A321 will be performance limited on some routes when operating in hot climates.

The -5B4 and -5B7 are both rated at 27,000lbs thrust, power the A320 and have a corner point temperature of 45 degrees *(see table, page 9)*. The -5B7 can also be used to power the A319.

The -5B6 is rated at 23,500lbs thrust, and can be used to power the A320 and A319. It also has a corner point temperature of 45 degrees. The -5B5 is rated at 22,000lbs thrust, has a corner point temperature of 45 degrees centigrade, and can also be used to power the A320 and A319 *(see table, page 9)*.

These six original variants of the -5B have an EGT of 950 degrees centigrade.

The second main group of -5B variants is recognised by the /P suffix following their variant nomenclature. The

The -5B series has nine variants. The series is also split into three sub-variants. These are the original or 'classic' engines, the -5B/P engines and the -5B/3 engines. There are less than 200 classic engines in the fleet, which is dominated by the -5B/P, accounting for more than 2,000 engines in operation. The -5B/3 will be the standard production engine from the fourth quarter of 2007.

/P suffix was used to designate an improved performance modification. The main features were a redesigned HPC compressor that used 3-D aerodynamic blades, a new HPT blade that had increased cooling, and a redesigned LPT stage 1 nozzle.

This was included as standard on the production line, but was also available as a modification that could be incorporated in a shop visit. The majority of classic engines were upgraded to /P engines, leaving only 48 in their original configuration.

The /P engines had about 3% lower specific fuel consumption (sfc) over the classic -5B engines.

This group includes all nine variants. The first of these was the -5B3, the highest rated -5B variant. It is rated at 32,000lbs for the A321, and has a corner point temperature of 30 degrees.

This group also includes the two lowest rated variants. The first is the -5B8, the lowest rated -5B variant, rated at 21,600lbs thrust. It is used to power the A318, and has a corner point temperature of 45 degrees centigrade *(see table, page 9)*. There is also the -5B9, rated at 23,300lbs thrust and used to power the A318 Elite, which is the corporate version of the A318.

The nine /P variants in this group are certified with an EGT of 940 degrees centigrade, 10 degrees lower than the classic engines.

The third group of engines has a /3 suffix. These will be standard production engines from late 2007, and the /3 designates a 'Tech Insertion' standard, which is a modification that offers several improvements to reduce sfc and NOx emissions, and provide a higher EGT red line limit and overall better durability. The main features include redesigned and more aerodynamic stage 1-9 HPC blades, an upgraded single annular combustor (SAC) that will meet CAEP6 NOx emissions standards, improved cooling for durability, and redesigned HPT blades that will assist in lowering sfc *(see CFM56-5A/-5B Modification programmes, page 10)*. The /3 'Tech Insertion' modification can also be installed on existing engines during a shop visit.

Sub-variants

In addition to the three main groups of -5B variants, there are also several sub-variants. The first of these sub-groups comprises the engines with the dual annular combustor (DAC). These are denoted by the /2 suffix. The DAC was designed to reduce NOx emissions, and airlines operating in areas that impose specific penalties related to emissions have specified the DAC. The standard specification of the -5A and -5B engines is the SAC.

Of the six variants of the classic engines, four were available as DAC engines: the -5B1, -5B2, -5B4 and -5B6. The majority of classic engines were specified with the SAC, but Swissair and Austrian Airlines ordered classic DAC engines.

The other main specification feature of -5B engines is the 'thrust bump'. As described, the engine's thrust is reduced from maximum thrust when operating in OATs above its corner point temperature. This can restrict an aircraft's performance by limiting its take-off weight and payload on certain routes. Thrust bump is achieved by extending the engine's corner point by a few degrees, so that the engine's FADEC will allow the maximum thrust rating to be provided to a higher corner point temperature. This facility could be useful not only for aircraft operating in hot environments, but also for those using high airfields or short runways, or where steep climb capability is required.

Of the /P engines, the -5B3 and -5B4, which are the highest rated engines for the A321 and A320, are available with thrust bump capability. This is provided via programme changes to the engine's FADEC, but it incurs penalties in cycle times counted on the engine's life limited parts (LLPs).

Airlines can choose from several combinations of specification. Besides the regular /P, the -5B3 and -5B4 are available as the /P1, which is the /P with the thrust bump capability.

Six of the /P variants are available with the DAC combustor. These are the -5B1, -5B2, -5B3, -5B4, -5B6 and -5B9, and are denoted with the /2P suffix. Finnair ordered /P engines with the DAC combustor.

The -5B3 and -5B4 are also available with the DAC combustor and thrust bump, and are denoted with the /2P1 suffix.

The third main variant group of /3 engines includes the option of a thrust bump for the -5B3 and -5B4 engines. These are the -5B3/3B1 and -5B4/3B1.

Life limited parts

The -5A series has 18 LLPs, which have a total list price of $1.75 million. These are split between three in the fan/booster module with a list price of $375,000, five in the HPC module with a list price of $460,000, four in the HPT with a list price of $419,000, and six in the LPT with a list price of $500,000.

CFMI's policy is to set target lives of 30,000 engine flight cycles (EFCs) for the three fan/booster LLPs, a target life of 20,000EFC for the nine HPC and HPT LLPs, and a target life of 25,000EFC for the six LPT LLPs.

There are several part numbers for each LLP, and some part numbers have had their lives limited to less than their target lives. Other part numbers have been issued as a consequence, so there is now a range of lives for each LLP. The fan disk and booster spool part numbers for the -5A series have lives of 23,000-30,000EFC. All parts for the fan shaft have a life of 30,000EFC. Most part numbers for all LPT LLPs have lives of 25,000EFC, and all part numbers of HPC LLPs have lives of 20,000EFC. The module with the most life restrictions is the HPT. The rotating forward air seal in particular has some part numbers that are restricted to lives of 11,000EFC in the -5A1, 7,700EFC in the -5A3 and 9,100EFC in the -5A5. There are other part numbers used in the HPT whose lives are also limited to several thousand EFC fewer than the target life of 20,000EFC.

The -5B has 18 LLPs with a total list price of $1.83 million. CFMI has the same target lives for the four main modules as the -5A series. The three parts in the fan/booster module have a list price of $406,000, the five parts in the HPC have a list price of $447,000, the four parts in the HPT have a list price of $474,000, and the six parts in the LPT have a list price of $503,000.

Part numbers for the fan disk are limited to 20,000-25,000EFC, while the other two LLPs in the module have lives of 30,000EFC. Five of the six LPT part numbers have lives of 25,000EFC, and the sixth LLP has lives of 15,000-25,000EFC. Most part numbers for the HPC have lives of 15,600-20,000EFC. Like the -5A, the HPT has part numbers with the most limitations. These have lives between 6,400EFC and 20,000EFC. The worst affected part numbers in this module are those used in -5A engines. Part numbers used in the HPT of -5B engines have lives of 12,400-20,000EFC. Moreover, only a minority of engines have parts with lives as short as 12,400EFC. There are a larger number of engines, however, with parts that have lives as short as 15,300EFC and 17,600EFC.

The /3 engines with the Tech Insertion programme will, however, have all LLPs with lives certified at the target lives.

CFM56-5A & -5B EGT MARGINS

Engine variant	-5A3	-5A1/ -5A1F	-5A5/ -5A5F	-5A4/ -5A4F
Thrust lbs	26,500	25,000	23,500	22,000
Application	A320	A320	A319	A319
Red line EGT (deg C)	915	890/915	890/915	890/915
Initial EGT margin (deg C)	71	57/82	50/75	55/80
Corner point temperature (deg C)	30	30	37	45

Engine variant	-5B3	-5B2	-5B1	-5B7	-5B4	-5B6	-5B5	-5B8
Thrust lbs	32,000	31,000	30,000	27,000	27,000	23,500	22,000	21,600
Application	A321	A321	A321	A320	A320	A319	A319	A318
Red line (deg C)	940	950/ 940	950/ 940	950/ 940	950/ 940	950/ 940	950/ 940	940
Initial EGT margin (deg C)	66	95	115	109	109	145	163	180
Corner point temperature (deg C)	30	30	30	45	45	45	45	45

EGT margin

As described, the engine's FADEC is programmed to keep the engine up to its maximum thrust rating up to the corner point temperature. The EGT increases at a rate of about 3 degrees per one degree increase in OAT. The EGT therefore rises to a maximum allowable level, which is lower than the engine's red line EGT. This is the exhaust temperature between 890 and 950 degrees centigrade, which must never be exceeded. The difference between the engine's actual EGT and the red line temperature is the EGT margin. The EGT margin is measured at the reference point of the corner point temperature. The engine will actually have a higher EGT margin for OATs below the corner point.

For OATs higher than the corner point temperature, the FADEC is programmed to keep the engine's EGT constant, so that the difference between the EGT and the red line temperature is the same. The engine's EGT margin is thus the same for all temperatures above the OAT, but the EGT margin increases by about 3 degrees for every one degree drop in OAT below the corner point temperature.

As the engine's condition deteriorates as a result of operation, the EGT gradually rises and the EGT at the corner gradually increases. The EGT margin therefore decreases by the same amount. The engine can remain in operation until the EGT margin has reduced to zero. The engine will still actually have some EGT margin at OATs lower than the corner point temperature.

The engine's EGT is highest for the highest rated -5B3 engines, which therefore have the lowest EGT margin. The -5B3, as well as the -5B1 and -5B2, also has a low corner point temperature of 30 degrees centigrade. Conversely, the lowest rated -5B8 has the highest EGT margin, as well as a higher corner point temperature of 45 degrees.

EGT margins are at their highest levels when the engines are new. The rate at which EGT margins decline with engine deterioration determines life on-wing. The highest rated -5B3 and -5B1 engines can therefore expect to have the shortest removal intervals. Moreover, EGT margins of engines following shop visits are only 60-80% of original levels, which means that second and subsequent removal intervals are shorter than the first intervals.

The high EGT margins and high corner point temperatures of lower rated engines therefore enable engines to achieve lower maintenance costs and allow aircraft to operate with fewer performance restrictions in high ambient temperatures than the higher rated family members. AC

CFM56-5A/-5B modification programmes

There are several upgrade and modification programmes for the CFM56-5A and -5B series of engines. Some of these have been incorporated. The most important new modification is the Tech Insertion programme, which will come available in late 2007.

The CFM56-5A1 was the first engine to power the A320 into service in 1987 and to be certified for extended twin-engine operations (ETOPs) on the aircraft. In addition there are the -5A3, -5A5 and -5A4. The -5A series was followed in 1994 by the -5B series, of which there are nine main variants *(see CFM56-5A/-5B series specifications, page 6)*.

-5A series TOW modification

The first major CFM56-5 modification, which has long since been integrated into the installed fleet, but which should nevertheless be mentioned here for the sake of completeness, is the exhaust gas temperature (EGT) margin upgrade that was applied to the -5A series powering A319s and A320s. This modification provides the engine with a higher certified EGT limit of 915 degrees, compared to 890 degrees on unmodified engines.

The modification is achieved through several hot section modifications. Engines with this modification are identified by an '/F' suffix on the name plate.

Also referred to as the 'Time On Wing' (TOW) upgrade, this modification is transparent in operation, since it does not alter the EGT limits indicated on the flightdeck instruments. The modified engines therefore still have an indicated 890°C EGT redline, but an actual corresponding EGT limit of 915°C. Unmodified engines have an indicated and actual EGT limit of 890°C.

The indicated EGT redline temperatures of 890°C are the same for modified and unmodified engines, since two different limits would require different calibrations of flightdeck instruments and could also possibly risk confusing flightcrew. When the modified engines appear to be at their redline limits, their EGTs are actually 25 degrees lower than the certified limit, thereby providing a comfort zone and ensuring that EGT margin deteriorates at a lower rate.

The three of the four -5A variants that had this modification are the -5A1, 5A4 and -5A5, and are identified as the -5A1/F, -5A4/F and -5A5/F. The CFM56-5A3 is the same as CFM56-5A1/F, with an EGT redline of 915 degrees, but it has a higher take-off thrust rating of 26,500lbs thrust. This compares to the -5A/F's rating of 25,000lbs thrust.

The /F modification was also applied on the production line to new manufactured engines, from October 1992 to the -5A1, from February 1994 to the -5A4/F, and from February 1996 to the -5A5/F.

3-D Aero -5B upgrade

The original -5B series engines, which had the basic name designation, are known as the classic variants. There are only six of them, with ratings between 31,000lbs and 22,000lbs thrust. Fewer than 300 classics were produced from 1993 to 1996, and these were shortly followed by an enhanced model.

The enhanced -5B/P model has been in production since 1996. It is an upgrade that can be retrofitted to classic engines, but it was also the standard build specification from 1996.

The /P upgrade involved improved '3D-Aero' turbomachinery components, replacing the original build standard from 1994. These improvements resulted in 3% lower specific fuel consumption (sfc) compared with the original -5B standard. The /P series includes all nine -5B variants rated between 32,000lbs and 21,600lbs thrust.

Most of the classic engines in the global fleet have now been upgraded, and only 48 remain unmodified. Air France is one notable large operator that has upgraded all its A320 engines to /P status.

The /P modification includes the following specific features: redesigned high pressure combustor (HPC) blading; a new high pressure turbine (HPT) blade with improved cooling; and a redesigned low pressure turbine (LPT) stage 1 nozzle.

All nine /P variants are certified with an EGT of 940°C, which is 10°C lower than the unmodified standard.

-5B series 'Acoustic Upgrade'

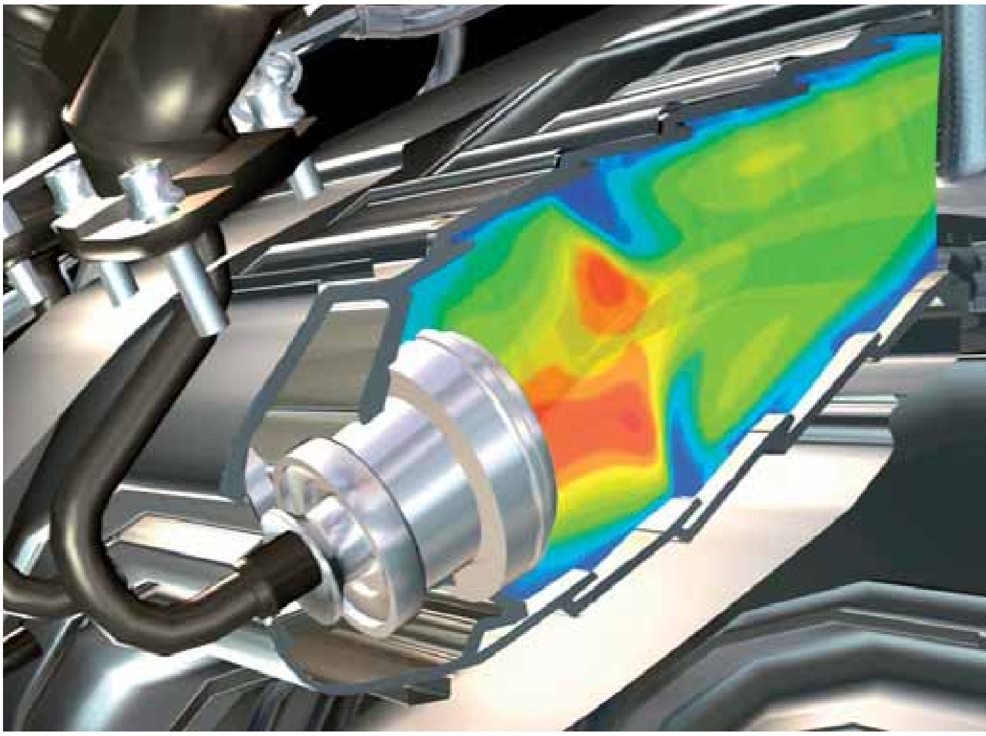
In 2002 CFMI announced that CFM56-5B engines could be equipped with an acoustic upgrade package, which included a distinctive 'chevron' type exhaust nozzle. The upgrade aimed to reduce the engine's cumulative noise signature to at least 10 EPNdB (equivalent perceived noise decibels) below Stage III levels. Specifically, the technology developed included: a core chevron nozzle; and improved reverser and inlet linings on the nacelle. The A321 with CFM56-5B/P engines in the highest maximum take-off weight (MTOW) configuration of 93.5 tonnes has a Stage IV margin of 1.2 EPNdB, and 11.2 EPNdB versus Stage 3 limits. The lower the MTOW configuration of the aircraft, the higher the margins relative to these limits. The acoustic package has been available in production since January 2004. Most of the A321 aircraft with the CFM56-5B3/P engine have the acoustic package.

LLP life extension

CFMI has a specific policy of gradually increasing the life of life limited parts (LLPs) on the CFM56-5A and CFM56-5B engines based on in-service experience. According to CFMI, the actual lives of the LLPs are being extended in anticipation of the fleet leader so as not to affect operations. The objective is of course to ensure that the LLPs are used to their full potential. These are 30,000 engine flight cycles (EFCs) for fan/booster module LLPs, 20,000EFC for core module LLPs and 25,000EFC for LPT module LLPs.

"CFMI is working on the programme, and life limits are revised every week. At this time we believe that about 80% of the parts have been certified for their target lives," says Paolo Lironi, senior technical manager at IASG. "We are also aware that CFMI is providing the biggest operators with some warranty conditions in case the life extension will not be met."

"LLP life extensions will be a 'double-



One feature of the Tech Insertion programme will be a TAPS combustor. This will reduce NOx emissions to a level that provides a margin over CAEP 6 standards.

tier' benefit, not only to the operators, but also to the leasing community which will be able to reduce maintenance reserves because of the extensions," notes Abdol Moabery, president of GA Telesis. "At the same time, it will benefit the likes of GE and MTU, which offer power-by-the-hour maintenance programmes, since they will not have to replace the LLPs as often."

This could help to eliminate the current problem, which is that 25-30% of LLP life is typically wasted because of varying lives in a stack. Indeed, taking the industry at large, hundreds of millions of dollars of cycle life are probably lost because LLPs do not have enough life to justify reinstalling them on the aircraft at shop visits. If operators can now plan for three shop visit cycles instead before changing an LLP (the initial operation from new, followed by two more shop visits), that will have a significant impact in terms of cost savings.

DAC upgrade

The Double Annular Combustion (DAC) chamber was first applied on CFM56-5B engines, to reduce NOx emissions. The resultant model designation then became 'CFM56-5B/2'.

In 1995, the SR Group, at the time including Swissair and Sabena, opted for this engine model. The DAC was innovative and it was the first of this type proposed to operators. The DAC incorporates a second dome, or inner ring, of fuel nozzle ports. Each nozzle has a second tip which serves this inner ring. At low power levels, only the outer (pilot) stage is used. This stage is designed with low throughflow velocities and low airflow to promote stable operation and complete combustion. At high power, both stages are operational, but the majority of the fuel and air is burned in the inner (main) stage. The higher throughflow velocities in this stage reduce combustor residence time. Total combustion airflow through the swirlers is more than twice as much as a conventional combustor.

According to IASG, the hot section in DAC engines was reaching higher temperatures than the 'basic' engine model, which had single annular combustor (SAC) chambers. This created several problems with the rear bearings and the low pressure module. Other technical issues on DAC engines included:

- LPT stage 1 blades: The temperature profile of the DAC chamber was different and generated increased internal stress. Several engines suffered blade failures during engine start. CFMI proposed a retrofit programme for all engines, by replacing the parts with a more robust and revised design blade.
- Combustion chamber: Due to the increased temperatures, the combustor suffered early deterioration and several engines had to be removed early due to problems with combustion chamber cracking. CFMI proposed a new chamber design, with improved cooling and materials, allowing the engine to remaining on wing for an increased length of time.
- Turbine rear frame: This is a structural component of the engine that was found to be cracked on several powerplants because of the increased exhaust temperature.

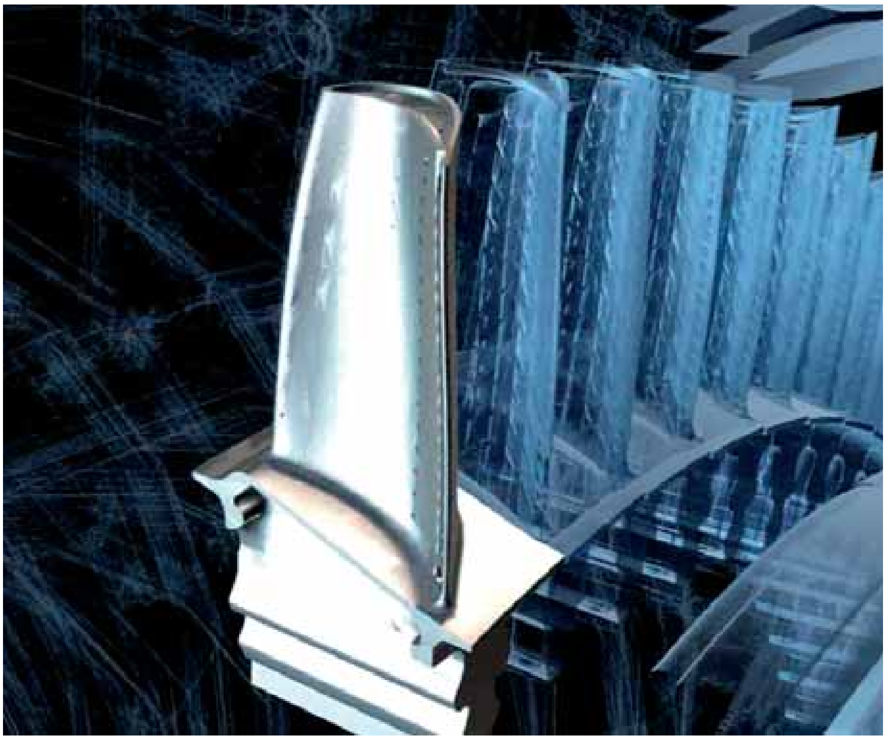
"The issues which affected the DAC engines are now fixed," explains Pierre Bry, vice president of marketing at CFMI. "They have been behind us for quite some time. The DAC burns a little more fuel, about 1%, and mostly at idle speed. The other maintenance cost is due simply to the fact that the DAC cluster is a little more complex, since it has more piping, two sets of injectors, and a centrebody. Importantly, the DAC model is now an engine which has fully equivalent operational capability to the SAC engine. Although the DAC engine burns a little more fuel, it does reduce NOx emissions by as much as 30-40% compared to the SAC."

Moabery notes that with DAC engines the value of the asset is affected by the ability to remarket or re-lease the engine to an operator that does not have DAC engines in the rest of its fleet. "If I have a CFM56-5B that is a DAC engine, it will be almost impossible for me to convince an operator to take it if they do not actually want a DAC, unless there is no other engine available on the market," says Moabery. "Of course, if I have a DAC engine, and there is a requirement for one, then I am going to get the deal. But unfortunately the market is limited to few operators. In addition, if there is a problem with the combustor, and it has to be replaced with a brand new one, the amount of spares in the market will be very limited indeed because fewer than 200 combustors were ever made. In the long run the lack of spares therefore makes the DAC engine more expensive to operate."

Tech Insertion upgrade

In 2004, CFMI launched a single major modification package for the -5B which included major changes aimed at improving fuel burn and EGT margin, and increasing durability. Dubbed 'Tech Insertion', this programme incorporates technologies developed and validated as part of Project Tech56, and includes improvements to the HPC, the combustor, and the HPT and LPT.

Following its certification at the engine level (FAR33) in December 2006 for the CFM56-5B, Tech Insertion will become available both as a retrofit for in-service engines, and importantly, as the standard production configuration, officially designated as 'CFM56-5B/3' from the end of the third quarter of 2007. Bry points out that the price structure of the CFM56-5B/3 production engine will



The Tech Insertion programme will feature a new low-shock HPT blade contour. This is designed to reduce interaction with the LPT, as well as feature improved cooling to aid reduction in fuel burn.

remain as before, as will the individual list prices for individual parts.

In particular, Tech Insertion uses advanced analytic tools for its twin-annular pre-swirl (TAPS) combustor technology developed for the future GEnx powerplant. This will improve cooling in the existing CFM56 SAC engines. The purpose of TAPS is to reduce NOx emissions, providing a margin over CAEP 6 emissions regulations scheduled to take effect in 2008. Other significant changes in the turbine include a new low-shock, HPT blade contour (validated as part of Project Tech 56). Furthermore, the associated blade design lowers the interaction loss between the HPT and LPT. When combined with additional durability improvements, these modules (with modified cooling) reduce fuel burn through improved efficiency, and lower maintenance costs. The design also includes improved aerodynamics in the rotor blades of the HP compressor and new materials for HPC stator bushings.

Overall, the package aims to provide operators with: 10% longer time on-wing, reflecting an escalation of the average time to first shop visit from 21,000 engine flight hours (EFH) to 23,000EFH; a 5-12% reduction in 'mature maintenance costs' depending on rating; 20-25% lower NOx emissions, in compliance with the latest emissions standard CAEP/6 for its SAC; reduced HPC deterioration (equivalent to 10 degrees centigrade EGT margin; and better fuel burn.

At the beginning of 2007 the price for kits remains undisclosed, but this will become available by the third quarter of 2007. As well as being offered for retrofit at a normal shop visit for engine overhaul, the improvements will become the production-build standard for the -5B. It will also become the technology standard for the - 7B engine on the 737NG.

It should be noted that while the full upgrade incorporates all the above, and is denoted by a '/3' suffix on the engine model name, 'sub-kits' will also be offered that allow operators to individually enhance particular engine modules. This will in effect be a portion of the full Tech 56 programme. These include kits for the HPC, HPT, LPT stage 1 nozzle, variable stator vane (VSV) bushing on the HPC, and a 20,000EFC life limit for LLPs in the core rotor. "Operators can actually choose between one or the other, depending on their particular requirements," notes Bry. "For example, if an operation is running in a hot environment, the engine may benefit from an HPC kit. In short, operators are not forced to swallow all the rest if they do not want to."

Moabery does not believe that the upgrade package will be economically attractive to low-cost carriers (LCCs), or airlines with small fleets. "It really comes down to who the operator is. Some LCCs may not have the capital available to do it. In my opinion the upgrade package will really be better suited to the major airlines, such as Air France and Lufthansa. The cost savings and the reliability benefits across a large fleet should exceed the up-front costs."

IASG's Lironi believes that engines without this set of modifications will hold less value, and operators will benefit from implementing it. "Operators will probably wait for the first engines to validate CFMI's performance promises before they commit to the upgrade. The Tech Insertion cost for the CFM56-3C1 engine is $1.3million, while it is more expensive ($1.8 million excluding LLPs) for the -5B series. If CFMI's indications of increased on-wing life and sfc are verified by operating the engines, Tech Insertion will have to be adopted by all airlines and engine owners. This is similar to what happened with the Phoenix modification on the V2500-A1 engines."

Bry points out that customers for the upgrade will typically be looking for a return on their investment within two or three years. "They will factor everything in such as the cumulative fuel saving and reduced maintenance costs. Also, since they will be removing some of the old blading from the current engine, they could conceivably realise significant savings by choosing to retain those parts and perhaps use them in another engine, or even sell them."

Bry adds that '/3' Tech Insertion engines will enter service with extended LLP lives from the outset: 30,000EFC for the fan/booster, 20,000EFC for the core, and 25,000EFC for the LPT. "When you look at the difference between the CFM56 and the V2500, you consider the costs of the LLP stacks, the lives, and the cost per cycle. We realise a difference of $26 per EFC in favour of the CFM56, simply because the list price for its LLP stack is lower and our lives are longer."

Another factor to be borne in mind is that Tech Insertion engines will be interchangeable with existing, unmodified engines on the same aircraft. For example, an A320 will be able to have a CFM56-5B/3 on one side, and a regular CFM56-5B on the other. The only pre-condition is that operators must ensure that the digital engine control unit is appropriately primed.

Regarding any impact on the asset values in relation to installed user base size, it should be noted that CFMI envisages production rates of more than 1,000 engines per year. Consequently, within three years there will be about 3,000 Tech Insertion engines in operation. AC

CFM56-5A/5B fuel burn performance

There are a large number of CFM56-5A and -5B variants. The fuel burn performance of the four A320 family members, each with several engine variants, is examined here.

The CFM56-5A and -5B series power all four members of the A320 family of aircraft: the A318, A319, A320 and A321. The A320 family offers operators the advantage of a wide variety of maximum take-off weights (MTOWs) and fuel capacity options.

The fuel burn performance of A320 family aircraft powered by CFM56-5A and -5B engines is analysed. The aircraft and engine model combinations covered in this analysis are as follows:

- CFM56-5A1 and -5A3, on the A320.
- CFM56-5B1/P, -5B2/P, and -5B3/P on the A321.
- CFM56-5B4/P on the A320 and A321.
- CFM56-5B5/P and -5B6/P on the A320 and A319.
- CFM56-5B7/P on the A319.
- CFM56-5B8/P and -5B9/P on the A318.

The CFM56-5B1 to -5B9 series engines have a common basic hardware and turbo-machinery and provide operators with up to eight different thrust ratings to suit different MTOWs. Similarly, the CFM56-5A1 and -5A3 on the A320, and the -5A5 on the A319, also use similar hardware to provide a range of different thrust ratings.

The CFM56-5B8 and -5B9 are rated at 21,600lbs and 23,300lbs on the A318. The -5B5, -5B6 and-5B7 on the A319 are rated at 22,000lbs, 23,500lbs and 27,000lbs thrust. The -5A1, -5A3 and -5B4 are rated on the A320 at 25,000lbs and 27,000lbs thrust, and the -5B4, -5B1, -5B2 and -5B3 are rated on the A321 at 27,000lbs, 30,000lbs and 33,000lbs thrust.

Airlines have the option of combining different thrust ratings with different MTOWs.

Route analysed

The route used to analyse these different aircraft is Toronto (YYZ) to Atlanta (ATL). Aircraft performance has been analysed in both directions to illustrate the effects of wind speed and direction on the actual distance flown, also referred to as equivalent still-air distance (ESAD). The chosen city-pair is typical of many A320 family operators, since it has a block time of about two hours. In this case the diversion or alternate airports used are Nashville when travelling to Atlanta, and Pittsburgh when travelling to Toronto.

Actual flight time is affected by wind speed and direction, and 85% reliability winds and 50% reliability temperatures for the month of June have been used in the flight plans performed by Airbus Industrie. It should be noted that for an 85% reliability annual wind, a wind component of minus 28 *(see table, page 14)* means that in 85% of all cases during this month of the year, the headwind component is at least 28 knots. The remaining 15% of the time, the headwind component is weaker, up to 28 knots.

The YYZ-ATL sector has a headwind component of 28 knots, while the ATL-YYZ sector has a headwind component of 18 knots.

The aircraft have been assumed to have full passenger payloads. These are 106 passengers for the A318, 124 for the A319, 150 for the A320, and 185 for the A321 *(see table, page 14)*. The standard weight for each passenger plus baggage is 220lbs. No additional underfloor cargo is carried. The payload carried by each aircraft is therefore 23,320lbs for the A318, 27,280lbs for the A319, 33,000lbs for the A320, and 40,700lbs for the A321.

The flight profiles in each case are based on domestic FAR flight rules, which include standard assumptions on fuel reserves, standard diversion fuel (for the alternate airports mentioned above), plus contingency fuel, and a taxi time of 20 minutes for the whole sector. This is included in block time.

Taxiing typically accounts for a fuel burn of 240-255lbs, at either end, depending on the specific aircraft-engine combination.

On the YYZ-ATL route, the 28-knot headwind increases the tracked distance of 675nm to an ESAD of up to 722nm. This route has a block time of 125-129 minutes *(see table, page 14)*. Since all aircraft in the sample are assumed to have a cruise speed of Mach 0.80, the differences in flight times are mainly due to wind differences.

On the ATL-YYZ route, with the headwind of 17 or 18 knots, the 675nm tracked distance flown increases to an ESAD of 703-705nm, depending on the aircraft type. This route has a block time of 125-127 minutes.

Despite there being large differences in the size of the four A320 family members, there is little difference in fuel burn per seat between the aircraft when equipped with CFM56-5B engines.

FUEL BURN PERFORMANCE OF CFM56-5A/5B SERIES

City-pair variant	Aircraft	Engine model	MTOW lbs	TOW lbs	Fuel capacity USG	Fuel burn USG	Block time mins	Passenger payload	ESAD nm	Fuel per seat	Wind speed
YYZ-ATL	A318-100	CFM56-5B8/P	130,073	125,844	6,303	1,377	127	106	721	12.99	-27
YYZ-ATL	A318-100	CFM56-5B8/P	135,580	125,844	6,303	1,377	127	106	721	12.99	-27
YYZ-ATL	A318-100	CFM56-5B8/P	138,890	125,844	6,303	1,377	127	106	721	12.99	-27
YYZ-ATL	A318-100	CFM56-5B8/P	142,200	125,844	6,303	1,377	127	106	721	12.99	-27
YYZ-ATL	A318-100	CFM56-5B8/P	142,500	125,844	6,303	1,377	127	106	721	12.99	-27
YYZ-ATL	A318-100	CFM56-5B8/P	149,900	125,844	6,303	1,377	127	106	721	12.99	-27
YYZ-ATL	A319-100	CFM56-5A5	141,100	132,314	6,303	1,439	127	124	721	11.61	-27
YYZ-ATL	A319-100	CFM56-5B5/P	149,920	132,868	6,303	1,433	127	124	721	11.55	-28
YYZ-ATL	A319-100	CFM56-5B6/P	154,330	132,868	6,303	1,433	127	124	721	11.55	-28
YYZ-ATL	A319-100	CFM56-5B7/P	166,450	135,437	7,884	1,457	127	124	721	11.75	-28
YYZ-ATL	A320-100	CFM56-5A1	145,504	140,568	4,185	1,519	129	150	722	10.13	-28
YYZ-ATL	A320-200	CFM56-5A1	162,040	143,289	6,303	1,551	129	150	722	10.34	-27
YYZ-ATL	A320-200	CFM56-5A3	166,450	143,289	6,303	1,551	129	150	722	10.34	-27
YYZ-ATL	A320-200	CFM56-5B5/P	162,050	143,759	6,303	1,536	129	150	722	10.24	-27
YYZ-ATL	A320-200	CFM56-5B6/P	166,450	143,759	6,303	1,536	129	150	722	10.24	-27
YYZ-ATL	A320-200	CFM56-5B4/P	169,750	143,759	6,303	1,536	129	150	722	10.24	-27
YYZ-ATL	A321-200	CFM56-5B4/P	183,000	167,241	6,261	1,793	125	185	721	9.69	-28
YYZ-ATL	A321-200	CFM56-5B1/P	187,400	167,241	6,261	1,793	125	185	721	9.69	-28
YYZ-ATL	A321-200	CFM56-5B2/P	196,200	168,496	7,040	1,802	125	185	721	9.74	-27
YYZ-ATL	A321-200	CFM56-5B3/P	206,130	206,130	7,842	1,768	127	185	722	9.56	-28

Source: Airbus Industrie

Fuel burn performance

The fuel burn for each aircraft/engine combination and the consequent burn per passenger are shown *(see table, this page)*. The fuel burn performance of the different aircraft-engine variants is compared on the YYZ-ATL sector.

The data shows that for the respective models the fuel burn per passenger increases in relation to actual take-off weights, rather than the certified MTOW of the aircraft. Higher MTOW capabilities, however, can in some cases mean that aircraft are physically stronger and so have a higher hull weight. In other cases, such as the A318s listed, the family sub-variants' operational empty weight (OEW) are the same, and they have identical actual take-off weights and fuel burns. Successive MTOW increases and thrust differences are simply 'paper changes'. The A318 comes with six MTOW specifications from 130,073lbs to 149,900lbs. In all cases the fuel used for this sector is identical at 1,366 US Gallons (USG) *(see table, this page)*. Most variants have the potential to carry higher payloads and fly longer distances than the YYZ-ATL sector analysed.

The effect is the same with three of the four A319 variants analysed, but the variant with the highest MTOW specification burns more fuel *(see table, this page)*.

For the A320, being the 'original' baseline variant, there are significant physical differences between the models analysed, and also the engines powering them. Not surprisingly, the fuel burn varies widely for each model. The first A320 model to be listed *(see table, this page)* is the earliest -100 model with CFM56-5A1 engines, and this was quickly superseded by the improved -200 which featured fuel-saving wingtip fences, among other changes. The -100 has an MTOW of 145,504lbs, an OEW of 90,422lbs, and fuel capacity of 4,185USG. In contrast, the subsequent -200 model, powered by the same engine, has an increased MTOW of 162,040lbs, a higher fuel capacity of 6,303USG due to larger tankage, and a higher associated OEW of 92,815lbs. This -200 model has a fuel burn of 1,551USG, while the -100's fuel burn is 1,519USG. This is explained by the -200's higher structural weight and OEW, which caters for its higher MTOW capability.

On the other A320-200 models equipped with -5B engines, their fuel burn decreases from 1,551USG to 1,536USG. This decrease is due to the CFM56-5B series' higher fuel burn efficiency over the older -5A1 and -5A3 models.

Moreover, the -5B's lower fuel burn also has to be considered in relation to aircraft with this engine having a higher OEW (93,432lbs versus 92,815lbs for the -5A1-powered aircraft). Interestingly, successive A320-200s (powered by -5B4/P, -5B5/P and -5B6/P engines) have higher specified MTOWs. These higher weights have no effect on their respective block fuel burns, however, which in all three cases are identical at 1,536USG. Correspondingly, the respective OEWs for these versions are 93,432lbs.

An interesting trend can be observed when considering fuel burn per passenger. As the aircraft grow in size (from the A318 through to the A321) all specification weights and actual take-off weights increase. The required engine thrust increases in line with higher take-off weights, as does the quantity of fuel consumed. Fuel burn per passenger *(see table, this page)*, is lowest with the largest aircraft. Fuel burns per passenger shown illustrate the relative fuel burn efficiencies of the A320 family members. The A318s all report the highest fuel burn per passenger at 12.99USG. This compares with the best A321 figure of 9.56USG per passenger. This equates to a fuel cost per passenger of $24 for the A318 and $18 per passenger for the A321. This is explained by only a 28% increase in fuel consumed for a 43% increase in the number of passengers carried.

CFM56-5A/-5B maintenance analysis & budget

The CFM56-5A/-5B series has a large number of variants. The removal patterns and maintenance of the three main groups are examined.

The CFM56-5A and -5B series are operated in fleets of 1,040 and 2,300 engines each. These collectively power 1,730 A320 family aircraft, equal to 57% of the global A320 family fleet. A further 640 A320s are on order with the CFM56-5B as the specified engine choice. The A320 will also continue to sell for at least another seven years before a replacement is launched, meaning that the CFM56-5A/-5B fleet is likely to exceed 6,000 units before A320 production is ceased.

The A320 family is operated globally, but the majority of aircraft are used in Europe. The second largest numbers are utilised by carriers in North America. An increasing number are also being used in China, the Asia Pacific and the Indian sub-continent, where high traffic growth rates are prevalent. Smaller numbers are also used in Africa, the Middle East and Latin America. The CFM56-5A and -5B therefore operate in a wide range of temperatures, which can vary from minus 20 or 25 degrees centigrade in parts of Northern Europe, the US and Canada during the winter, and up to 35-40 degrees centigrade (95 to 104 degrees Fahrenheit) in many parts of the world during the hottest months of the year.

Operating temperature is one factor that affects the maintenance costs of the many -5A and -5B variants. Maintenance costs and reserves are also affected by engine thrust rating, take-off derate, engine flight hour (EFH) to engine flight cycle (EFC) ratio, and previous engine management.

Engine in operation

Many A320 family aircraft are utilised as short-haul workhorses in Europe and North America, but are also generally used on longer average route lengths than those traditionally flown by narrowbodies. Lionel Maisonneuve, engineer at Total Engine Support (TES) explains that the average EFC time for the -5A and -5B fleets is 1.8EFH. This average disguises the fact that the shortest operations have cycle times of 0.7EFH, while the longest are up to 6.3EFH. The A320 and A321 are now used by many carriers as medium-haul aircraft. "We use our A320 family types across our European network, and many of these routes have flight times exceeding 2.0EFH," says Nuno Jesus, CFM56-5A/-5B powerplant engineering manager at TAP Maintenance & Engineering. "We also use the aircraft on routes from Lisbon to Dakar in Senegal and the Cape Verde Islands off the west African coast. These routes have flight times of about 4.0 hours. We also have domestic Portuguese routes of 30-40 minutes."

Finnair operates a fleet of 29 A321s, A320s and A319s equipped with -5B3, -5B4 and -5B6 engines. "Our fleet of CFM56-5Bs is one of the few fitted with dual annular combustor (DAC) engines," says Tuomo Karhumaki, vice president of the powerplant department at Finnair Technical Services. "We have a mix of -5B3, -5B4 and -5B6 engines for our fleet, and we operate at an average EFC time of 2.0EFH. We experience cooler temperatures than most airlines, often lower than zero degrees centigrade in winter. In summer they average 20 degrees centigrade, although we can experience temperatures of 25 or 30 degrees on some parts of our route network."

The relatively long average cycle time of most operators means that high rates of annual utilisation are also achieved. Compared with annual flight hours (FH) of 2,000-2,200 typically experienced by short-haul aircraft in the past, A320 family aircraft are generating 2,500-3,000FH per year in most cases.

The -5A went into service in 1988 with the first A320s. The first variant, the -5A1, is rated at 25,000lbs thrust. The -5A series was widened to four variants. The highest rated -5A3 at 26,500lbs also powers the A320, while the -5A4 and -5A5 are rated at 22,000lbs thrust and 23,500lbs thrust *(see CFM56-5A/-5B series specifications, page 6)*, and power the smaller A319.

The -5A series did not have the capacity to be developed for the higher thrust ratings that were required for the A321. This led to the development of the -5B, whose main difference over the -5A was an additional low pressure compressor (LPC) stage. This allowed the -5B series to be developed to deliver up to 32,000lbs thrust. The -5A and -5B both have a 68.3-inch diameter fan and single-stage high pressure turbine (HPT).

The -5B has nine different variants with eight different thrust ratings between 21,600lbs and 32,000lbs thrust *(see table, page 18)*. The highest rated variant is the -5B2 at 32,000lbs for the A321, while the

The CFM56-5A/-5B are now operated in large numbers by a large number of airlines across the globe. The -5B series has high EGT margins, and consequently there is limited shop visit experience of these engines.

Most variants of the CFM56-5B series can remain on-wing up to LLP limits, but engines also start to experience mechanical degradation after about 25,000EFH. One particular problem is the wear of high pressure compressor VSV bushings.

-5B9 is rated at 21,600lbs for the A318. The nine variants have the same engine hardware, and thrust rating is changed via the engine's full authority digital engine control (FADEC). The engine can therefore quickly be re-rated *(see CFM56-5A/-5B specifications, page 6)*. For example the -5B2 can be re-rated after using all its exhaust gas temperature (EGT) margin on the A321 to a lower thrust for the A320 and A319.

There are three main variant groups of the -5B series. The majority of engines are the second group of /P engines, but the /3 engines will be the standard production engines from late 2007. These will have several hardware improvements to reduce fuel consumption and NOx emissions, a higher EGT limit and standard lives for all life limited parts (LLPs) *(see CFM56-5A/-5B specifications, page 6)*.

EGT margin

EGT margin is an important factor in engine performance. EGT margin deterioration is more significant in engines used on short-haul operations, while mechanical deterioration of engine hardware is experienced after long EFH intervals on-wing.

The initial EGT margin of newly produced engines is generally high for the -5B series compared to the -5A engines.

There are four 'classic' or original variants of the -5A series, three of which have also had a modification that installed specific hardware to allow the engines to run with a higher EGT temperature certification of 915 degrees centigrade. This gives the engine up to a 25 degree higher EGT margin.

The lowest rated -5A4 engine has an installed EGT margin of 55 degrees centigrade, while the -5A4/F has an installed margin of 80 degrees centigrade. The -5A5 has a margin of 50 degrees, and the -5A5/F an EGT margin of 75 degrees. The -5A1 has a margin of 57 degrees, and the -5A1/F a margin of 82 degrees. The -5A3, which has not had the /F upgrade, has an EGT margin of 71 degrees *(see table, page 18)*.

New production -5B3 engines, rated at 32,000lbs thrust, have an installed EGT margin of 66 degrees. This increases to 95 degrees for the -5B2 rated at 31,000lbs thrust, and is 115 degrees centigrade for the -5B1 rated at 30,000lbs thrust.

EGT margins generally increase with reduced thrust ratings. The -5B4 and -5B7 rated at 27,000lbs have an initial margin of 109 degrees, while the -5B6 rated at 23,500lbs and used to power the A319, has an EGT margin of 145 degrees centigrade. The -5B5 has a new margin of 163 degrees, and the -5B8 and -5B9 at higher ratings have margins of up to 180 degrees *(see table, page 18)*.

The EGT margins are therefore high on most -5B variants, with only the -5B1, -5B2 and -5B3 variants generally experiencing a loss of EGT margin that forces removals for shop visits.

EGT margins, however, are measured at different corner point temperatures. The engine's EGT and EGT margin are kept constant at all outside air temperatures (OATs) above this corner point temperature. This is achieved by the engine's FADEC reducing engine thrust as OAT rises. Thrust is kept constant below the corner point temperature, so EGT margin varies with OAT. EGT changes at a rate of 2.9-3.4 degrees per degree of OAT for the -5A and -5B series.

The corner point temperature is where the EGT is the highest when operating at maximum thrust. An engine with a high corner point temperature will be able to operate at maximum thrust in a higher OAT, compared to an engine with a lower corner point temperature, which will have to operate at less than maximum thrust when experiencing the same OAT.

The corner point temperatures for EGT margin measurement differ for the four -5A and nine -5B variants. The EGT margins and their respective corner point temperatures are summarised *(see CFM56-5A/-5B specifications, page 6)*. The lower rated variants have higher corner point temperatures, as well as higher EGT margins.

Because engine thrust reduces from its maximum level at OATs higher than the corner point, the aircraft's performance becomes more limited as OAT rises. The aircraft may therefore suffer a take-off weight and payload limitation at high ambient temperatures. Engines with a higher corner point temperature may still be able to operate at maximum thrust, while engines with lower corner point temperatures will have to operate at less than maximum thrust.

The -5A4 has a corner point temperature of 45 degrees centigrade (113 degrees Fahrenheit), the -5A5 a corner point of 37 degrees (99 degrees Fahrenheit) and the -5A1 and -5A3 a corner point of 30 degrees centigrade (86 degrees Fahrenheit).

Similarly, the -5B8, -5B9, -5B5, -5B6, -5B7 and -5B4 which power the A318, A319 and the A320 all have corner point temperatures of 45 degrees centigrade. The -5B1, -5B2 and -5B3 have corner point temperatures of 30 degrees.

The implications of this are that A320s equipped with -5A1 and -5A3 engines, and A321s powered by -5B1, -5B2 and -5B3 engines, will have low EGT margins that will limit shop visit intervals.

The drop in engine EGT below the corner point temperature increases the EGT margin available when operating at OATs lower than the corner point.

Restored EGT margin

Besides the EGT margins of new production engines, operators have to consider the EGT margins of engines

CFM56-5A & -5B EGT MARGINS

Engine variant	-5A3	-5A1/ -5A1F	-5A5/ -5A5F	-5A4/ -5A4F
Thrust lbs	26,500	25,000	23,500	22,000
Application	A320	A320	A319	A319
Initial EGT margin (deg C)	71	57/82	50/75	55/80
Restored EGT margin (deg C)	42-56	34-45 49-65	30-40 45-60	33-44 48-64

Engine variant	-5B3	-5B2	-5B1	-5B7	-5B4	-5B6	-5B5	-5B8
Thrust lbs	32,000	31,000	30,000	27,000	27,000	23,500	22,000	21,600
Application	A321	A321	A321	A320	A320	A319	A319	A318
Initial EGT margin (deg C)	66	95	115	109	109	145	163	180
Restored EGT margin (deg C)	40-52	57-76	69-92	65-87	65-87	87-116	98-130	108-144

following a shop visit. The margin of the new production engines cannot be reattained, and the percentage of the original margin that can be regained depends on the shop visit workscope. Clearances between blade tips and engine casings, for example, will increase the EGT margin that is recovered, but the rate of initial EGT margin loss that is experienced following a shop visit will generally be high.

Virtually all the -5A series engines have been through their first shop visit, while the first -5B series engines were delivered in 1993. The early produced engines have been removed for at least two shop visits, while later built engines will have only been removed for their first shop visit. The youngest engines will have not yet been removed, which means that the shop visit experience of later built engines is limited.

Maisonneuve estimates that the restored EGT margin following the first shop visit is only 60-80% of the initial margin, depending on the workscope. “Only 60% can be regained if a hot section restoration is carried out, but a higher recovery of 80% can be realised if a full performance restoration is performed. A hot section restoration is usually performed for most engines at the first removal, and then a full performance restoration is usually made at subsequent shop visits. The workscope selected is influenced by the EFH interval, EFH:EFC ratio, as well as the remaining LLP lives, since the EGT margin will affect the on-wing life,” explains Maisonneuve.

Jesus explains that the initial shop visits applied to the first engines off the production line were to replace early HPT blades installed in the engines. “These engines then had a second removal interval after which engines reached their LLP limits, and a core performance restoration which resulted in a better EGT margin recovery. Later built engines, with improved HPT blades, experienced longer first intervals. The -5B3 will have an average EGT margin of 40 degrees centigrade following a shop visit, but the scatter around this average will be 20-60 degrees centigrade. The -5B4 engines will have an average margin of 70 degrees, and the -5B5 an average of 130 degrees following a shop visit.”

Take-off de-rate

Engine thrust is often less than the maximum rating at take-off. Take-off thrust de-rate is often applied for moderate temperatures, and when the aircraft is operating at a take-off weight less than maximum and from long runways. It also prolongs on-wing life. The average EFC time of 1.8EFH for many operations means that most aircraft are being flown on routes that are a fraction of their maximum range. “We can apply up to 18% derate in our operation,” says Jesus. “We have a mix of -5A1s, -5B3s, -5B4s, -5B5s, and -5B6s in our fleet and we can apply rates of derate ranging from 11.4% to 18.3% in our trans-European operation.”

Finnair, which also has an average EFC time of 2.0 EFH, has an average de-rate of about 10%.

The effect of derate on prolonging engine on-wing life can be anticipated using a severity curve, which predicts relative rates of engine deterioration in relation to average EFC time and take-off derate. The severity curve shows that engines operating at an average EFC time of 1.9EFH will have a 10% reduction in severity when increasing de-rate from 5% to 10%, and a further 7% reduction in severity when increasing de-rate to 15%. The same 10% reduction in severity can be experienced for engines with a 5% de-rate, but a longer EFC time of 2.6EFH.

“Data shows that a 6% de-rate can increase on-wing life by 10% compared to zero de-rate, and increasing de-rate to 15% will increase on-wing life by 25%,” says Maisonneuve.

EGT margin deterioration

EGT margin loss is often a prime removal driver for engines operated on short-haul missions. While the average EFC for all operators is 1.8EFH, some airlines have cycles as short as 1.0EFH, while others are as long as 3.0EFH.

The rate of EGT margin deterioration is affected by average EFC time. As with most engine types, the initial loss of EGT margin is highest in the first 500-1,000EFC on-wing following a shop visit. Rates then reduce to a more steady level.

“The -5A3 loses eight degrees of EGT margin per 1,000EFC for the first 2,000EFC on-wing. This rate then slows to three degrees per 1,000EFC thereafter,” says Lothar Haertel, propulsion system engineering CFM56-5A at Lufthansa Technik. “The -5A1 has a higher rate of 10-11 degrees per 1,000EFC during the first 2,000EFC on-wing, and the rate reduces to four degrees per 1,000EFC. The lower rated -5A5 has the slowest rate of EGT margin loss. In the first 2,000EFC it loses six degrees of margin per 1,000EFC, and then slows to 2-3 degrees per 1,000EFC.”

The -5B1/2/3 engines powering the A321 have the highest rates of EGT margin loss of the -5B series variants. “These average 12-13 degrees centigrade in the first 1,000EFC on-wing, and then reduce to 5-6 degrees per 1,000EFC thereafter,” explains Karhumaki. “This means that these engines will have lost 20 degrees of EGT margin after 3,000EFC on wing, which is a lot of the initial margin. This also means that after 6,000EFC on wing the highest rated -5B3 engines will only have 10 degrees of EGT margin left. A -5B3 will therefore lose all its initial margin of 60 degrees after 9,000-11,000EFC in most operations, since the mature rate of EGT margin loss is 3-4 degrees per 1,000EFC.” The highest rated -5B3 will lose all its EGT margin before reaching the life limit of the LLPs with the shortest lives. “In the case of all engines except the early production engines, the shortest LLP lives are 15,000EFC. It is expected that performance problems or fully eroded

EGT margin will start to occur before an interval of 15,000EFC is reached," says Jesus. "The -5B3 can normally last for 10,000-11,000EFC before all EGT margin is lost. It is possible for some engines to reach LLP limits before losing all their EGT margin. The engine can, however, be re-rated to a lower thrust for the A320 or A319 and get another 5,000EFC on wing, up to a total time of 15,000EFC, before being removed."

Karhumaki reiterates the value of re-rating the highest rated -5B3 and -5B2 engines to get the maximum possible on-wing intervals. "We test all our engines at the -5B3 rating to see its EGT margin, but we also test them for lower ratings. The EGT margins are higher when the engines are derated, and there are some -5B6 engines that still have margins of 80-100 degrees after having been on wing for several thousand EFC. We re-rate engines used on the A321s after they have used most of the available EGT margin. They last 10,000-12,000EFH, which is 6,000-7,000EFC in our operation. They are then re-rated at 23,000lbs or 27,000lbs and regain about 60 degrees of EGT margin at this point, and can probably last about another 10,000EFH or 6,000EFC."

The lower rated -5B2 and -5B1 engines will lose EGT margin at about the same rate as the -5B3 engines, but the -5B1 and -5B2 engines have higher margins of 115 and 95 degrees centigrade, so they will still have 35-55 degrees of EGT margin left after 9,000EFC on-wing. These engines may therefore be able to reach the shortest LLP limit of 15,000EFC before losing all their EGT margin.

The initial rates of loss for -5B4 engines powering the A320 are similar to the higher rated -5B1/2/3 engines in the first 1,000EFC, but have a lower mature rate of loss. "The EGT margin loss curve is less pronounced than for the higher rated engines, and on average a -5B4 will have lost 38 degrees after 9,000EFC on-wing," says Jesus.

"Initial rates in the first 1,000EFC are slightly lower for -5B5 and -5B6 engines powering the A319s, and are 11-12 degrees," continues Jesus. "Total loss is 16 degrees after 2,000EFC, and reaches 30 degrees after 9,000EFC. Mature rates of loss are 3 degrees per 1,000EFC for these lower rated engines. Moreover, these engines have initial and post shop visit margins in excess of 100 degrees centigrade, so they have enough EGT margin to remain on wing for up to 30,000EFC. This exceeds the life limits of LLPs."

Possible or probable removal intervals that are determined by EGT margin would ideally be matched to LLP lives. LLP lives therefore have to be taken into consideration.

RANGE OF LLP LIVES FOR ALL CFM56-5A VARIANTS

Engine variant	-5A1/ -5A1/F	-5A3	-5A4/ -5A4/F	-5A5/ -5A5/F
Fan disk	25-30	23-30	25-30	25-30
Booster spool	22.4-30	21.1-30	21.1-30	21.1-30
Fan shaft	30	30	30	30
Front shaft	20	20	20	20
Stage 1-2 spool	20	20	20	20
Stage 3 disk	20	20	20	20
Stage 4-9 spool	20	20	20	20
Compressor CDP seal	20	20	20	20
Front shaft	20	20	20	20
Front air seal	8-17.8	7.7-17.8	8-17.8	8-16.7
HPT disk	9.1-19.5	7.1-17.3	9.1-17.3	9.1-17.3
Rear shaft	19.5-20	18.5-19.5	18.5-19.5	18.5-19.5
Stage 1 disk	25	25	25	25
Stage 2 disk	25	25	25	25
Stage 3 disk	25	25	25	25
Stage 4 disk	25	25	25	25
Shaft	25	25	25	25
Conical support	11.3-25	25	19.8-25	19.8-25

Life limited parts

The -5A series has 18 LLPs: three in the fan/booster module, five in the high pressure compressor (HPC) module, four in the HPT, and six in the low pressure turbine (LPT). These 18 parts have a total list price of $1.75 million, split between $375,000 for fan/booster parts, $460,000 for HPC parts, $419,000 for HPT parts and $500,000 for LLP parts.

The -5B series also has 18 LLPs, with the same number in the four main modules as the -5A. The -5B's full set of LLPs has a list price of $1.83 million, split between $406,000 for fan/booster parts, $447,000 for HPC parts, $474,000 for HPT parts and $503,000 for LPT parts.

Certain turbine rear frame and LPT case part numbers also have limited lives in some -5B variants. These are limits between 14,900EFC and 30,000EFC, and their list prices total $404,000.

CFMI's LLP policy is to set target lives of 30,000EFC for LLPs in the fan/booster module, target lives of 20,000EFC in the HPC and HPT modules, and target lives of 25,000EFC in the LPT module. The latest /3 engines, which will start being manufactured in late 2007, will have all their LLPs certified at these targets from the start.

Many of the LLPs of earlier produced engines have lives restricted to less than the target lives. CFMI's objective, however, is to get these restricted lives removed or gradually extended during operational experience. This will be done by testing LLPs removed from leading high time engines, with the aim of extending the lives of the LLPs in most engines before they reach their restricted life limits.

Each LLP can have up to 13 different part numbers. Some part numbers have been introduced after lives on earlier part numbers were continuously restricted. There is a wide range of life limits for each LLP, and the life limit for an individual engine will depend on the part number installed. The range of lives allowed for the various part numbers for each LLP in the -5A and -5B engines is summarised *(see tables, pages 19 & 20)*.

These tables disguise the fact that some LLPs have part numbers with short lives, others have part numbers with long or complete target lives, and there are also some part numbers with a wide range of lives.

The -5A series is relatively simple with just four main variants and only seven variants overall. The LLPs in the fan/booster and LPT modules are all at or close to their target lives of 30,000EFC and 25,000EFC. There are a few part numbers for the fan disk and booster spool which have lives of 21,100-28,600EFC, and a few in the LPT which have lives of 11,300EFC and 19,800EFC, however. All parts in the HPC module have their target lives of 20,000EFC *(see table, this page)*.

The HPT, however, has parts with the most limitations. "The -5A series has had a problem with the front rotating air seal. The part in the first -5A1s had a life of 15,300EFC, but cracks reduced the life to 11,000EFC," explains Haertel. "There are other part numbers with lives as short as 8,000EFC, 9,000EFC and 15,000EFC. The part number with the longest life has a life of 17,800EFC. This particular part

RANGE OF LLP LIVES FOR ALL CFM56-5B VARIANTS

Engine variant	-5B1	-5B2	-5B3	-5B4	-5B5	-5B6	-5B7	-5B8	-5B9
Fan disk	23-25	20-23	20	20-25	23-25	20-25	20-25	24.7-25	24.7-25
Booster spool	30	30	30	30	30	30	30	30	30
Fan shaft	30	30	30	30	30	30	30	30	30
Forward shaft	20	20	20	20	20	20	20	20	20
Stage 1-2 spool	20	20	20	20	20	20	20	20	20
Stage 3 disk	18.2-20	18.2-20	18.2-20	18.2-20	18.2-20	18.2-20	18.2-20	18.2-20	18.2-20
Stage 4-9 spool	15.6-20	15.6-20	20	15.6-20	15.6-20	15.6-20	14-20	20	20
Compressor CDP seal	17.2-20	17.2-20	17.2-20	20	20	20	20	20	20
Front shaft	14.6-20	14.3-20	14.3-20	14.3-20	14.6-20	14.6-20	7.7-20	17.6-20	17.6-20
Front air seal	17.7-20	17.7-20	20	17.7-20	17.7-20	17.7-20	7.9-20	20	20
HPT disk	14-20	14-20	15.3-20	14-20	14-20	14-20	6.4-20	13.1-20	13.1-20
Rear shaft	9.8-20	9.8-20	12.4-20	9.8-20	9.8-20	9.8-20	7.1-20	12-20	12-20
Stage 1 disk	25	25	25	25	25	25	25	25	25
Stage 2 disk	25	25	25	25	25	25	25	25	25
Stage 3 disk	25	25	25	25	25	25	25	25	25
Stage 4 disk	25	25	25	25	25	25	25	25	25
Shaft	25	25	25	25	25	25	25	25	25
Conical support	15.1-25	15.1-25	24.9-25	15.1-25	24.9-25	15.1-25	24.9-25	25	25

has limited the on-wing intervals achievable by the -5A series engines. With the HPT disk, some part numbers have lives of 7,100EFC and 9,100EFC. Others have longer lives of 17,300EFC or 19,500EFC."

The -5B series is more complex. The six variants of the original -5B engines have mainly part numbers in the fan/booster, LPT modules and HPC modules that are close to their target lives. There are parts in the HPC that are limited to 15,600EFC, however. Most HPT parts have lives close to the target of 20,000EFC, but some part numbers for the rear shaft are limited to 9,800EFC.

There are four sub-variants of the /P group of engines. Most part numbers for the fan disk have lives of 20,000-25,000EFC. All other part numbers in the fan/booster module have lives of 30,000EFC. Similarly, all part numbers for LPT parts have lives of 25,000EFC. Most HPC part numbers have lives of 20,000EFC, but a few are limited to 17,200-18,200EFC *(see table, this page)*. The HPT is the limiting module, with some part numbers having lives as short as 12,000-15,300EFC, and presenting a probable limitation to on-wing life for engines with these parts installed.

The caveat to the currently restricted part numbers is that they may yet have their lives extended. "CFMI will publish a notice that lists a group of part numbers, their current and projected life limit, and the expected date of life limit extension," explains Kleinhans, propulsion systems engineering CFM56-5B at Lufthansa Technik. The /3 engines will all have parts that are at the target lives.

Removal causes & intervals

-5A series

The -5A series has been limited by the LLP limits of the front rotating air seal and HPT disk. Some part numbers of the front rotating air seal had their limit reduced to 11,000EFC in the -5A1, 7,700EFC in the -5A3 and 9,100EFC in the -5A5. Other part numbers for this part also have restricted life limits.

"The -5A series has good EGT margin, but the LLP lives and other problems like HPT blades are still a major removal cause," says Haertel. The restored EGT margin for -5A1s and -5A5s is 45-52 degrees, and for -5A3s is 62-67 degrees. This should allow the -5A1 to remain on-wing for up to 9,000EFC, the -5A3 for up to 17,000EFC, and the -5A5 for up to 13,000EFC.

The -5A has faced other difficulties, however. Most -5As were built between 1987 and 1995, although a small number were produced up to 2003. Most engines accumulate 1,700EFC per year, so virtually all -5As will have been through their first shop visit, and most will have been through their second and third removals.

"Besides the limits imposed by the two LLPs, the early -5As had a problem with the HPT nozzle guide vanes, and our first -5A1s only lasted for 4,000EFH on-wing," says Haertel. "The HPT blade has also been a consistent problem, with successive blades having short lives. The original HPT blade in the original engines suffered cracks in the airfoil trailing edge cooling air exit slot just above the blade platform. These HPT blades were replaced with a second generation blade which utilised a DSR142 material. These also experienced problems, however, so a third generation HPT blade was introduced with a platinum-aluminium coating, although the on-wing life was limited to 14,400EFC, as recommended by CFMI. Several blade fractures had occurred and a service bulletin (SB) cancelled all repairs.

"There is now a fourth generation HPT blade, which uses an N5 single crystal material. These are expected to have an on-wing life of 10,000-12,000EFH, after which a repair to the blades will allow a second run of similar duration. A third run may be possible following a second repair, but I think it is more likely that the blades will have to be replaced after the second removal," continues Haertel. "This interval will be an extension of the current mature interval, which is in the region of 8,000-9,000EFH. This is equal to 6,800-8,200EFC in our operation at an average EFC time of 1.1-1.2EFH."

Maisonneuve makes the point that -5As operating on average EFC times up to 2.0EFH can remain on wing up to their respective forward air seal LLP limits of 7,700-11,000EFC. This is equal to 15,500-22,000EFH for engines operating at 2.0EFH per EFC. Even when operating at longer average cycle times, the time on wing is not expected to exceed 22,000EFH for the -5A1, -5A4 and -5A5 engines due to deterioration of engine hardware. The highest rated -5A3

Finnair is in operator that practices re-rating of engines between different thrust ratings. It re-rates -5B3 engines used on the A321 to lower ratings to then be used on the A320 or A319. This allows them to accumulate about 6,000EFC while operating on the A321, and then achieve another 6,000EFC on the A320 or A319.

engines average 15,500EFH on wing.

The -5A series has now reached maturity in most cases, and has an average interval of 9,000EFH and 8,000EFC for a 1.1EFH operation. With this interval the core LLPs would require replacement every second shop visit, after an interval of 16,000EFC. The LPT and fan/booster LLPs would have to be replaced every third shop visit, after an interval of 24,000EFC *(see table, page 19)*.

In this case, the engine could conform to a simple alternating shop visit pattern of a performance restoration followed by an overhaul. A heavier core workscope would be required at the second shop visit to replace LLPs. It may be possible to leave the LPT until the third shop visit, but a workscope is likely to be required at the second. The fan/booster can usually last until the third shop visit *(see table, page 19)*.

If the fourth generation, single-crystal HPT blade extends the removal interval to 10,000-20,000EFH as Haertel predicts, then at the same EFC time of 1.1EFH, the interval of 9,000-11,000EFC will allow all core LLPs to be completely used and LPT LLPs to be scrapped every second shop visit. Fan/booster LLPs would therefore have to be replaced every third shop visit having utilised all their life. This would allow an alternating shop visit pattern of core performance restoration and overhaul for the core modules. A full disassembly and overhaul would be required on the LPT every second shop visit, while the fan/booster modules would have a full disassembly at the third removal.

A321 -5B engines

The -5B series has not experienced the same degree of mechanical and parts-related problems that the -5A series has. The first and subsequent on-wing intervals are expected to be limited by EGT margin degradation and LLP expiry.

The highest rated -5B3, with an EGT margin of 66 degrees, can theoretically last up to 11,000EFC for its first interval with the rates of EGT margin degradation described. "We can run our -5B3 engines for up to 14,000-16,000EFH, or 7,000-8,000EFC, before EGT margin expires. These engines will lose 20-22 degrees of EGT margin in the first 3,000EFC on-wing, and will be left with only 40 degrees. We will lose another 18 degrees in the following 3,000EFC, and so only have 10 degrees left after 6,000EFC. All the -5B3's EGT margin will be eroded after 7,000-8,000EFC," says Karhumaki. "We then regain 60 degrees centigrade of EGT margin by re-rating them to 22,000-27,000lbs thrust for the A319 and A320. This way they can possibly get another 10,000EFH or 5,500EFC on wing before losing all their performance. This would be a total time of up to 24,000-26,000EFH and 12,500EFC."

TAP has so far not experienced any problems with its -5B3 engines, which were first delivered in 2001. "There tends to be full performance loss for -5B3 engines after 11,000-13,000EFC, equal to 22,000-26,000EFH in our operation," says Jesus. "These engines can then be re-rated for the A320 or A319 so they can completely use LLP lives. Some LLPs in the HPT module are limited to 12,000-13,000EFC.

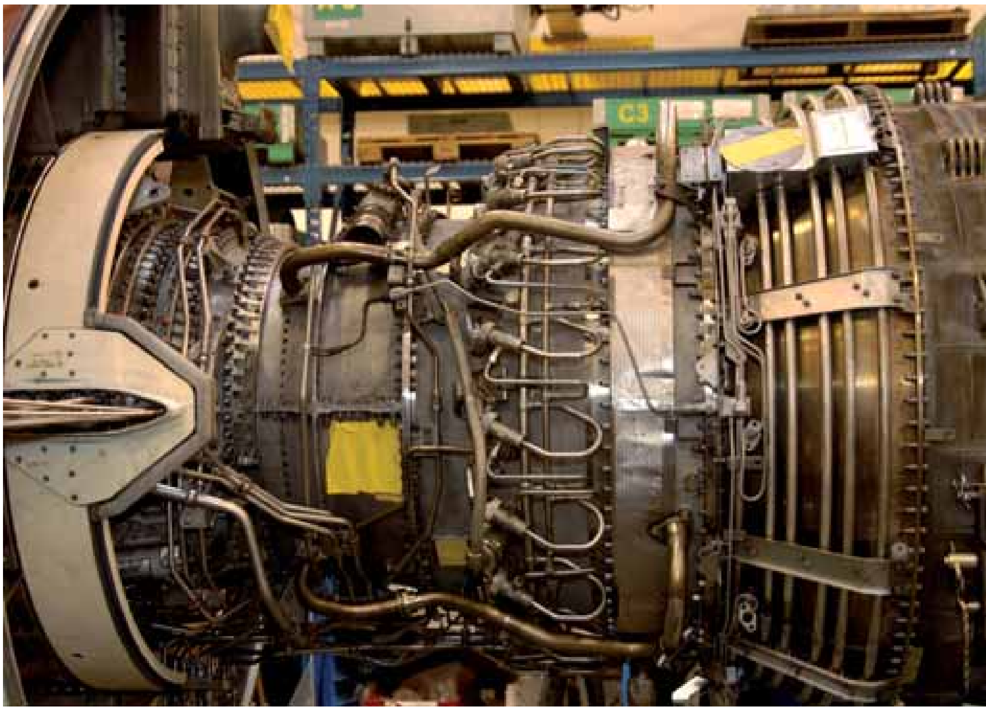
"When following this policy of re-rating the engines to get up to 15,000EFC on wing, we have to consider the remaining lives of other LLPs," continues Jesus. "This will be just a few thousand EFC for core LLPs, so these will be replaced at the first shop visit. The next limit is the 25,000EFC for LPT parts, so we aim to get to this limit on the second run, which means a second interval of 10,000EFC."

Kleinhans estimates that the -5B3's first removal interval is limited by EGT margin, which is up to 14,000EFC. "This would mean replacing all core LLPs at this stage so as not to limit the second interval to just 6,000EFC. The second interval would be limited by the LPT LLPs, and a maximum of 11,000EFC. If the engines only manage 9,000-10,000EFC for their first run, then the core LLPs would be left in the engine and the second run would be determined by LLP limits. This might only be optimal, however, if the core LLPs had remaining lives of at least 8,000EFC. If we re-rate engines after they have used their EGT margin at a high rating, so that we can use the full 20,000EFC lives of their core LLPs, we must take into consideration the fact that mechanical problems start to arise once engines have been on wing for longer than 25,000EFH." One example is the degradation of variable stator vane (VSV) bushings in the HPC. An interval of 20,000EFC is equal to 36,000EFH for an average cycle time of 1.8EFH. Re-rating might therefore be more practical for shorter cycle operations, where the limit of 25,000EFH coincides with the total cycles accumulated at the two ratings for the A321 and the A320/319.

The target would be for the engine to achieve 10,000EFC in the first interval before being re-rated for the A320/A319 to gain another 5,000EFC, or an interval up to the first core LLP limit after a total time of 15,000EFC. Core LLPs would be replaced at this shop visit, and a relatively heavy workscope would be used to regain the maximum possible EGT margin. LPT LLPs would limit the second interval to 10,000EFC *(see table, page 26)*.

A second interval at the -5B3 rating might first allow 6,000EFC on wing, and LPT LLPs would then limit a re-rated interval to 4,000EFC. LPT and fan/booster LLPs would be replaced at this stage, meaning that full workscopes

Once engines have been through their first shop visit, subsequent removal intervals will be in the range of 10,000EFC for all variants. This will be because operators will have to compromise between EGT margin loss and maximising the use of LLP lives.



would be required on these modules *(see table, page 26)*.

All removal intervals would ideally be 10,000EFC at this stage, thereby allowing core and LPT LLPs to be replaced every 20,000EFC at every second shop visit. The core could therefore have alternating restoration and overhaul workscopes, while the LPT would only have to be worked on every second removal. Fan/booster LLPs would be replaced every third shop visit at 30,000EFC, when this module was fully disassembled *(see table, page 26)*.

The -5B2 and -5B1 have initial EGT margins of 95 and 115 degrees, so they could last up to 15,000EFC and 19,000EFC, and remain on wing up to their first LLP limit. These intervals could be equal to 27,000-34,000EFH, however, and the engines would be expected to start experiencing mechanical degradation problems after 25,000EFH. All core LLPs would then be replaced at the first shop visit, which would be a full core disassembly and workscope.

In the case of the -5B2, the LPT LLPs would be left in, and would influence the length of the second interval. Assuming the -5B2 could regain an EGT margin of 57 degrees after the first shop visit, its second interval would be 8,000EFC. This would be a total time of 21,000-23,000EFC. The core would require a performance restoration, while the LPT would need a full workscope to replace LLPs.

The third interval would be 7,000-8,000EFC, so the core LLPs installed at the first shop visit would require replacement. The core would therefore require a full workscope, as would the fan/booster module which would need to have its LLPs replaced.

The mature engine would require core LLPs to be replaced every second shop visit, LPT LLPs every third and fan/booster LLPs every fourth shop visit.

In the case of the -5B1, the LPT parts would probably be left if the first interval was up to 17,000EFC, but they would be replaced if the interval was longer than this, in which case the second interval would be limited to 30,000EFC. The -5B1 can be expected to have an EGT margin of 70 degrees after the first shop visit, and so have an EGT limited interval of up to 10,500EFC.

A shorter first run and lower subsequent EGT margin would mean the second interval would be up to LPT LLP replacement, as in the case of the -5B2. The optimal removal intervals and shop visit pattern for maximising LLP life utilisation are similar to those described for the -5B2.

A320 & A319 -5B engines

The lower rated -5B series engines have high enough initial EGT margins to remain on wing up to the limits of core LLPs. This is even the case where all core LLPs are 20,000EFC. "We did have some initial -5Bs engines with HPT blade problems that forced early removals, and 22 had their first shop visits before reaching 11,000EFC. It is possible for later build engines to get to their first LLP limit of 15,000EFC," says Jesus. "This is equal to 27,000EFH on wing for our operation. Mechanical degradation problems start to emerge after this amount of time on wing, however. Contact between the rotors and stators in the HPC due to VSV bushing attachment wear starts to occur after 24,000EFH. The interstage seal metal sheet can wear through due to this contact and go into the flowpath. We therefore start borescope inspections after 18,000EFH on-wing, and get findings at this stage. Engines can just about stay on wing for 15,000EFC and 27,000EFH."

Kleinhans estimates that -5B4/P and -5B7/P engines operating at cycle times of 1.0EFH have enough EGT margin to allow first intervals of 18,000EFH and 18,000EFC, although some core LLPs in the /P engines have lives as short as 12,000EFC. This will change to 14,000-15,000EFC and 25,000EFH for engines operating at cycle times of 1.8EFH. First removal intervals would not be much longer than 25,000EFH for aircraft operating at longer cycle times. The same applies to -5B5, -5B6, -5B8 and -5B9 engines with lower ratings.

The -5B4 and -5B7 would have restored margins of 84 degrees, so second intervals would last 11,000-12,000EFC on wing. This will influence the first shop visit workscope. "The rate of EGT margin loss in the second interval is expected to be the same as the first, but it is too early to say," says Jesus. "The aim is to take lower rated engines to the second removal at a total time of 25,000EFC, where LPT and fan disk LLPs will have to be replaced. All core LLPs will be replaced at the first shop visit."

Consideration has to be given to the two booster LLPs, which have lives of 30,000EFC. If left in the engine these would limit the third interval to just 5,000EFC. It is therefore better to replace them at this second shop visit.

If all core LLPs were replaced at the first removal after 14,000-15,000EFC, they would be replaced with new parts that had target lives of 20,000EFC in the case of most engines. The second interval would be limited to 10,000-11,000EFC because of the LPT LLPs. The objective would be to have a mature interval of 10,000EFC, with core and LPT LLPs being replaced every second removal at 20,000EFC, and booster LLPs replaced every third shop visit *(see table, page 26)*.

"While it is possible to run lower rated engines to 15,000EFC, there are several technical drivers that force removals. These are factors such as LPC blade cracking and combustor cracking," says Karhumaki. "An interval of 15,000EFC is the limit, while our top engines have reached 18,000-19,000EFH.

The three main groups of LLP lives means the CFM56-5A and -5B will not follow a simple shop visit pattern, with the fan/booster module requiring work every third shop visit, and the LPT needing a full disassembly every second shop visit.

We expect our highest time A319 engines to run to 30,000EFH and reach LLP limits, but we are assuming the average will actually only be 20,000EFH, or 11,000EFC. This will leave a stub life of 5,000EFC. There is relatively little shop visit experience with the -5B, but we have found that the LPT on all -5B variants requires work as well as the HPC and HPT modules. The fan/booster section should last to the second shop visit.

"We are one of the few operators with DAC engines. These had early reliability problems related to vibrations affecting the LPT blades," continues Karhumaki. "There was a modification programme to fix this, and the DAC is now comparable to the single annular combustor (SAC). The DAC had a modified combustor liner, and our engines have the latest combustors."

Workscope inputs

There are three main categories of inputs: labour; cost of materials and parts; and cost of sub-contract repairs. The amount of labour used varies according to the percentage of parts being replaced and their associated cost. There is also a converse relationship between the cost of materials and labour versus the cost of sub-contract repairs, since a shop that performs a large number of repairs on parts will use a lot of its own labour and materials, and spend less on sub-contract repairs. The opposite is true for shops that do relatively few parts and component repairs.

There are four main types of workscope: a core or performance restoration; an LPT module workscope; a fan/booster module workscope; and a full engine overhaul, which includes all modules. There are lighter and heavier inputs for each of these four types.

For the -5A engine, the amount of labour for a performance restoration will vary from 1,900 man-hours (MH) for a light workscope up to 2,800MH. Using a standard labour rate of $70 per MH the resulting labour cost will be $133,000-196,000. Similarly, the cost of materials varies from $650,000 for a light workscope to as much as $900,000 for a heavy workscope performed by a shop that does few sub-contract repairs. The total cost for the shop visit will be $1.1-1.35 million.

A medium fan/booster module workscope on the -5A will use a total of 200-250MH, while a heavier one can require more than 300MH, incurring a labour cost of $15,000-22,000. The cost of materials will be $100,000 and sub-contract repairs $10,000-20,000, taking the total cost of the workscope to $140,000.

A light LPT workscope on the -5A series will use 250-300MH, costing $18,000-20,000. Additional materials will be $150,000 and sub-contract repairs $50,000, taking the total cost to $220,000. A heavier workscope uses up to 550MH, uses $200,000 of materials, and up to $40,000 of sub-contract repairs, taking the total cost to about $280,000.

A full overhaul on the -5A will use 3,700-4,400MH, depending on several factors. This will incur a labour cost of $260,000-310,000. The cost of materials will vary from $1.1-$1.5 million, while sub-contract repairs will be $120,000-$450,000, depending on shop capability. This will take the total cost to $1.7-$2.25 million.

The associated costs for the same workscopes for the -5B series are marginally higher than for the -5A series engines. A performance restoration, for example, will use more labour and materials, increasing the total cost by $100,000.

The related cost for the fan/booster module will be $10,000-20,000 higher, while the cost for the LPT will be $50,000 higher.

An overhaul is expected to use $200,000 more in material and sub-contract repairs than a -5A, while using a similar amount of labour.

Unscheduled removals

Unscheduled removals fall into several categories. The first two main types are are engine-related and non engine-related. Engine-related removals are forced by the failure of engine hardware, and are further sub-divided into light and heavy visits following removal.

Light visits will usually involve incidents such as oil leaks, and will incur a shop visit cost of up to $300,000. Heavy visits can be the result of an event such as a bearing failure, which can incur some of the highest shop visit costs, and exceed more than $2 million.

Non-engine related removals will be due to events such as foreign object damage (FOD) and birdstrikes. These will require a similar shop visit workscope to heavy engine-related removals and cost in excess of $2 million. Light visits do not interrupt planned removals and removal patterns, so they can be considered separately. Heavy and non-engine related visits should be considered together because they incur shop visit workscope costs, interrupt the schedule of planned removals and shop visits, and also reduce the average planned removal interval.

All unscheduled removals occur at an average of once every 30,000EFH. An average cost of $250,000 would mean that a reserve of $9 per EFH should be added to the reserve for planned removals.

Heavy and non-engine related events occur on average once every 70,000EFH. An engine, for example, with an average planned removal interval of 17,500EFH would therefore see an unplanned heavy shop visit once every four shop visits. The randomness of these unplanned heavy events, however, means that they can occur shortly before a planned event or halfway between planned events, thereby

CFM56-5A/5B SERIES SHOP VISIT MANAGEMENT & MAINTENANCE RESERVES

Removal	First	Second	Third
CFM56-5A series			
EFH:EFC ratio	1.2	1.2	1.2
Removal interval-EFC	8,000	8,000	8,000
Removal interval-EFH	9,600	9,600	9,600
Accumulated interval-EFC	8,000	16,000	24,000
Shop visit workscope	Performance restore	Core overhaul & LPT	Performance restore & fan/booster
Shop visit cost-$	1,150,000	1,500,000	1,300,000
LLP replacement	-	Core	LPT & Fan/booster
LLP cost-$	-	880,000	875,000
Shop visit reserve-$/EFC	144	188	163
LLP reserve-$/EFC	92	92	92
Total reserve-$/EFC	236	280	255
Total reserve-$/EFH	196	233	212
Average reserve-$/EFH including unscheduled shop visits	240	240	240
CFM56-5B3/2/1			
¶			
EFH:EFC ratio	1.8	1.8	1.8
Removal interval-EFC	15,000	10,000	10,000
Removal interval-EFH	27,000	18,000	18,000
Accumulated interval-EFC	15,000	25,000	35,000
Shop visit workscope	Core overhaul	Full overhaul	Performance restore
Shop visit cost-$	1,400,000	2,100,000	1,250,000
LLP replacement	Core	LPT & Fan/booster	Core
LLP cost-$	921,000	909,000	921,000
Shop visit reserve-$/EFC	93	210	125
LLP reserve-$/EFC	99	83	86
Total reserve-$/EFC	192	293	211
Total reserve-$/EFH	107	163	117
Average reserve-$/EFH including unscheduled shop visits	150	150	150
CFM56-5B4/7/6/5/9			
EFH:EFC ratio	1.8	1.8	1.8
Removal interval-EFC	15,000	10,000	10,000
Removal interval-EFH	27,000	18,000	18,000
Accumulated interval-EFC	15,000	25,000	35,000
Shop visit workscope	Core overhaul	Core restore, LPT & fan	Core overhaul
Shop visit cost-$	1,400,000	1,600,000	1,400,000
LLP replacement	Core	LPT & Fan/booster	Core
LLP cost-$	921,000	909,000	921,000
Shop visit reserve-$/EFC	97	145	140
LLP reserve-$/EFC	104	89	87
Total reserve-$/EFC	201	234	227
Total reserve-$/EFH	111	130	126
Average reserve-$/EFH including unscheduled shop visits	145	145	145

simply reducing the average planned interval, rather than adding a full additional shop visit. Such unplanned heavy events have therefore been budgeted for by increasing maintenance reserves by adding the equivalent cost of half a shop visit to the number of planned shop visits over the 70,000EFH interval.

Maintenance reserves

These have been calculated using the removal intervals, shop visit workscope patterns and LLP replacement timings described. The -5A has been examined as a mature engine, with an interval of 8,000EFC, and an average cycle time of 1.2EFH. The -5B series has been examined as new, and with consequent maintenance over the second to fourth removals. The -5B series has been examined with the -5B1 being used first on the A321 and then re-rated for the A320 or A319 to maximise removal interval, and the -5B2/-5B1 being used on just the A321, as all other lower rated variants can achieve longer removal intervals. All -5B variants have been examined at an average cycle time of 1.8EFH.

Both time on wing and thrust rating influence the cost of a shop visit, and so maintenance reserves. This is because thrust rating has an impact on the scrap rate of engine airfoils. Costs can vary by 30% between the lowest and highest rated engines. The -5B9 or -5B6, for example, would have lower airfoil scrap rates than the -5B4. The lower rated engines would then have lower reserves, despite possibly having similar removal intervals.

The cost of a shop visit will also rise for longer intervals. Costs start to rise when airfoil coatings start to fail, which causes a rapid rate in the scrap rate of airfoils. Both interval and parts scrap rates have to be taken into account when considering maintenance reserves.

Reserves for the -5A series engines are compromised by the expected interval of 8,000EFC. This forces core and fan/booster LLPs to be replaced with a remaining stub life of 4,000-6,000EFC. This puts LLP reserves to an average of $91 per EFC. The short removal intervals put the shop visit cost reserves at a high level. The overall effect is for an average reserve of $268 per EFC, which is equal to $223 per EFH when operated at a cycle time of 1.2EFH.

This reserve increases to $240 when reserves for heavy unscheduled visits are added *(see table, this page)*. A further reserve of $9 per EFH should be added for light unscheduled removals.

Reserves for planned shop visits on the -5A series would fall by $14 per EFH to $206 per EFH if the interval could be extended to 9,000EFC, as is expected by the fourth generation HPT blade.

Reserves for the -5B3 can be minimised by achieving the expected mature interval of 10,000EFC that will allow the lives of most LLPs to be fully used. Shop visit reserves will also be kept low by the long removal intervals that are possible by re-rating the engine. The overall reserves for planned maintenance are $131 per EFH, but these are increased to $150 per EFH when heavy unscheduled visits are budgeted for *(see table, this page)*. An additional $9 per EFH should be added for light unscheduled removals.

The -5B2's and -5B1's higher EGT margins can allow them longer on-wing lives than the -5B3. This should allow the -5B2 and -5B1 to have similar planned intervals to the -5B3 without having to be re-rated to lower thrust ratings, or to have longer intervals when re-rated. The probable limit would be 25,000-27,000EFH, equal to 14,000-15,000EFC. This potential interval is compromised, however, by the different lives of core,

Large savings for shop visit costs can be made through the use of PMA parts. These are estimated to be up to $150,000 for an overhaul.

LPT and fan/booster LLPs. The engines would therefore have to follow the same planned intervals as the -5B3 and so have similar maintenance reserves.

The lower rated engines for the A320, A319 and A318 can benefit from long intervals that allow the highest utilisation of core and fan/booster LLPs. This also provides long intervals between workscopes on all major modules. The overall reserves for planned shop visits are $126 per EFH, but these should be increased to $145 per EFH when considering heavy unscheduled removals *(see table, page 26)*. An additional $9 per EFH should be added for light unscheduled removals.

Reducing shop visit costs

Some of the CFM56-5B's main removal drivers are loss of EGT margin, particularly in the case of the higher rated engines for the A321, and mechanical deterioration. Constant improvements in parts reliability should reduce the impact of mechanical deterioration, for example in the case of HPC VSV bushings. Loss of EGT margin can be minimised by water washing, and re-rating to lower thrusts can extend on wing intervals.

The costs of shop visit inputs are dominated by the cost of parts and materials, and to a lesser extent by sub-contract repairs, which also include an element of material cost. Original equipment manufacturers' (OEMs) list prices generally increase at a rate higher than inflation. Some operators have sought to circumvent this cost by using parts manufacturing approval (PMA) components and materials. There are several providers of PMA parts and components for the CFM56-5A/-5B. "The price gap between our parts for these two engines series and the list prices of those provided by the OEMs continues to widen," says Rob Baumann, president of HEICO Parts Group. "Our prices start at 50-60% of the OEMs', but sometimes are as low as 25%, meaning a discount of 75%. The discount rates we offer on CFM56-5A/-5B parts are 25-65%.

"We supply parts mainly for the -5B, and offer about 500 different part numbers for this engine series," continues Baumann. "These range from simple consumables to shrouds, and unit prices range from $0.42 to about $15,000. Moreover, these include some of the blades and vanes used in the engine. One example is HPC blades. We are also developing other blades and vanes, which are parts that overlap with the CFM56-5C and -7B series. It is worthwhile developing these parts, since there is a global fleet of 6,000 engines in these three series. Another benefit of these engines is the long production run and in-service period.

"It is also worth noting that as the engine passes from its early years of operation to its first shop visits and then maintenance maturity, each type of part experiences different levels of demand from the market," adds Baumann. "Some parts need to be replaced at the first shop visit, while others can be repaired once or twice before being replaced. The number of different parts we can offer for the -5B will therefore continue to evolve as the engine continues in operation. Our customers so far include Air Canada, Iberia, Alitalia and Air Portugal."

Baumann estimates that PMA parts can generate savings of at least $150,000 for a heavy shop visit or overhaul, and a saving of up to $100,000 can be possible for performance restorations. This saving translates into $5-10 per EFH when considered over a series of removals and shop visit workscopes.

Summary

The costs of shop visit inputs and LLP reserves in accordance with the shop visit intervals and workscopes described are summarised *(see table, page 26)*. These are described in rates per EFH, and include an allowance for the extra maintenance required for heavy unscheduled and non-engine related shop visits. An additional $9 per EFH should be budgeted for light unscheduled shop visits.

These reserves are based on average EFC times of 1.2EFH for the -5A series and 1.8EFH for the -5B series. Reserves vary with removal intervals and shop visit workscopes, but the averages with an additional allowance for unscheduled visits are shown *(see table, page 26)*.

Reserves are influenced by EFC removal intervals, which in turn are influenced by LLP lives. High rated -5B engines therefore have reserves that are only marginally higher than lower rated engines for the A320 and A319. This is because the intervals of lower rated engines are compromised to a degree by the core engine LLPs with lives of 20,000EFC.

Reserves are high for the -5A series because EFC intervals are currently limited by HPT blade material, but also by the EFC time of 1.2EFH. EFH intervals would be longer for longer cycle times, thereby diluting reserves per EFH.

Many -5A operators have longer cycle times, and so longer EFH removal intervals, and therefore achieve lower maintenance reserves. A cycle time of 1.7EFH would bring reserves down by $40 per EFH compared to those shown.

The main benefits that /3 engines should enjoy are longer first intervals due to better EGT margin and unrestricted LLP lives. Mature engines may also be able to have longer intervals due to lower rates of mechanical deterioration, but they will continue to have removal intervals of 10,000EFC because engine maintenance will still be based around LLP limits.

CFM56-5B values & aftermarket activity

The popularity of the A320 family has led to a shortage of spare -5A and -5B engines. This has firmed up values and lease rates, and engines trade quickly.

Both the -5A and -5B series engines are in short supply, with demand for A320 family aircraft as strong as it has ever been. The supply of engines is not only affected by the percentage of the fleet in active service, but also by how many aircraft have been scrapped for parts, the number of spare engines built, and the average time between shop visits and engine shop activity.

-5A series

There is still high demand for the -5A series, with few A320s now available on the market and only one or two aircraft having been acquired for stripping for engines and components. "There is actually little trading activity of -5As in the market, and their values have strengthened as a consequence," says Andrew Pearce, director at MacQuarie Aviation Capital. "The -5A is perceived as an engine with a short life-span, but many of the aircraft are also getting old. The oldest A320s are 17-18 years old, and there will come a point in the next 5-10 years when a large number of aircraft will get retired or parked. There will then be a surplus of engines, at which point values will decline. The engines are now full priced, which means that market values are what the major appraisers estimate them to be. This is is because demand is at such a level that engines are quickly bought when they come available. There are also many prominent parts and engine suppliers looking for -5As."

Lease rates are also strong, as Abdol Moabery, president and chief executive officer at GA Telesis points out. "Short-term lease rates are 50-75% higher for -5As than they are for -3C1s, which are the higher rated engines for the 737-300/-400. The -5A's long-term lease rates are 25-50% higher than the -3C1's because 25 737 Classics have been parted out, and there are also spare engine pools for the -3 series.

"Another issue affecting market values is the cost of maintenance, and maintenance status," continues Moabery. "Maintenance is expensive because the cost of replacement parts is similar to new parts, there are virtually no used life limited parts (LLPs) on the market and the shop visit costs are 25-30% higher than for the -3 series. The engine operates reliably, and achieves 7,000-9,000 hours on wing between removals.

"Short-term lease rates are $2,500-3,500 per day plus reserves, while long-term leases of more than 18 months command rates of $1,800-2,500 per day plus reserves," estimates Moabery. "Freshly overhauled, fully-dressed -5A3s have a market value in the region of $5.5 million, while lower rated -5A1s have values of about $4.8 million. The values of time-continued engines are simply these values less the cost of maintenance, so they are about $3.8 million."

Maintenance reserves for the -5A series include LLPs at about $92 per engine flight cycle (EFC). Shop visit reserves vary with workscope, but are $145-190 per EFC *(see CFM56-5A/-5B maintenance analysis & budget, page 15).*

-5B series

Demand for the -5B series is even stronger, since it is the predominant engine powering the A320. "Most -5Bs are still young, achieving long on-wing lives and reaching LLP limits in many cases," says Pearce. "There are now more than 2,000 -5B/P engines in operation. Like the -5A series, supply of -5Bs and -5B/Ps has been tight, and few are being traded. Any engines that are being sold are traded at the full list price corrected for maintenance condition and LLP life." The engine's full set of LLPs has a list price of $1.83 million, while parts in the fan/booster module have lives of 30,000EFC, parts in the two core modules have lives of 20,000EFC and those in the low pressure turbine (LPT) have lives of 25,000EFC.

"The -5Bs are very desirable assets, and have the advantage of a large fleet and wide, global customer base," continues Pearce. "Moreover, the engine continues to be manufactured, with about 100 new aircraft going into service each year.

"Another factor that will influence the availability of engines is the level of shop visit activity. This is currently low, because many engines have not even been through their first shop visit yet," says Pearce. "Supply that is already tight will get tighter still as more engines are removed for the first time, and the older

The supply of spare -5As and -5Bs is tight, with any available engines trading quickly. The engines are fully priced; meaning trading values are similar to appraisers' estimates of fair market values.

engines start being removed for the second time. First run removal intervals are up to about 17,000EFC, but second and mature intervals are more likely to be in the region of 10,000EFC for most models. This would then effectively double the number of engines undergoing maintenance in the long term, thereby seriously reducing the supply of engines available for lease and trade. This issue is further complicated by LLPs. They have varying lives of 17,000-30,000EFC, and the supply of used LLPs on the market will depend on what airlines do in terms of removing or retaining them at the first removal."

A major issue affecting the supply of -5Bs is the low ratio of spare engines to installed powerplants. "The percentage of spare -5Bs is low compared to -7Bs," says Moabery. "Even when -5Bs do become available they are very easy to lease or sell. Short-term lease rates are about $4,500 per day plus reserves, while long-term lease rates for a three-year lease are about $75,000 per month. Airlines are not investing in as many engines as they used to. A few months ago there were only five or seven -7Bs on the market and no -5Bs available at all. Moreover, -5Bs are rarely available on the market, and when there are you have to pay the catalogue price.

"Time-continued engines, without a full quick engine change (QEC) kit, and which have accumulated 4,000-5,000EFC since new, have market values of $6.5-7.0 million. This compares to a list price of about $7.5 million, although the actual price varies with thrust rating," continues Moabery.

Pearce puts values even higher. "The -5B fleet only has a spares ratio of about 8%, which compares to about 12% for most other engine types. A fully dressed -5B4/P engine with a QEC kit has a list price of about $8.0-8.5 million. With the QEC kit worth $1.3-1.5 million, this means that the value of a bare engine is $6.7-7.2 million. There have been a few sale and leasebacks with long-term lease rates in the region of $75,000-80,000 per month, which is a lease rate factor of about 1.1%. This is borne out by recent long-term leases that have been signed for about $75,000 per month. Short-term lease rates will be higher."

Reserves for -5Bs depend on thrust rating. The highest rated -5B3/2/1 engines for the A321 are limited by temperature margin, so they have shorter removal intervals. LLP reserves are $85-105 per EFC, while shop visit reserves average about $145 per EFC for the highest rated -5Bs and about $127 per EFC for the lower rated variants powering the A320, A319 and A318.

"It would be desirable for lessors and traders like us to acquire -5Bs from the market through sale and leaseback transactions with airlines," explains Moabery. "Unfortunately, there are few airlines interested in selling their engines, which may be because there is plenty of liquidity the market. However, this could change if market liquidity were to diminish."

The -5B market is made more interesting by the presence of a smaller sub-fleet of engines with the double annular combustor (DAC). "The DAC did have some initial technical problems, but these have now been resolved," says Moabery. "The engines are still more expensive to operate than ones with a single annular combustor (SAC) because there is a limited number of spare DAC combustors, and the unit requires special repairs even though the engine has overcome its reliability problems. The demand for DAC engines is also limited because there are only a few operators that operate them, although airlines can be willing to take them if there is no other alternative available."