Acquiring time-continued or 'green time' engines can be an economic solution for airlines operating older aircraft for a few years rather than conducting full maintenance. Charles Williams examines the technical issues and economics that airlines should consider.

The economics of 'green time' engines

The practice of acquiring time-continued, or 'green-time', engines and engine modules is a tried and tested one that can save an airline significant costs compared to paying full level engine maintenance reserves and shop visit (SV) costs for existing engines in a fleet. This particularly applies to savings related to buying new life limited parts (LLPs). This can suit airlines that operate owned fleets in the last few years of their life before scrapping and retiring them, or that have a policy of operating older types that have been retired in large numbers, which has left a supply of green-time engines on the aftermarket.

Acquiring time-continued engines to save maintenance costs applies to engine types that power older aircraft whose numbers are declining in operation. These include the 737 Classics, the 757, the A300-600, 767, 747-400 and MD-11. The relevant engine types are therefore the CFM56-3, RB211-535, PW2000, PW4000-94 and the CF6-80C2.

Full engine maintenance

Full engine maintenance should be practised for an aircraft in the early and mature phases of its operating life. If the timing of engine overhauls is closely matched with the replacement of most or all of the engine's LLPs, then the lowest maintenance cost per engine flight hour (EFH) and engine flight cycle (EFC) can be achieved.

Most elements of full engine maintenance are unnecessary, however, in the last few years of an engine's operational life, and many high-cost items can be avoided.

The two main elements of engine maintenance are the on-condition maintenance and refurbishment of turbomachinery and combustion chambers, and the replacement of fixed life LLPs. The timing of maintenance for turbomachinery can be approximately ascertained for an established engine type. Engine removal intervals are affected by several factors, but are not always predictable or reliable.

Most engine types and individual engines within a type will often conform to a pattern of alternating performance restoration and overhaul SVs.

An alternating pattern of SVs will often be a performance restoration, just involving full disassembly of HP modules; followed by an overhaul, involving the disassembly of all engine modules. Some LP modules are only worked on every third shop visit.

Airlines have several choices for managing the maintenance of engines, but can only optimise costs per EFH and EFC if they have complete control over the timing of removals for SVs, the SV workscopes, and the timing of LLP replacement.

This is only possible when an airline owns its engines, and it either has its own engine shop or opts for certain types of engine maintenance contract.

Maintenance contracts

An airline with its own engine shop will first perform all its own engineering management in terms of health monitoring, determining removal times for maintenance, and defining SV workscopes. The small number of airlines with their own shops has the full flexibility to determine engine SV workscopes. There is limited or no freedom to do this with some the types of maintenance contract available.

There are four main types of maintenance contract an airline can use.

The first type is a time and material (T&M) contract, which is offered by airline and independent engine shops.

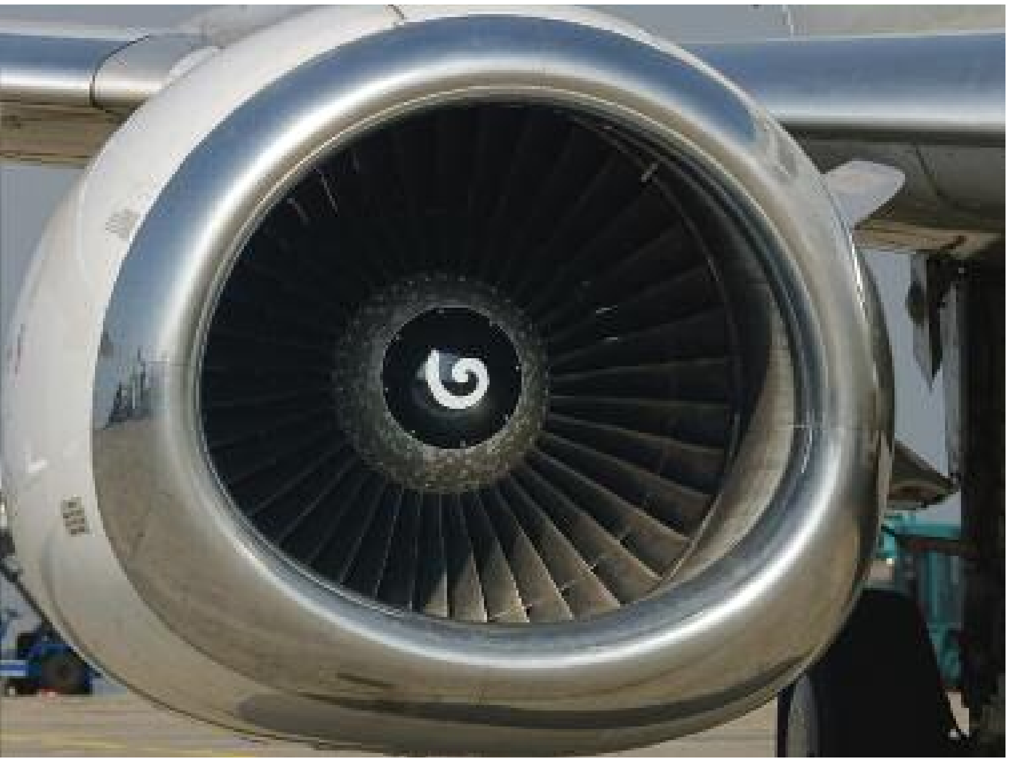
Under a T&M contract, maintenance is simply charged according to what is actually used. The airline controls the management of engines, and so maintains knowledge of how its engines perform and what maintenance costs are likely to be. The airline also defines SV workscopes, and takes the risk with the size and cost of the workscopes. Despite this risk, airlines are in full control in that they can choose to repair rather than replace parts, or minimise workscopes by building modules for a shorter subsequent on-wing interval before it is retired and scrapped.

The second type is a fixed-price contract, but in other respects it is similar to a T&M contract. The airline therefore maintains control over the management of the engine and defines workscopes. Again, the airline has the freedom to minimise engine maintenance if it wants. The use of fixed-rate prices removes the risk for the airline, although extra non-inclusion items often have to be paid for.

Power-by-the-hour (PBH) contracts were introduced in the 1990s to provide airlines with a predictable, fixed rate per EFH or EFC. PBH contracts remove risk for the operator, but it relinquishes control of engine management and SV workscope definition.

The fourth option is integrated services or total care programmes for engines. These include PBH maintenance and other services such as health monitoring, engineering management and spare engine provisioning. These contracts are used by original equipment manufacturers (OEMs) for an increasing number of engines, and are often signed by airlines as part of an aircraft order. These are also long-term contracts, and can last for up to 20 years.

The drawback to these contracts is that the operator often pays a premium



There is strong interest in time-continued CFM56-3B2s and -3C1s. Small shop visits can be performed for an economic price, and provide an emngine with sufficient performance for two to four years of operation.

for the convenience of a zero-risk service and predictable engine support cost. Another disadvantage is that there can be remaining LLP life on the engine halfway between SVs at contract expiry, which can cause difficulties at the end of a contract, since the operator will have paid some reserves for maintenance or LLP replacement that it will not benefit from.

Mature engine maintenance

With most engines now maintained under PBH or total care contracts, airlines have less or no flexibility to reduce or minimise SV maintenance inputs.

Full level on-condition maintenance for turbomachinery is only necessary while the engine is due to operate for a period that is at least equal to or longer than the overhaul interval. Similarly, LLPs only need to be replaced if they expire before the engine is retired.

Ideally, reserves will not have to be paid either for SV maintenance or LLP replacement if the two events come due at a similar time or coincide, and the engine is retired and scrapped just before they come due. LLP reserves can then be completely avoided, and SV maintenance reserves completely or almost completely avoided for the last few years of an engine's life in the case of some types.

LLP replacement can come due at an inconvenient time, such as just a few years before expected retirement. Paying for new parts at the OEM's list price can be avoided by buying time-continued LLPs. These are parts that have some of their life limits consumed, but still have enough EFC remaining to allow the engine to operate for several more years. Time-continued LLPs will be available on the market as a result of the first engines being retired from the oldest aircraft. The supply will continue as more of the fleet is retired, and values will fall as a result. When the supply is high, values will be lower than the pro-rated value according to the remaining life of the parts.

A similar pattern could be used for turbomachinery maintenance. Costs can first be saved by installing repaired and reconditioned and serviceable parts in engines. Serviceable material will be available at low rates on the market, and the rate of discount will be high when the availability of engines, modules and parts is high, due to a large number of engine retirements.

Time-continued engines

The policy of using time-continued engines and modules to replace existing engines is followed by airlines that are: phasing out a fleet type; extending the use of an old fleet type; or following a policy of operating old aircraft for a few years before acquiring a new type. In all cases, airlines can make large savings on engine maintenance costs when a fleet is beyond its mature phase, and the aftermarket supply is high.

An airline that has adopted the policy of using green-time engines is Philippine Airlines (PAL). The airline has experienced delivery delays with new widebodies that are due to replace its A340-300s. "We have a joint venture with SR Technics to supply PAL with CFM56-5C engines for the A340-300 fleet for a few years," says James Bennett, director sales and marketing at AerFin. "We have leased PAL CFM56-5Cs from Cathay Pacific's retired A340-300 fleet for four years, while SR Technics provides engineering support. The maintenance condition of the engines should mean they require no major SV inputs for the lease term, and SR Technics performs light maintenance as it is required. The whole lease is provided on a $ cost per FH basis."

Acquiring time-continued or 'green-time' engines can involve buying or leasing whole engines, or buying modules, assemblies and components from several engines. Modules from different engines may have a different number of accumulated LLP cycles since new, but the remaining lives may closely match. That is, LLPs in the CFM56-3's fan and LPC have limits of 30,000EFC, the parts in the HP modules have lives of 15,000-20,000EFC, and the LPT parts have lives of 25,000EFC. An airline may wish to have an engine completed that has LLPs throughout with at least 7,000EFC remaining, for example. Some traders and brokers can acquire several engines and modules for these purposes, and these will be built to form a complete engine in a maintenance shop.

"More airlines are asking to buy time-continued modules to replace those that have used up all their maintenance life," says Rudiger Heinrich, vice president of material management at MTU Maintenance Lease Services. "This is to match other modules that have remaining time on-wing to build an engine that will continue to operate for a few more years. MTU Maintenance is investing in these modules to make them available. We are seeing demand for this with the V2500, CFM56-5B/-7B and the CF6-80C2. We are providing an economic solution for airlines, especially when the cost of time-continued LLPs is considered against the current list price (CLP) of new LLPs."

Several considerations are usually made when buying an engine. "It does not make sense to mismatch modules in terms of remaining LLP life," says Heinrich. "We perform expert examinations on each module, and also do technical evaluations to get guidance on the probable remaining time on-wing. Although exhaust gas temperature (EGT) margin erosion can cause problems, the rate of erosion is usually very stable and predictable after the first 1,000EFH on wing. We examine the engine's build standard, and consider it carefully."

There are several risks operators should consider when taking the green-time option for engines. "There are often expensive surprises with a bought engine or modules, and it is often the case that expensive maintenance work has been skimped on, and the engine requires some expensive inputs," says Chris Grey, chief executive officer at Aer Auster. "There is also a risk with predicting the possible remaining time on-wing the engine is likely to achieve. This is particularly with predicting the rate of EGTm erosion."

Other potential pitfalls include the risk of a mismatch of modules. A buyer can also find there are airworthiness directives (ADs) and service bulletins (SBs) that have not been complied with.

"An engine that has been bought has no warranty, while an engine shop will give you one for an SV workscope," continues Grey. "This is an important consideration for a technical director, who takes responsibility for the fleet."

CFM56-3

The CFM56-3 is a good example of an engine type that is acquired on a green-time or time-continued basis by a range of operators. "We work with airlines that operate old aircraft, and these include 737-300s and -400s, which are mainly powered by CFM56-3B2 and -3C1 engines," says Glen Marston, general manager at Aero Norway. "Some of these airlines operate old aircraft that are either passenger aircraft in the last few years of operation or converted freighters. Many of our customers ask us to build for a certain number of EFC, which sometimes depends on the retirement plan. The engine's accumulated EFC since the last SV, its performance trends, the last SV workscope, and its overall maintenance status all need to be considered to assess its likely time remaining on-wing.

"A time-continued CFM56-3 can often operate for several thousand EFC on wing following what I describe as a surgical strike SV workscope," continues Marston. "This may mean replacing just a few LLPs. We try to minimise the workscope and its cost, and aim to have a workscope that results in a specific time on-wing."

Aero Norway buys green-time LLPs and modules, and will even tear down an engine to get a particular module. "We can buy three engines, and use the better modules to build two engines that will probably each have 4,000EFC or 5,000EFC remaining on-wing time," says Marston. "We can then keep the carcass of what will make the third engine. We will perform something like a full SV if an airline requires such an engine. The actual build standard depends on what the customer wants, and every engine is a bespoke case because of its condition when it is acquired.

"A surgical strike can achieve a good EGTm at minimal cost," continues Marston. "We are performing this type of SV for eight -3s for Air Bulgaria, which is operating 737 Classics. It is possible to get an EGTm of 26deg C, which will give a removal interval of 4,000EFC. This is equal to about two years of flying for a passenger airline, but four years for a freight carrier."

By comparison, a full SV will give up to 6,000EFC for a -3C1, and 6,000-8,000EFC for a -3B2, so an engine shop will provide a guarantee for a post-SV interval of about 4,500EFC.

"A surgical strike SV often involves work on the three core modules," says Marston. "An example is work on the high pressure turbine (HPT), including replacement of one to three LLPs. Some of the HPT blades need to be repaired, and others may have to be replaced. Blade clearance is also optimised. If the blades fail inspection but the shrouds pass, they can both be cleaned up or repaired to get the sufficient clearances. This level of SV will regain enough EGTm without having to rely on full

HPT refurbishment. Some repair work can also be done on the combustor. We can then provide a guarantee for a minimum number of EFCs, which removes some of the risk compared to the operator just buying a time-continued engine and operating it without any work.

"We are good at getting EGTm from the CFM56-3, and can get margins of about 40deg," continues Marston. "We will guarantee a post-SV margin of 35deg. This is high compared to other shops. The -3C1 usually has an EGTm of about 25 deg post-SV, and a -3B2 about 30deg post-SV. We are doing lots of customised workscopes."

The cost of surgical strike and bespoke SVs, plus the possible cost of a few LLPs, added to the cost of the purchased green-time engine has to be considered against full maintenance. "Some operators build engines for a minimum of 5,000EFC, which is close to a full removal interval," says Marston. "A full core performance restoration will cost about $950,000, without LLPs. This is cheaper than the original cost, which used to be about $600,000 higher. The cost has dropped, and there is no need to buy new material in most cases now, because of the high quality of repaired parts and material available on the market. HPT blades can be repaired three or four times if they are within repairable limits. High-tech repairs are not cheaper than they used to be. Repaired blades are cheaper than new ones."

Marston adds that in most cases, it is possible to buy green-time LP modules, and workscopes rarely have to be carried out on them. These are matched to the HP modules. The cost of the SV can also be minimised by using parts manufacturer approved (PMA) parts. Aero Norway has a recommended PMA parts list. Marston says that while some customers prefer not to use PMA parts, it has many that do not mind using them, and find that some PMA parts are as good as, or better than, the equivalent OEM parts. These customers do not have an issue with using PMA parts for their own green-time engines that will be operated for a few years before being scrapped. This includes HPT blades and nozzles.

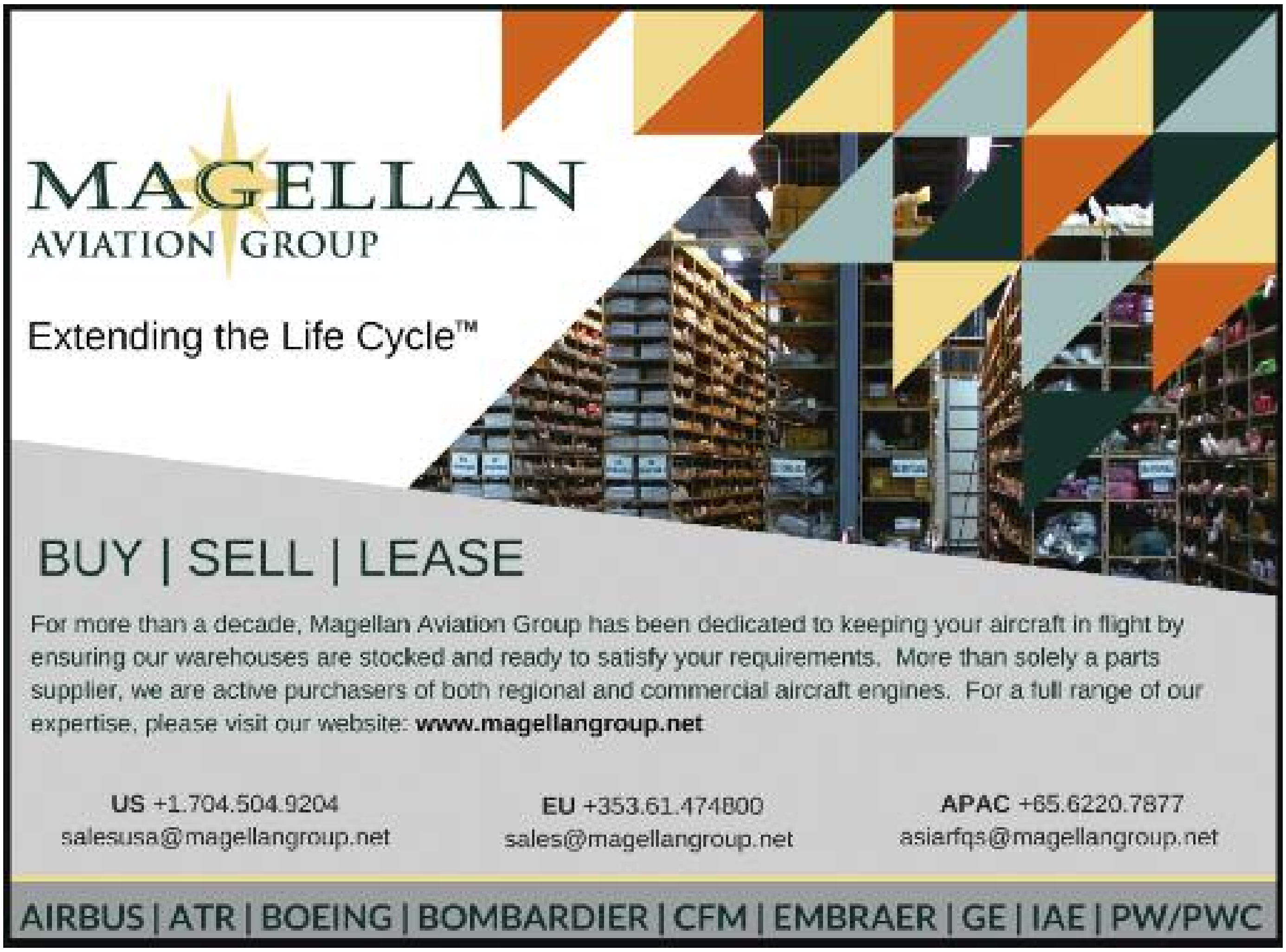
Several scenarios have to be considered when the economics of time-continued engines are looked at.

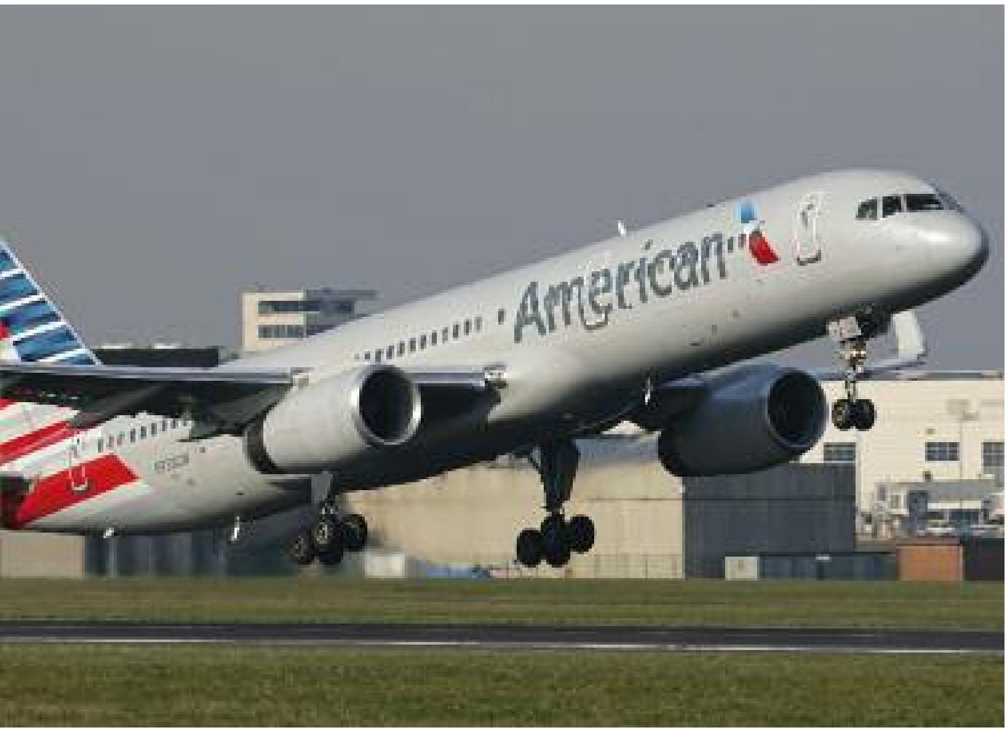
The first issue will be the purchase of time-continued engines. "The supply of green-time CFM56-3s is smaller than it was two years ago," says Marston. "Southwest is selling its fleet, but these engines tend to be in good condition, and so will command a high price."

The general consensus is that values of green-time engines with 1,000-3,000EFC remaining will command a price of $400,000-700,000 in the aftermarket. "A green-time CFM56-3 will have this kind of value, and will cost $1.0 million more if it is fresh from an SV. Bennett estimates a value of $500,000 for a time-continued engine, and Bill Polyi, president and chief executive officer, at Magellan Aviation Group puts it at $500,000-600,000. Polyi estimates that the value of an engine fresh from an SV will be about $1.25 million.

"The market value of LLPs is also competitive. The market price of these parts will be lower than the pro-rated value when their remaining life is considered," says Marston.

The current list price of high pressure compressor (HPC) and HPT parts is $1.53 million, and they have full life limits of 20,000EFC and 15,000EFC. Parts with, for example, 8,000EFC remaining would have a pro-rated value of $680,000 for the two modules. The market value will be less than this. "It is now possible to get green-time LLPs at heavily discounted rates, and to pay the equivalent of 6,000EFC remaining for parts that actually have 8,000-10,000EFC left. This is a price of only $450,000-500,000 for all parts in the two modules," says Marston. A small number of parts can probably be acquired for





American Airlines has retired most of its RB311-535E4-powered 757-200s. It still has 55 aircraft in service, but these are being phased out. It is possible to acquire time-continued RB211-535E4 engines that wil remian on-wing for 3,000EFC or longer.

$100,000-125,000 when performing a surgical strike SV. "It is even possible to get some time-continued LLPs for -3s at distress values of $15,000 per part," says Bennett. "This is despite a buoyant trade in CFM56-3 material. The value of used parts is usually about 25% of CLP, which includes big ticket LLPs such as some honeycomb parts. This is regardless of the remaining life left."

The first scenario to consider is the purchase of a green-time engine, and performing a minimal or surgical strike on the HP modules, which may include the replacement of a small number of LLPs. "A good SV can be achieved for about $700,000, which includes the replacement of LLPs with time-continued parts," says Grey. "This will provide sufficient EFC on-wing time for another two or three years' operation."

The additional cost of LLPs for this level of SV may add another $100,000.

The overall cost therefore of buying a time-continued engine will be $600,000-700,00, while putting it through a relatively small workscope will be $800,000. This takes the total to $1.4-1.5 million, and will provide an engine that can remain on-wing for at least 3,000EFC, and more likely up to 4,000EFC. The overall reserve for this will therefore be $350-500 per EFC.

The second scenario would be the purchase of the same time-continued engine for $600,000-700,000, plus the cost of a full core performance restoration. This would now be at a competitive cost of $950,000, reduced from $1.6 million. The remaining life of HP module LLPs would have to be considered to determine if any parts would need replacing. A conservative budget of $150,000 should be allowed. This would take the total cost to $1.7-1.8 million. There is also the possibility of some SV work being required on one or both of the LP modules, which would have to be factored in.

When amortised over the probable on-wing interval of 5,000-6,000EFC this would result in a reserve of $290-360 per EFC. This is more competitive than building an engine with a minimum workscope, but will only be used for those operators that require the full interval of up to 6,000EFC.

A third scenario is the purchase of an entire aircraft with time-continued engines. "A 737-300 or -400 that is less than 20 years old, can be acquired for $2-3 million," says Bill Cumberlidge, chairman and chief commercial officer at GCAP Aviation Partners. "Besides the engines the aircraft could be stripped for the most prominent and high value parts and components such as the landing gear, auxiliary power unit (APU) and avionics. These could recoup a value of $1.0-1.5 million over 18 months, meaning a net price of $1-2 million will have been paid for the two engines, or $0.5-1.0 million each. These could be installed on an aircraft straight away, or a small SV might be required to mitigate some risk if it was thought to be necessary." Assuming the engines removed from the purchased aircraft could achieve 2,000-3,000EFC without much risk, this would provide an equivalent reserve rate of $300-500 per EFC.

These three scenarios have to be considered against the cost of performing maintenance on an owned engine. The cost of an SV in this case will be similar to the cost of engine maintenance in the second scenario. The difference will therefore be between the cost of LLP replacement in the owned engine and the cost of replacing some LLPs and purchasing the engine in the second scenario. HP module LLPs, for example, have a CLP of $1.5 million.

PW2000 & RB211-535

The fleet of passenger-configured 757-200s has declined from a peak of 920 aircraft to 400. Some of these aircraft have been converted to freighter, via the Boeing or Precision Conversions modifications. There are now about 230 757-200s operating as converted freighters, alongside about 83 factory-built freighters that are mainly operated by UPS and FedEx.

The active 757-200 fleet has therefore imploded from about 1,000 active aircraft to 695, split between 253 PW2000-powered and 442 RB211-535-powered aircraft. These are 13-35 years old.

Besides freight operators, few other airlines are buying or leasing used 757-200s. The retirement of many aircraft has therefore released a large number of used airframes and engines onto the market.

PW2000

There are two main PW2000 variants that power the 757-200: the PW2037 and PW2040 rated at 38,250lbs and 41,700lbs. There are two sub-variants for each variant: those with a reduced temperature (RT) modification and those without. The RT engines have higher build standards and so higher EGTm, and have mature, post-full SV planned intervals of 15,000EFH or 5,000EFC for the PW2040 variant, and slightly longer at 17,000-18,000EFH or 6,000-7,000EFC for the PW2037 variant. The non-RT modified engines have mature intervals that are 6,000EFH or 2,000EFC shorter.

Of the two engine types on the 757-200, the PW2000 has the lower SV maintenance costs, as well as cheaper LLPs. The earlier built PW2000s had 30 LLPs, while later built ones have 25. The HPT disks have lives of 15,000EFC, while the remaining parts have uniform lives of 20,000EFC. The CLP for a full shipset of parts is $1.44 million for the two parts at 15,000EFC, and $5.1 million for the remaining parts. This a total of $6.5 million at 2017 prices. The annual CLP rise of 7% should also be considered.

Delta, which includes Northwest's 757-200 fleet, and United Airlines are the two largest PW2000-powered 757-200 operators. United's fleet also includes aircraft that were operated by Continental Airlines, but which are RB211-535-powered. The Delta and United fleets are therefore the two largest potential sources of PW2000 engines.

Polyi says values of the PW2000s have stayed relatively high, with Delta known to have swapped engines and modules on its 757-200 fleet so as to use as much on-wing engine and LLP life as possible before retirement. Polyi estimates PW2000 values at $3.0 million for a unit fresh from a performance restoration SV. Mid-life engines, so with 2,500-3,000EFC remaining on-wing life, have values of $1.5-2.0 million. "We expect these values to fall when the rest of the Delta and United fleets retire over the next few years," says Polyi.

A 757-200 operator interested in acquiring time-continued PW2000s can consider these values against the cost of full maintenance. No additional maintenance costs need be incurred when acquiring green-time PW2000s, since the uniform lives of LLPs mean none will have to be replaced if engines are carefully selected. A small 'surgical strike' SV may be needed to give a buyer assurances or guarantee a minimal on-wing life.

The maintenance or all-cost 'reserve' for acquiring a mid-life time-continued engine at this value will therefore be equal to $600-670 per EFC.

As with all older aircraft types, it can be economic to buy an aircraft, remove time-continued engines and sell the main rotable components. Cumberlidge estimates the value of a mid-1990s 757-200 at $3-4 million, and adds that it may be possible to realise about $1 million over an extended period from the sale of components. Taking the cost of disassembly into account, the net cost of the two engines would be $3-4 million, or $1.5-2.0 million per engine. This is about the same as individual engines on the aftermarket.

Such an engine might be able to achieve at least 2,500EFC on-wing, although this would only be equal to two to three years' of operation in the case of most airlines. This would result in an equivalent reserve of $600-800 per EFC. Reserves would be reduced if the engine could deliver a bonus of a longer on-wing interval.

A third scenario would be the purchase of a used engine with little remaining performance, but with ample LLP life, and putting it through a performance restoration. The market value of an engine in this condition would be less than $1 million.

The full or near full utilisation of remaining on-wing life by Delta of its PW2000s before retirement means there is also a limited supply of serviceable material available. It will therefore be hard to source low-cost SV inputs. These can be $2.5-2.8 million for performance restoration workscopes.

An airline with an existing engine that has at least 5,000EFC and up to 7,000EFC remaining LLP life can therefore avoid LLP replacement, and be satisfied with a performance restoration at up to $2.8 million that will result in an on-wing life of 5,000-7,000EFC. The purchase of an engine at $0.8 million will result in a total cost of $3.4 million. This will be equal to a reserve of $680 per EFC over a 5,000EFC interval.

The cost of a performance restoration and the replacement of HP module LLPs will have a higher total cost than all of these three scenarios. It will only be considered, therefore, for an engine if it

Low fuel prices over the past 18 months has renewed interest in operating 1980s generation widebodies. Consequently demand for CF6-80C2 engines and their associated parts and components has recovered.

required a long period of operation.

The cost of just a performance restoration for an owned engine that has LLPs with remaining life at least as long as an expected removal interval of 5,000-6,000EFC, will be about $2.6 million. This is only cheaper than buying a low-time engine and putting it through a performance restoration. The options of acquiring time-continued engines are lower in overall cost, but result in higher reserves per EFC because of their probable shorter removal intervals.

RB211-535E4

The RB211-535E4 has a reputation for achieving long removal intervals, but also having high SV costs. The RB211-535 powers about half of the 757-200s that have been converted to freighter, so demand for engines and engine maintenance will continue for at least 10 more years. In addition to its high SV and LLP costs, the only engine shops that are independent of Rolls-Royce are Ameco Beijing and Iberia.

The SV workscopes are defined as level 1 to 4, with level 3 and 4 being the major SV workscopes, and the disassembly of the engine into modules. "One main problem with the RB211-535 is that a level 3 workscope can easily turn into a larger level 4 workscope. There can be the intention to start at level 3, but if there are enough findings it can easily increase to a level 4 for the HPT and combustor modules," says Bill Tarpley, president at Creative Conversion Management. "Workscopes are expensive in that they can cost $3 million. With the cost of any LLPs that need to be replaced, they can easily climb to $4 million."

The shops available for the RB211-535 are very busy following the closure of American Airlines' shop TAESL. Some are being forced to go to Ameco Beijing for smaller SV workscopes.

The supply of RB211-535s can be better than the PW2000 at times, due partly to the retirement of a large number of 757-200s by American Airlines and several small carriers. A serviceable E4 engine with 5,000-6,000EFC remaining can be acquired for $2.2-2.8 million. The availability of engines should continue, with American Airlines still operating 55 aircraft, and the ex-Continental 757-200 fleet now operated by United and numbering 58 units. There are another 126 RB211-powered 757-200s in passenger operation.

The supply and availability of parts is also good, following the retirement of a large number of engines. "The removal intervals are also good at about 16,000EFH or 6,000EFC, depending on operating ratio," says Tarpley. "Freight operators mainly achieve 2.25-3.0EFH:EFC. Cargojet Canada operates in a cool environment and achieves intervals longer than 6,000EFC."

When an operator is considering acquiring time-continued engines they do not want to have to buy any new discs afterwards. "They therefore look for engines that have 8,000-10,000EFC remaining for at least one removal interval of up to 6,000EFC, and preferably up to 12,000EFC," says Tarpley. "This way the engines can achieve up to two SVs at intervals of 6,000EFC. The engine can therefore be operated for two intervals, have an SV after the first and then retire when the second comes due." If an engine with this LLP life remaining can be acquired, it can operate for as long as a freighter aircraft. "Engines with disc lives of 8,000-10,000EFC are not desirable, and those with up to 6,000-7,000EFC or 11,000-12,000 are preferable," adds Tarpley.

An airline with an engine with at least 6,000EFC remaining LLP life can therefore avoid the cost of replacing any of the parts for the 8-10 year period. The problem is complicated, however, by the RB211-535 having several operating profiles that affect the life limits of the LLPs.

The original operating profiles were profile A and B. The profile used depends on the engine's rate of utilisation, EFH:EFC ratio and the environment it operates in.

Profile A has lives of 18,000EFC for the HPC stage 1-2 disc, lives of 16,000EFC for some parts in the LPT, and the shortest lives of 15,000EFC in the HPT. Many other parts have longer lives of up to 27,650EFC.

Profile B reduces the HPC stage 1-2 disc to 12,600EFC, but all other parts have the same lives as in profile A. Profiles A and B are now used just for -535E4 engines.

Rolls-Royce issued four new profiles C, D, E and G for the RB211-535E4 and -535E4-B engines powering the 757-200 in December 2012. These were revised through various SBs in February 2016 and August 2015. These four new profiles reduced the lives of some parts because the number of accumulated EFC were not being monitored by several airlines.

SB RB211-72-AG875 was issued in December 2012, and revised in February 2016. It issued life limits for some of the LLPs in profiles C, D and F for the -535E4-B and -535E4-C engines powering the 757-200.

It also issued profile E for engines powering the 757-300.

Profile C is for the -535E4-B, and is the same as the original profile issued for the engines under the original A and B profiles, depending on how the aircraft is operated.

Profile D is also for the -535E4-B, and has different EFC limits for the some of the parts. The four most limited parts are the HPC rotor disc stage 1-2 and rotor disc stage 3 at 15,700EFC and 15,000EFC; and the HPT disc at 13,900EFC or 14,500EFC, depending on part number. The LPT shaft is limited at 16,000EFC.

SB RB211-72-AH972 was initially

issued in May 2015, and issued life limits for some of the LLPs in profile G for the -535E4 and -535E4-B engines powering the 757-200.

The six most limited parts are: the LPC shaft at 14,230EFC; the HPC stage 1-2 rotor at 12,600EFC; HPC stage 3 rotor at 15,000EFC; HPC rear rotor shaft at 15,000EFC; the HPT disc at 11,000EFC or 14,000EFC depending on part number; and the LPT stage 2 disc at 13,300EFC. The life of this last part can be increased to 20,900EFC after re-working detailed in a SB.

There are three scenarios to consider for time-continued engines. The first is the purchase of an engine that can be expected to achieve at least 4,000EFC on wing without any significant maintenance. If available, an engine in this condition can be acquired for about $2.8 million and can be expected to stay on wing for about 4,000EFC. This results in an equivalent reserve of about $550 per EFC, although this will be lower if a bonus of a longer interval is achieved.

The second scenario is the purchase of an entire aircraft with two serviceable engines. These have a value of $4-5 million, resulting in a net engine cost of about $2 million. An interval of at least 3,000EFC can be expected, resulting in a reserve of about $500 per EFC.

Buying an engine with little performance and EGTm remaining, but good LLP lives, can cost about $1 million. The cost of a performance restoration will be about $3.75 million, taking the total to $4.75-5.0 million. The engine can be expected to have an interval of at least 5,000EFC, resulting in a reserve of $950 per EFC.

The option of a performance restoration with no LLP replacements on an owned engine will therefore be cheaper than acquiring an engine with low EGTm on the aftermarket. Acquiring engines with remaining performance and on-wing life is the cheapest option overall, and the risk is low given the RB211-535's reliability.

CF6-80C2

The CF6-80C2 is the ubiquitous engine for 1980s generation widebodies. It had about half the market share for the A300-600/-600R, A310, 767-200ER/-300ER, 767-400ER, 747-400 and MD-11. Most A300s, A310s, 747-400s and MD-11s have been withdrawn from service, due to a combination of age and high fuel prices. Consequently the supply of time-continued or 'green-time' CF6-80C2 engines reached a peak in 2014-2015. Market values were weak and SV activity was poor.

The fall in fuel prices over the past 18 months, however, has given a new lease of life to a reduced number of 747-400s, including freighters, and some A300-600Rs. Moreover, a large number of 767-300ERs and -400ERs remain in operation. Now almost fully depreciated and financed, these medium-sized widebodies provide unbeatable trip and seat-mile costs in their size category. These two 767 variants therefore keep the market for the CF6-80C2, and the PW4000-94, alive.

There are 18 different variants of the -80C2. All engines powering the MD-11, with a D suffix, most engines with a B suffix that power the 767 and 747-400, and some A suffix engines powering the A300-600RF have full authority digital engine control (FADEC) units. These have precise control over engine power, and the thrust rating of any variant can be changed. This includes when switching the aircraft type on which the engine is installed. Despite this, the quick engine change (QEC) kits of line replaceable units (LRUs) mounted on the outside of the engine have to be changed when switching aircraft types.

Some of these aircraft, the A300-600/-600R, all engines powering the A310, and some B suffix engines for Boeing aircraft do not have FADEC controls, so they are not interchangeable with engines that do have FADEC controls.

Most CF6-80C2s are used on long-haul operations, so they accumulate 600-800EFC per year. Operating ratios for 767-300ER/-400ERs and 747-400s are 5-9EFH:EFC. Engines therefore accumulate 4,000-5,000EFH and 550-800EFC per year on these aircraft. Mature removal intervals for engines used on these types of missions are 15,000-20,000EFH, although it is possible to get 25,000-30,000EFH through high level workscopes at each removal. These typical intervals are equal to 2,500-3,000EFC.

These have to be considered against LLP lives. Most parts have uniform lives. The four parts in the HPT have lives of 15,000EFC, and a CLP of $1.35 million. The other parts in the fan/LPC, HPC and LPT have lives of 20,000EFC and a list price of $5.95 million. Replacement of these expensive parts on fully used and owned engines may be avoided by buying green-time engines.

"The retirement of large numbers of CF6-80C2s has been 18 months behind the wave of PW4000-94 retirements," says Polyi. "Large numbers of MD-11s and 747-400s have been retired and phased out of passenger operation."

Of the 747-400s built with CF6-80C2 engines, 171 have been retired, while 155, including 50 factory-built and 29 converted freighters are still in service. Some passenger-configured aircraft are also earmarked for conversion. Remaining passenger-configured 747-400s in operation include those operated by Asiana, China Airlines, EVA Air, KLM, Lufthansa, Thai International, and Virgin Atlantic. "Some of the Asia Pacific operators are retiring their fleets, so there may be a glut of engines over the next 18-24 months," says Polyi.

Although the MD-11 only proved moderately popular, 76 CF6-powered freighter variants are still listed as being in active service. This includes 12 Lufthansa aircraft, compared to 43 retired freighters.

The 767 fleet has proved the most resilient. While most 767-200ERs with CF6-80C2s have been retired, there are 27 767-300s, 251 767-300ERs, 165 767-300ERFs, and 37 767-400ERs totalling almost 500 aircraft equipped with CF60-80C2s in service. Most of these aircraft are equipped with FADEC engines, compared to 115 CF6-powered 767s that have been retired. Overall, more than 710 CF6-powered MD-11s, 767s and 747-400s are in service, while there are 330 retired aircraft. There are also 50 A300-600RFs in service with FADEC engines.

This number of retirements initially put a large number of run-out and time-continued engines on the market. "There was a big drop in CF6-80C2 values two years ago," says Bennett. "This has now changed with low oil and fuel prices, so retirement of older aircraft has slowed. The other issue is that few engines were put through the shop, and this has drained the supply of green-time engines. MTU Maintenance is seeing an increase in SV activity. The values of -80C2s have therefore increased."

The activity in the market for green-time -80C2s was high, but supply has tightened and it is only possible to get engines with low time remaining. "The largest supply has come from 747-400s. Some engines have been torn down to get cheap parts, especially for the HPT and stage 1 LPT nozzles," says Vesa Paukkeri, president and chief operating officer at CTS Engines Miami. "There is also interest in the HPC blades and vanes, and it is getting harder to find parts, so prices have gone up a lot. This is reflected by the fact that Chromalloy is doing well in its sales of PMA parts that include stage 1 HPT blades."

The overall effects are strengthened engine values. "A freshly overhauled engine may have a value of $4 million, and should have LLP lives that give the engine at least 10 years of operation," says Paukkeri. "A time-continued engine will have a value of $1.5-2.0 million, depending on remaining LLP life. A completely run-out engine had a value of

$0.5 million, but this has now climbed to about $750,000.

"The core performance workscope on a CF6-80C2 will involve the HPC, combustor and HPT. The engine also has an issue with oil leaks at the compressor rear frame (CRF)," adds Paukkeri. "A shop visit of this level will cost about $2.0 million. It was possible to get this cheaper, but supply of materials and shop capacity has reduced." The cost may well increase as the supply of serviceable materials is acquired and used up in SVs over the next few years.

Paukkeri adds that it is also possible to put an engine through a minimal workscope at low cost. "This will involve fixing broken blades via case removals, and minimising blade tip clearances. This will not increase the number of possible EFCs on-wing, but will make the engine operable for one or two years. This can cost just $150,000. A slightly larger workscope can be done for $600,000-800,000, and can increase EGTm by about 10deg."

The first option for an operator is to acquire green-time engines by buying the entire aircraft following airline retirement. With almost no opportunity for further freighter conversions, the value of 747-400s is now low. "These are actually hard to sell, but the value is probably less than $10 million for an aircraft with engines that are approximately half-life," estimates Cumberlidge. "Values may even be considerably lower. It is possible to gain some value from the sale of rotables, but this will be increasingly hard. The cost of dismantling and engine removal has to be considered. This puts the value of each of the four time-continued engines at $1.0-2.0 million. Buying a 747-400 is only likely if three or four of the engines have LLPs at approximately half-life. These engines might be able to achieve a mid-life interval of at least 1,200EFC.

"The market value of a 767-300ER with decent quality engines is probably $8-10 million, since most aircraft are now more than 20 years old," adds Cumberlidge.

With this sale of parts, the net cost for two engines could be $6-7 million or $3.0-3.5 million per engine. Buyers will only pay this of they can get engines with at least 10 and preferably 15 years of equivalent LLP life. This is 7,000-11,000EFC.

Operators will only consider green-time engines with long remaining LLP life compared to their own with run-out or short remaining LLP lives. This is the only way a green-time engine can provide an economic alternative. "A few LLPs may be required, and LPC and LPT parts can probably be bought for less than pro-rated values," says Paukkeri. "Pro-rated values will probably have to be paid for HPT and HPC parts.

A run-out engine but which has at least 2,500EFC of LLP life remaining, will cost about $0.75-1.0 million. The additional $2.0 million for a performance restoration will lead to a total cost of $2.75-3.0 million, and a reserve of about $1,250 per EFC when amortised over 2,300EFC.

These values for a mid-life engine are similar to the cost of a performance restoration on an owned engine. The owned engine is likely to achieve a longer interval, however.

"The economics of acquiring green-time CF6-80C2s has changed with the rise in value of engines, and the relatively low SV costs favouring owned engines," says Paukkeri. "The SV costs are noticeably cheaper than they are for the PW2000 and RB211-535E4." AC