High fuel prices mean that engine deterioration and the related rise in fuel consumption has begun to be considered as in issue in engine maintenance and overall engine management. The rate of fuel burn rise with accumulated time on-wing and overall engine costs should be analysed.

Engine deterioration & the rise in fuel burn

An engine's increased rate of fuel burn with time on-wing and accumulated degradation has always been an accepted consequence of aircraft operation. It has rarely, however, influenced removal timing for shop visits or maintenance practices, and engine management related to maintenance, due to the relatively low cost of fuel over a sustained period.

The steady rise of crude oil and jet fuel prices now means the cost of fuel accounts for a larger percentage of the total cost of operating engines. The relationship between an engine's time on-wing and the change in its rate of fuel consumption therefore needs to be examined. The departmentalisation of flight operations and maintenance & engineering (M&E) in many airlines, however, means there is little cooperation in these two areas of engine management.

Engine operation

The efficiency of air compression in the low pressure compressor (LP) and high pressure compressor (HOC), and expansion and extraction of energy in the combustor and turbine sections depends on several factors, including: clearances around the tips of rotating blades and rotating seals; the preservation of airfoil aerodynamic profiles and dimensions; and the cleanliness of airfoils and cooling passages.

These factors are all optimised in a new engine, but deteriorate once an engine starts to operate. When new, the exhaust gas temperature (ECG) will be at its maximum value, even at maximum thrust, since all seals and clearances are at their optimum. The ECG margin, which is the difference between the EGT and the highest permitted redline EGT, will therefore also be at its highest.

Deterioration of blade tip clearances occurs partly because the engine's turbomachinery expands and contracts as a result of varying amounts of engine throttle, fuel flow and combustion temperature. At take-off the engine operates at the highest thrust setting and combustion temperature than at any other stage of the flight. Thrust is reduced for climb power, and still further for cruise, but is increased again during the landing phase. The expansion and contraction of the rotating turbomachinery relative to the non-rotating seals embedded in the inner wall of the engine case result in the inevitable blade tip wear. This is because the engine blades and casing expand and contract at different rates. The clearances therefore vary during different phases of flight, and blade tips inevitably wear against embedded rub strips and seals on the inner walls of cases.

Such wear increases the amount of airflow that escapes around the rotating airfoil tips, rather than passing through the rotating blades and stators, as intended. This ultimately leads to a rise in EGT, and so a fall in EGT margin.

Some modern engines have blade tip clearance control devices, such as turbine cooling rings, but perfect alignment of blade tips and rub strips is never completely possible. EGT continues to rise with accumulated time on-wing.

Higher EGT results in a faster rate of hardware deterioration, otherwise known as hot corrosion, so EGT can start to rise faster with more accumulated time on-wing. Hot corrosion results when elements in the base metal of the HPT blade react chemically with elements in the gas flow, which changes the properties of the HPT blade element to an extent that it causes decay. "The only part of the HPT blade where base metal is exposed is the blade tip, which is due to contact with shrouds," says Dion Verbocht, customer support engineer at Air France Industries KLM Maintenance & Engineering. "The blade tip is affected by corrosion, so cracks ultimately form. Thermal stress also causes cracks in the nozzle guide vanes (NGVs), and ultimately further hot corrosion and oxidation of NGV and blade material."

Hot corrosion of blades can be slowed and reduced by the use of thermo-protective coatings. These have been developed over the past three decades by engine manufacturers, as well as by specialists such as Chromalloy.

Deterioration of an engine's HPC variable stator vane (VSV) system also results in a loss in engine efficiency. The VSV is a mechanical system that alters the angle of attack of stator vanes in the HPC. "The VSV system uses a combination of seals and washers, in the HPC casing, as part of the mechanism for changing the stators' angle of attack," explains Verbocht. "These seals and washers prevent leakage of the primary airflow through the HPC casing. As these washers and seals deteriorate, so does engine efficiency, causing a need for a higher throttle setting, higher EGT and so higher fuel burn."

Overall, the deterioration of compressor blade tips, embedded seals, and turbine blade tips ultimately leads to a loss in engine gaspath efficiency. Air leakages through widened blade and seal clearances mean engine thrust is ultimately weakened. Higher throttle settings are needed for the engine to produce the same thrust, and mean a higher rate of fuel flow in the engine's combustors, so a higher EGT, and therefore a reduced EGT margin.

"There are several other causes of a loss in EGT margin and engine performance. One of these is the seals in the bleed air system which taps off air from engine compressors and directs it to the aircraft cabin. Seals in the system wear with accumulated engine flight hours (EFH), and cause air to leak. This

Deterioration of engine hardware with accumulated time on-wing results in higher throttle settings to achieve the same engine thrust.

results in a drop in engine efficiency, and causes a rise in EGT.

"A further issue concerns thrust reversers," continues Epstein. "These have rubber/plastic seals to prevent air leakage during aircraft operation. These seals deteriorate every time the thrust reversers are deployed, so the leaks cause a small degradation in engine thrust. The aircraft's flight management system will have to increase throttle settings to achieve a particular Mach cruise speed for a particular all-up weight, which gives a small increase in EGT and fuel burn."

De-rate & EFH:EFC ratio

"The rate of deterioration of blade tips, embedded seals and other engine hardware depends on operational and environmental factors," says Versteeg. "The most important operational factors are the EFH to engine flight cycle (EFC) ratio, and thrust setting. Flight crews can use engine de-rate wherever possible, since full thrust and engine throttle is only needed for very few operations."

The level of engine de-rate will decrease as required thrust increases. Higher thrust settings are needed for take-off at higher ambient temperatures, shorter runways and higher take-off weights. Flightcrews have to operate with reduced or even zero de-rate when operating missions at the end of the aircraft's payload-range envelope, when carrying high payloads, when departing at high ambient temperatures; or a combination of these factors.

Short EFH:EFC ratios, for short-haul operations, however, also result in a high rate of engine blade tip and seal deterioration, despite lower engine thrust settings generally being required. This is because much of the flight experiences engine throttle movement, and so a lot of engine expansion and contraction.

Environmental factors

"External factors are mainly related to the airline's operating environment. Engine airfoils deteriorate at the highest rates in a sandy environment," says Versteeg. "The abrasive effect of sand particles causes blade erosion, with respect to a change in both aerodynamic shape and blade dimensions. One particular issue in blade dimensions is the chord width of HPC blades, which reduces their ability to compress air. Blades wear in dimensions and aerodynamic curvature, and also crack.

"The engine is particularly sensitive to salty environments, such as coastal regions or trans-Ocean route networks," adds Verbocht. "Contaminants stick to rotating blades, which affects their aerodynamic efficiency. Industrial pollutants containing aggressive elements such as sulphur cause corrosive degradation of blades and affect the efficiency of the gaspath. HPT blades in particular are affected by corrosive degradation, which results in increased airflow around the blade tips."

EGT margin

The rise in EGT is always initially high for new engines, or those fresh from a shop visit. "The rise of EGT in older generation engines followed a curved profile, and engine manufacturers always quoted EGT margin when the engine was brand new," says Epstein. "The problem with this was that there was initially a high rate of climb in EGT. The engines of the past three decades have a more linear profile for their EGT margins. The initial rate of EGT margin loss is only high for the first 50-100EFH on-wing. After this the EGT margin becomes more stable and forms a more-or-less linear profile. A lot of work has been done to retain performance in engines, so EGT margin does not erode as fast as it used to."

The rate of EGT margin erosion is clearly influenced by EFH:EFC, since this is a major factor in engine hardware degradation. In general, the deterioration of engines operated on short EFH:EFC ratios is related to accumulated EFC time on-wing, while engines operated on medium- or long-haul EFC times experience deterioration of hardware in relation to accumulated EFH on-wing. There is still a lot of scatter around a general EGT margin curve plotted on a chart.

"The rate of EGT rise/EGT margin erosion depends very much on the engine type and operation, and of course individual engines within an airline's fleet will experience different EFH:EFC ratios and rates of wear and degradation," says Thilo Seitz, director of propulsion systems engineering at Lufthansa Technik. "EGT margin erosion can be moderated with constant use of engine de-rate. After the initial period on-wing when blade tips rub and wear due to the first expansions and contractions, EGT margin erosion stabilises, and may even almost flatten in modern engines, although it does continue to slowly fall.

"Our experience is that engines used on long-haul operations (eight hours or more per flight) show an average EGT margin erosion rate of one degree centigrade per 1,000EFH; after the initial higher rate of EGT margin erosion in the first few hundred EFH on-wing. Some engines in the same fleet, however, experience EGT margin erosion rates as high as 20 degrees per 1,000EFH; and need to be removed earlier than normal for a shop visit. At the other extreme some engines only lose 10 degrees centigrade of EGT margin in 12,000EFH on-wing, a loss equal to 0.83 degrees per 1,000EFH.

"New engines generally have a better rate of performance retention and EGT margin erosion than those fresh from a shop visit," continues Seitz. "The quality of some engines' hardware is improved through upgrade programmes, which involve several SBs, and often replace

Regular water washing of engines helps keep airfoils clean and therefore maintain their aerodynamic efficiency. This in turn means throttle settings have to be increased at a lower rate with accumulated time on-wing, and so preserve an engine's rate of fuel burn.

airfoils with improved parts."

The EGT margin of overhauled engines is 80% of initial EGT margin of an all-new engine, mainly because airlines must compromise between replacing and repairing parts in the engine at each shop visit. The difference in cost between repairing and replacing parts is large, while the difference between shop visit removal intervals is small when opting between complete part replacement and repairing a large percentage of parts, so it is always economic to repair as many airfoils and seals as possible. The repair status of a high proportion of parts in the engine means initial EGT margin can never be regained.

"Despite this, the EGT margin does not erode any faster in an engine that has been through a shop visit, than an all-new engine," says Epstein. "The engine's design and the quality of the shop visit are more important issues. The operating environment is also important. The rate of EGT margin erosion can double in a sandy or other harsh environment."

Julian Rees, lease manager at TES Aviation, says there are several variants of the same engine model. Each has or more thrust ratings. "The CFM56-3 has three variants, and the -C1 can be rated at 23,500lbs, 22,000lbs, 20,000lbs or 18,500lbs. The -B2 is rated at 22,000lbs, and the two lower ratings, while the -B1 is rated at 20,000lbs. The -C1 rated at 23,500lbs has the highest rate of EGT increase, of 35 degrees in 8,000EFC. The -C1 rated at 22,000lbs will suffer a smaller rise of only 25 degrees over the same interval, while the -B2 at the same rating will increase in EGT by 30 degrees.

"The CFM56-5B series has an EGT margin deterioration profile of 16 degrees in the first 2,000EFH on-wing, and an erosion rate of three to four degrees per 1,000EFH thereafter," continues Rees.

On widebody engines, EGT margin erosion rates are initially 10-15 degrees per 1,000EFC, but reduce to a steady rate of 2-5 degrees per 1,000EFC thereafter.

Another example is the CF6-80C2. When used on long-range missions, initial EGT margin erosion rate is 3.5-5.0 degrees centigrade per 1,000EFH for the first 2,000EFH on-wing. Rates then settle down to 2.0-3.0 degrees per 1,000EFH.

Fuel burn rise

The rate of fuel burn rise follows the path of EGT margin erosion and hardware deterioration in parallel. "Fuel burn increases by 3-6% over the overhaul removal interval, when the engine is in nominal use," says Epstein. "The rate of fuel burn rise can be double this for engines operating in a harsh environment. Maximising removal interval to achieve the lowest maintenance cost per EFH or EFC was the only issue in engine management while fuel prices were relatively low. The high price of fuel now means that the increasingly higher rates of fuel burn with accumulated time on-wing are now an element in determining removal timing and overall engine management. Some airlines are putting engines through shop visits to regain operating performance and fuel consumption."

Seitz agrees that the rate of fuel burn is 4-6% between two shop visits or overhauls. The shop-visit workscope at the first removal will determine the actual rise. "The lower the restored EGT is after the first shop visit, the lower the rise during the second interval that leads up to the overhaul," says Seitz.

Operational techniques

Engine operation on the ground during taxiing causes engine hardware deterioration. "One technique to reduce this is to run one or two engines at idle after landing," says Verbocht. "While shutting down an engine after landing reduces fuel consumption, it has a negative effect on engine hardware. When running at idle, the engine takes in cool, fresh air and uses little fuel. This allows the heat accumulated in the internal parts to exit prior to shut-off, whereas shutting down an engine immediately causes all the heat to dwell in the core, and to rise up to the upper half of the engine. This causes heat distress, especially in the hot section."

Other operational techniques can be used to slow the rate of degradation and performance erosion. "Besides the usual recommendation of engine de-rate, the accumulation of dirt and grease on airfoils reduces performance and requires a higher throttle setting to achieve a particular level of engine thrust," says Epstein. "Water washing has therefore become common among some operators. Our Eco wash at Pratt & Whitney (PW) can be used once every six months to reduce the rate of EGT margin erosion.

"Another technique is polishing fan blades while on-wing, using a specialised PW tool," continues Epstein. "This has the same effect as water washing by removing dirt and keeping the fan blades clean so that they maintain their aerodynamic performance. Another issue is reverse thrust, which increases fuel burn, and is rarely required to decelerate an aircraft on the runway length available. It is used by airlines to trade against the wear of wheel brakes and their associated maintenance costs. Fuel burn can be reduced by only using reverse thrust in adverse weather conditions."

Maintenance techniques

Techniques available to airlines in line and shop visit maintenance to moderate the rate of EGT margin erosion, include achieving optimal tolerances and clearances at blade tips and rotating seals in shop visits. "Component tolerances and the dimensions of time-continued and repaired parts in the engine are also an issue," explains Rees. "The cost of repair versus replacement in terms of total maintenance cost is far more

The rate of fuel burn rise can be 3-6% over the interval of an engine overhaul; the interval of two shops visits in the case of many engine types. Removing engines earlier for maintenance to avoid such a high increase may prove overall more economic than trying to maximise shop visit intervals.

important than fuel burn, provided the subsequent time on-wing is not compromised by using repaired parts."

Epstein says the turbine and HPC blades, and seals are the main areas of the engine that are among the most sensitive to performance recovery. "Rub strip seals on the inner casing walls are sprayed with plasma and then machined down," says Epstein. "Re-establishing blade tip clearances by re-building blade-tip lengths is a core issue. Having a mixture of repaired and new blades on the HPT disc probably results in a faster rate of degradation of engine performance and EGT margin, compared to an HPT disc with all new blades."

Maintenance versus fuel burn

With a steady rise in fuel burn as time on-wing is accumulated, are fuel prices now high enough for the rate of fuel consumption to be considered as an element in engine management? The aim is to achieve the lowest cost per EFH.

The relationship between average time on-wing between shop visits and resulting maintenance cost per EFH or per EFC forms a U-shaped curve. The costs of a shop visit increase marginally with extended removal intervals due to a higher degree of parts degradation. The increase in shop-visit cost for short- and medium-length removal intervals is not in proportion with the interval itself. Moreover, longer removal intervals also result in a better use of available lives of LLPs. Longer intervals therefore result in lower costs per EFH, or per EFC. The rate at which engine hardware deteriorates can increase at higher rates and so resulting maintenance reserves per EFH/EFC can increase. Despite this rise for the longest on-wing intervals, airlines rarely achieve such these because of practical engine management issues, so they aim to achieve the highest possible intervals. Maintenance reserves therefore improve as on-wing intervals increase.

Counter to this is the rise in fuel burn as intervals increase, due to the previously described degradation in engine hardware. The issue is whether an overall cost of operation per EFH can be achieved with reduced removal intervals due to better engine performance retention and fuel burn performance.

Taking the CFM56-5B and PW4000-94 as engines operated under short- and long-haul regimes, the trade between maintenance cost and fuel burn cost per EFH/EFC can be examined.

A CFM56-5B4 operated on an A320 will typically operate at a EFH:EFC ratio of 1.8:1, a flight time of 110 minutes. The aircraft's nominal fuel burn is 1,550 US Gallons (USG), equal to 800USG per EFC, and a fuel burn cost of $2,500 per EFC at current prices.

Typical first and second removal intervals are 15,000EFC and 10,000EFC. Fuel burn may increase by 3% by the time the first interval is complete; equal to a rise on fuel cost of $75 per EFC. This extra cost will be as much as $150 per EFC by the time of the second interval.

First and second shop visit costs will cost $1.8 million and $2.0 million. Additional costs of LLP replacement will result in total reserves of $235 per EFC and $300 per EFC for the first and second removals. The total additional fuel and maintenance reserves is $310 per EFC for the first interval, and $450 per EFC for the second.

With 25% shorter intervals, the additional fuel cost per EFC would reach $56 for the first interval, and $112 for the second. Maintenance reserves would be higher, however, for both the shop visit costs and LLP replacement. Reserves would be higher, at $290 per EFC for the first interval, and $390 per EFC for the second. The total cost of additional fuel burn and maintenance would be $345 per EFC and $502 for these two intervals; a higher cost than for longer removal intervals. The high cost of fuel is therefore not enough for the rise in fuel burn to be a factor in influencing engine management.

The PW4000-94 powering the 747-400 can be used as an example of long-haul operations. On an eight-hour mission on a 747-400, fuel burn will be 29,000USG, equal to 3,600USG per FH, and so 900USG per EFH. At current fuel prices this is equal to a nominal fuel cost of $2,800 per EFH.

Maintenance shop-visit intervals for the PW4056 powering the 747-400 on such an EFH:EFC ratio are 15,000EFH and 1,900EFC. PW4000-94 engines tend to conform to a simple shop-visit pattern of alternating performance restoration and overhauls. The costs for these will be $2.5 million and $3.0 million. When reserves for LLPs are added, total maintenance reserves will be $195 per EFH for the first interval, and $228 per EFH for the second. The additional cost of higher fuel burn will reach $115 per EFH by the time the first interval is reached, and $230 per EFH by the time of the overhaul. Total cost of extra fuel burn and maintenance reserves is $300 per EFH for the first removal interval, and $456 per EFH for the second.

The option of 25% shorter intervals results in higher maintenance reserves of $220 per EFH for the first interval, and $265 per EFH for the second. Additional fuel costs will be $70 and $140 per EFH higher, so the overall cost per EFH will be $290 and $402 for the first and second intervals. These costs are lower than for engines managed with longer removal intervals, because maintenance reserves are lower per EFH when operated on longer EFH:EFC ratios; especially since the reserves for LLPs are diluted by the long EFC times. AC