The complexity of engine maintenance means the lowest possible cost per engine flight hour may not be known. Improved engine maintenance techniques lead to lower possible costs, but take years to analyse and constantly move the cost target.

Fine tuning engine maintenance costs

The on-condition concept of engine maintenance causes a variety of repair and overhaul workscopes and the resulting costs per engine flight hour (EFH). The main driver in cost per EFH is the time on-wing that an operator can achieve between subsequent removals. The quest to find the lowest cost per EFH and extend on-wing times is ongoing. Airlines and manufacturers alike are convinced that a lot more improvement is possible.

Maintenance principles

Earlier-generation engines have had the shortest on-wing times between removals and the largest workscopes in the shop. This has kept costs per EFH high for such powerplants.

The weakest characteristic of these earlier engines was their relatively fast deterioration of hardware in the hot section. These engines therefore suffered fast exhaust gas temperature (EGT) margin loss and were 'pulled' or removed for a shop visit as a consequence.

The design of more recent engines has concentrated primarily on slowing down this rate of deterioration by improving and preserving EGT margin. This will extend on-wing time, with the objective of lowering cost per EFH.

With improved hot-section durability, other parts of the engine have increasingly shown themselves to be susceptible to deterioration – and the cause of engine removals. These problems become apparent in poorer engine reliability during operation. These can be tracked by condition monitoring, which can then be used to predict when an engine should be removed.

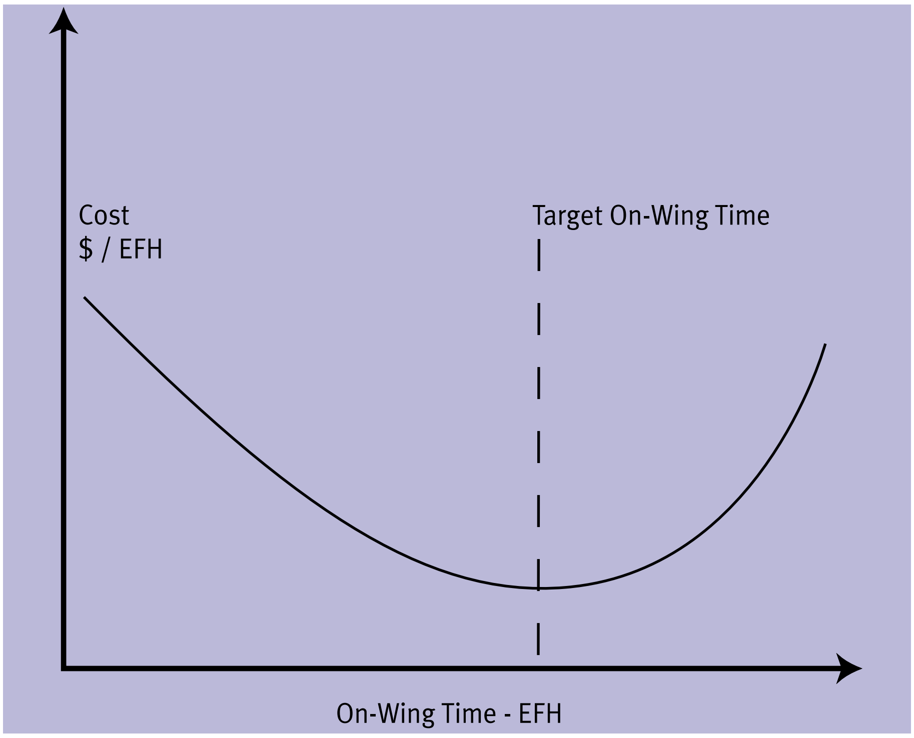
Longer on-wing times have generally meant a higher level of wear and deterioration for all other parts. This generally leads to a higher degree of parts being replaced.

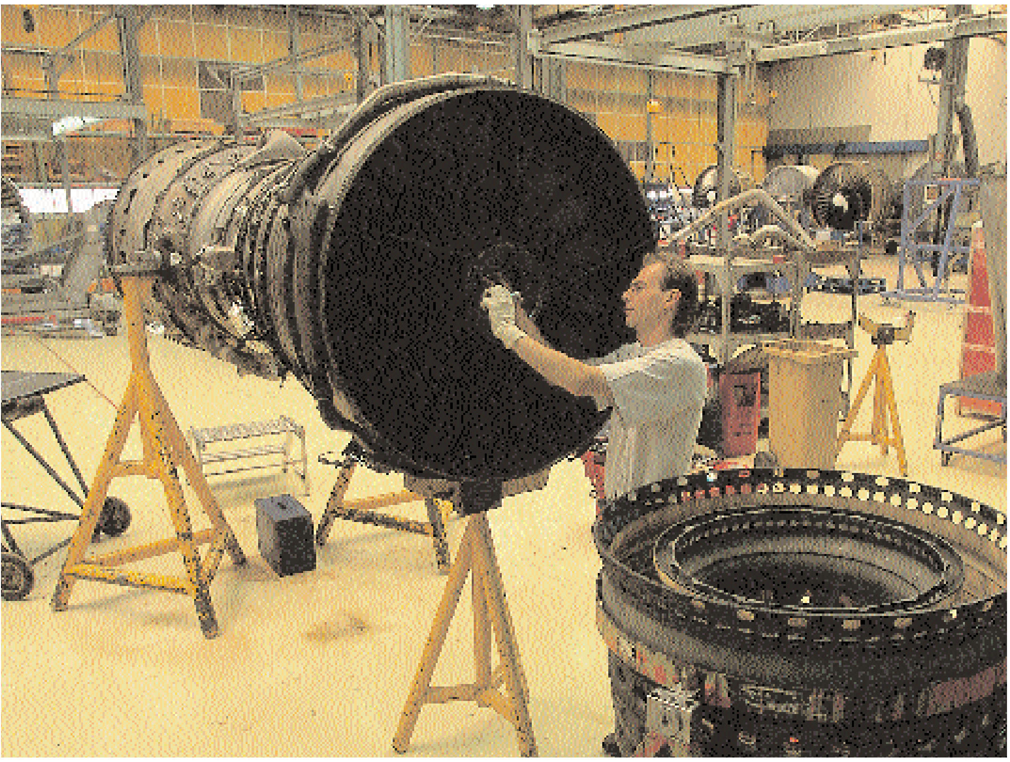
Increased time on-wing can therefore lead to a higher cost workscope compared to a workscope after a shorter time on-wing. A relationship therefore exists between time on-wing and cost per EFH. This generally takes the shape of a U-curve *(see chart, this page)*.

While engine design and reliability improves on-wing, the time between removals increases. Improvements in reducing shop visit workscope costs through a higher level of component repair and increased durability of parts has led to a flattening of this U-curve.

The key to fine-tuning engine maintenance costs is knowing the U-curve characteristic of the engine, improving on-wing time and reducing the cost of the workscope for a corresponding removal interval.

It is relatively easy to increase on-wing time by replacing a high portion of parts. This practice is referred to as "gold plating" an engine. It often results in the economics moving up the right-hand side of the U-curve. Increasing the proportion of repaired parts reduces shop visit cost. Repairing rather than replacing components may result in shorter on-wing times. Repairing parts, however, costs five to 10 times less than replacing them. The resulting cost per EFH will therefore move to the centre of the U-curve. If on-wing times are the same when switching from replace to repair,





Aiming for the lowest possible cost per EFH is complicated by so many factors that it is almost impossible to assess, let alone target.

the U-curve flattens and the optimum centre point moves to the right.

Hit and miss

The difficulty in getting longer removal intervals arises from the fact that engine shops have to experiment with techniques to reduce workscope costs, but do not know what the full effects are until the next removal and shop visit. This requires a feedback mechanism to evaluate the effect of new techniques. The behaviour of the engine and components can, however, be monitored.

Engines in the same generation as the CFM56-3, RB211-535, CF6-80C2 and PW4000-94, typically have on-wing times of between 10,000 and 15,000EFH. These engines tend to fall on the left side of the U-curve. More recent generation engines, such as the PW4000-100 and Rolls-Royce Trent, tend to fall on the right side. They are achieving longer on-wing times, the EGT margins and reliability issues having been addressed. The challenge with these powerplants is for the shops to reduce shop visit costs.

"The right philosophy with older-generation engines was to increase on-wing time, since their costs would come down towards the middle of the U-curve,"says Stephan Regli, powerplant engineering technical support at SR Technics. "For example, the SR Technics target for the PW4000-94 was 16,000FH, but we only got about 11,000–12,000FH. We expect new engines like the PW4000-100 and Trent 500 to reach longer times of at least 16,000FH.

The EGT margins of the latest generation turbofans are now as high as 150-200°C. The CFM56-5B4, for example, has a 165°C EGT margin.

"The newer engines have about 25°C higher EGT margins. A sign of a good quality shop is if the EGT margin after a shop visit is within 5°C of the original," claims Regli. One example of gold plating an engine is getting an even better restored level of EGT margin. "A shop should not be too excessive in restoring margin because it will cost too much, that is, the economics will be riding up the right side of the U-curve. The trick is in predicting the workscope, or rather the degree of part replacement."

Performance considerations

One important aspect is the flight hour:flight cycle (FC) ratio. Engines that are operating shorter average FCs will experience a faster rate of deterioration. Average FC times can be from less than one FH up to 10FH or more.

Average FC times are relevant with respect to life limited parts (LLPs). LLPs have lives fixed around 20,000–30,000FCs. For example, an engine with an average FC of 1.5FH and an average time between removals of 10,000FH will use 6,700FC of the LLP's lives. An LLP life of 20,000FCs will therefore mean LLP replacement every third shop visit. At the other extreme an average FC of 8FH and time between removals of 10,000FH will mean that an engine achieves 1,250FCs between removals. LLPs in this case would only need to be replaced every 16 shop visits, or after 160,000FH. This would be equal to about 40 years' operation, meaning the LLPs would probably never be replaced during the life of the engine.

On-wing times of engines operated on short cycles, therefore, can be compromised by LLP replacement. One technique manufacturers use to extend on-wing times is to get certification for longer LLP lives.

The EGT margins on the lower thrust rated variants of new engine families, for example the CFM56-7, are so high that LLP replacement can be the main driver of on-wing times and removal intervals.

Planning shop visits, setting targets for on-wing times and aiming for the lowest cost per EFH has to revolve around LLP lives for engines operated on short cycles.

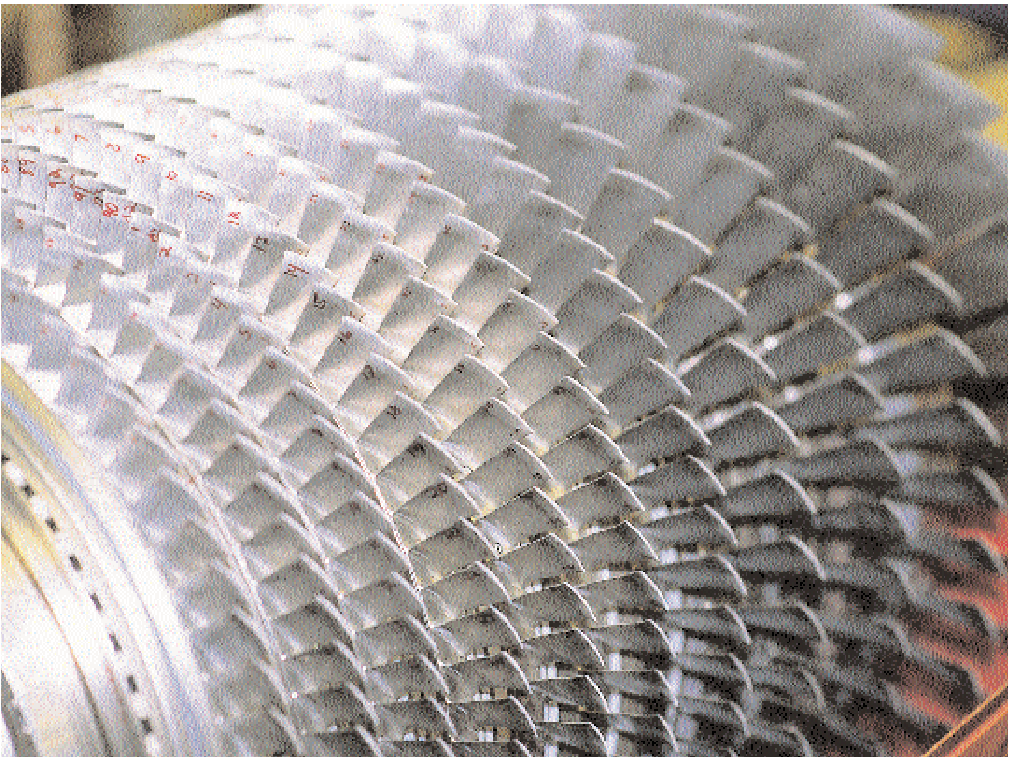
Re-rating a higher thrust engine variant to a lower thrust variant in a family is a technique that reduces turbine entry temperature to preserve EGT margin. This will also extend on-wing time and will often reveal factors other than EGT margin erosion that trigger engine removals.

Engine design

Besides improving maintenance and repair techniques, manufacturers can improve engine designs. The turbine sections can have the temperature margin capability improved by using more tolerant materials. "The CFM56-5B and -5 series, for example, use single crystal first-stage turbine blades," says Francis Couillard, sales engineering director at CFMI.

"Engines can also be designed with a cooler thermodynamic cycle so that they have a lower turbine temperature for the same thrust rating. With a combination of better materials and thermodynamic cycle it is possible to get up to a 46°C improvement in EGT margin," claims Couillard.

Manufacturers have also begun to incorporate and retrofit the new designs and features of their more recent engines into earlier models. An example is the three-dimensional compressor on the CFM56-7 series. "CFMI is going to redesign the -3 series' compressor and develop a modification than can be retrofitted in the engine during a shop visit," says Jim Davies, manager engine services marketing at General Electric Engine Services (GEES). "This way the -3 series will have an improved specific fuel consumption, and because it has a



Engine design features, such as more efficient compressors that achieve cooler thermodynamic cycles, are factors that contribute to longer on-wing times.

more efficient compressor and cooler thermodynamic cycle, it will achieve longer removal intervals. Also, we are going to take the improvements in the -80C2 series and launch an upgrade programme to retrofit them in the -50 series."

Condition monitoring

Besides the EGT margin, there are a multitude of other factors that affect an engine's ability to remain on-wing, or drive the need for a removal.

The area of an engine most susceptible to deterioration is the hot section. This includes the high-pressure turbine (HPT) blades, combustors and nozzle guide vanes (NGVs). "Excessive on-wing times can affect the hardware," explains Simon Morrien, manager product development at KLM engineering & maintenance. "An operator always needs to maintain the repairability of a part. If it is on-wing too long it may have to be scrapped. Excessive on-wing times can also lead to reliability problems."

Examples of factors that drive removal intervals are high pressure compressor stability, durability of bearings, blade tip wear leading to vibration and increased fuel consumption and blade erosion and cracking. "The number of factors which cause engine removals can be just a few or many," explains Rolf Burmeister, manager of engineering and repair at MTU Maintenance. "To find the causes of engine removal a fleet's removal and workscope statistics have to be examined. A good engine shop will produce engines that have a concentration of weak areas causing removals. A poorer shop will produce engines that get removed for all sorts of reasons.

"The prime reason for the CF6-80C2 removals, for example, was its HPT blades. The second factor was the EGT margin. Now that these problems have been resolved the next main driver for removals is wear of the variable stator vanes," says Burmeister.

Condition monitoring is used to track the multiple causes of engine removals, to predict when engines will have to be removed and also to anticipate the workscope required in the shop. "This means sophisticated monitoring systems are required," says Regli. "The engine manufacturers have their own packages, for example, GE has Sage, Pratt & Whitney (PW) has Eagle Link and Rolls-Royce has Compass. These can monitor the performance of modules. In addition, they are computer systems that continuously record engine parameters throughout the flight. For example, 500 different parameters are recorded on the A320. We try to use these parameters to assess the workscope. This is because we can predict which parts can be repaired and which will need replacing.

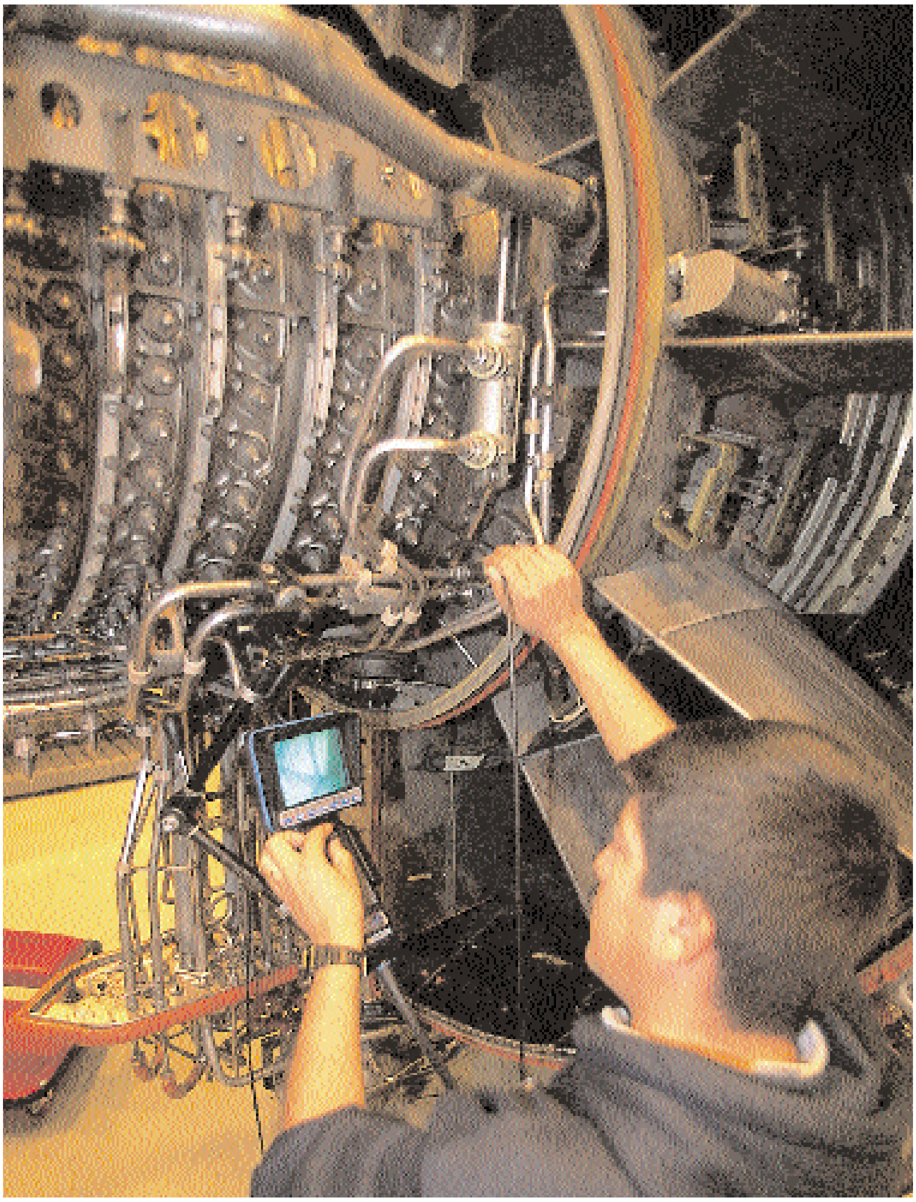
"Using this we can advise the engine shop on what material will be required three or four months before the removal. This has an added benefit of minimising turn time," explains Regli. "By being able to predict the workscope we can then plot the shop visit cost versus the on-wing time and so can get an idea of the optimum on-wing time.

"The most important items to monitor are the high-cost parts. This includes the HPT blades, the low pressure turbine blades, NGVs, combustors and seals. To get an idea of how these deteriorate with on-wing time we remove some of the youngest engines early," explains Regli. "This is at about 10,000–12,000EFH so we can plot a graph of on-wing time versus shop visit cost. The opportunity to examine the youngest engines early usually comes from foreign object damaged engines anyway".

The techniques that have evolved to monitor engine condition while on the wing have grown in sophistication. "Video borescoping is a useful technique," says Morrien. Line mechanics do the borescoping and they have to be able to interpret the state of the hardware as effectively as the shop mechanics can. This way we have a better idea of the right time to remove the engine."

One of the latest innovations in engine condition monitoring is GEES's remote diagnostics system. This is based on engine parameter data being transmitted in real time to an automated diagnostic system at GEES in Cincinnati and it is a service provided to GEES's customers. GEES has a unit staffed by remote diagnostics engineers 24 hours a day that can monitor engines while in flight. Many parameters are processed and analysed. "The newer aircraft have the best transmission capability in terms of how many parameters they can transmit," explains Dave Brandel, manager of remote diagnostics at GEES. "We then diagnose the data to get information to identify faults and abnormal conditions to determine how best to treat the engine in terms of which parts are required, finding faults and what repairs are needed. The end result is that we can reduce delays and engine removals.

"Industry-wide experience is that the savings opportunity made over the past 10 years from increasingly sophisticated condition monitoring systems are in the region of $5-15/EFH," claims Brandel. "The whole point of remote diagnostics is that we can reduce premature and unscheduled removals by identifying problems, which improves overall on-wing times. The engine's condition can be monitored, engine faults can be tracked and maintenance can be diagnosed and planned. It can provide real-time operational support and can aid in remote engine fleet management.



GEES has developed sophisticated condition monitoring techniques, such as remote diagnostics systems and on-wing support allowing quick-turn light workscopes.

Ultimately remote diagnostics is used as a feedback mechanism for engine maintenance, to develop maintenance repair procedures and design modifications to improve reliability."

Workscopes

Work performed on different engines in the shop is highly variable. The basic objectives are to restore the engine's performance and to build the engine to a standard at which following on-wing time will amortise the cost of the shop visit to the most economical level.

The difficulty in establishing what workscope will provide the lowest cost per EFH is that there are so many parts in the engine. Parts and modules all have different rates of deterioration. This means it is impossible for all parts to arrive at the economical optimum stage for repair or replacement at the same time.

Parts should neither be removed too early or late. Determining the optimum on-wing time that provides the best economics for each part alone is difficult.

The optimum time for removal is basically changed when better repair techniques are developed. These can extend the threshold between a part being repaired and replaced. Most shops follow the policy of only repairing parts if their repaired condition is close to that of a new part.

Engine shop visit workscopes basically fall into four categories: inspection, inspection repair, performance restoration and full overhaul. "Performance restoration of parts brings them back close to their original specification. For example, compressor blades would be polished, some would be repaired and would be reinstalled with the original clearances with the stators," explains Morrien. "Overhauling them would involve taking the whole assembly apart and overhauling each component so it complies with overhaul inspection limits.

"Rarely does the whole engine require a full overhaul. Modules are overhauled individually at different shop visits and this makes each shop visit unique," says Morrien. The workscope planning guide (WPG) has thresholds for inspection, performance restoration and overhaul. The WPG also recommends what work is required for the three levels. Initial inspection will then determine what is required, and also what is the cause of the requirement. "We then determine if the cause of the requirement is an isolated case or whether it occurs in all engines and we need to redefine the thresholds," explains Morrien. "As an example the second NGV started blowing out in the CF6's HPT. This triggered a change to our repair policy."

Bob Gamache, director engine service programs at Pratt & Whitney notes: "We have a philosophy of providing total management for the engines and include the cost of incorporating SBs in our power-by-the-hour rates. Each engine has to have its own specific maintenance plan. We have a maintenance planning committee for each customer and engine. All decisions regarding maintenance are taken to increase on-wing time.

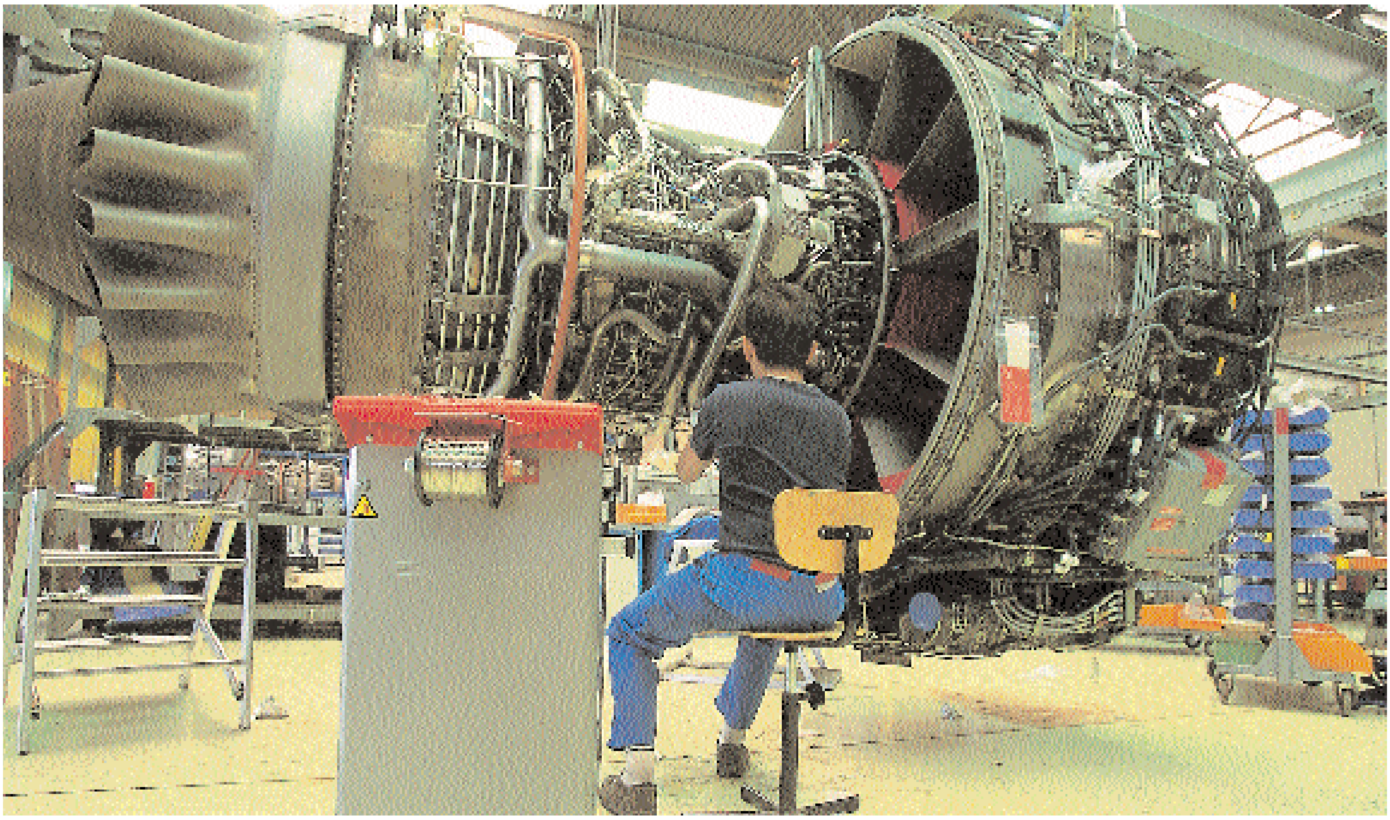
He continues: "The important factors in arriving at the bottom of the U-curve are to match engine modules. That is, if we are doing a performance restoration on a module or the engine, then the expected resulting on-wing life must match the expected life of other modules and remaining life of LLPs."

GEES has developed a new philosophy to work on engines in the field prior to taking them into the shop. GEES has nine mini facilities located near major airports around the globe where it takes in engines for minor work. Known as On-Wing Support, GEES can provide on-wing repairs for engines. If the work cannot be done on-wing, the engine can be removed, but it can still have repair work done on it without disassembly of modules. These quick-turn light workscopes include repairs to compressor blades either through borescope ports or by removing a section of compressor casing.

"This system allows us to determine whether we can use on-wing support or if the engine requires a shop visit," explains Gary Short, business leader of GE on-wing support. "Our On-Wing Support system means we can delay an early shop visit and so get more time on-wing."

Fine tuning & feedback

The issue of improving the economics of engine maintenance is to increase the degree of part repair without compromising resulting on-wing time. "Basically it is an issue of waiting to see if



Ultimately, getting the lowest cost per EFH is a result of the continuous cycle of developing new repairs and assessing their effects.

repair techniques have improved on-wing life. They may actually shorten subsequent on-wing life," warns Morrien. "The WPG provides a guide on how long parts should be run until they need an inspection, performance restoration or overhaul. An operator constantly plays with these thresholds. It is also constantly trying to find the optimum mix of these thresholds between different engine modules and ultimately would like to match these thresholds.

"For example, a shop may do just an inspection and actually find that it should have done a performance restoration. The threshold between the two should then be reduced. Thresholds can also be maintained or extended by changing the workscopes for each. If it is not economical to improve a repair then thresholds get reduced. Eventually the bottom of the U-curve can be found.

"The ultimate goal is to align the U-curves of each module. The problem is that you get a lot of interaction between modules," explains Morrien. "It is essential that records and the life history of all parts are kept to monitor these thresholds because decisions taken to alter repairs will take several years to detect. Improving engine maintenance costs is a constant re-assessment cycle of finding the relation between workscope, cost, performance and time on-wing."

This constant reassessment centres on developing repairs. Only a full understanding of the engine will allow improved repair techniques to be developed. "We have to know what to adjust in the engine to get more EGT margin, for example, and life on-wing. This means that we may have to adjust limits and design our own repair techniques," says Burmeister. "Repairs have to be relevant to on-wing time performance. We have a feedback mechanism where engineers examine the engine at teardown and compare it with the last repair workscope.

"We also have to involve the customer. We have to discuss improvement potential and items such service bulletins (SBs). It is necessary to know the engine well, your engine shop well and to understand the engine operator in order to increase on-wing time. A shop will actually experience diminishing returns in terms of dealing with problems, since the costs of dealing with a problem can exceed the benefits. We therefore concentrate on improvements that have the lowest costs.

"The weakest link in this process is where we might have a fixed price contract for a shop visit because this often results in poor on-wing times," says Burmeister.

Identifying the right workscope and repairs is part of the fine-tuning and feedback process that is crucial to extending on-wing time. "This includes developing more sophisticated repair techniques. Because our maintenance contracts are done on a fixed cost per hour basis it is in our interests to lower costs," says Jim Davies, engine services marketing at GEES. "This encourages us to develop repairs."

Because of the time and feedback required to analyse the effectiveness of new techniques, engine shops need the full cooperation of the operator. Airlines that are looking for quick fixes and the lowest cost for the next shop visit will not achieve the lowest cost per EFH in the long-term.

"This means the engine maintenance concept has to be developed with a long-term view," says Regli. "It also requires exhaustive on-wing and shop experience which means that there needs to be close cooperation between the operator and engine shop if on-wing times and economics are to be improved. With experience of an engine a shop gets to know what are the most important items to monitor. Ultimately it is down to the policy of the shop and the airline. Most airlines and shops seem to be in the position of improving reliability and on-wing time. That is, they are on the left side of the curve and trying to move towards to the middle. This means they have not got to the stage where they have reached sufficiently long on-wing times to get the optimum cost per EFH."

The feedback process of identifying cost reduction techniques will take several years. "It takes about three years from deciding to make an improvement before one can be made," explains Gamache. "When they come due for an overhaul, SBs and modifications can be implemented. It then takes until the next removal, up to another three years, to see what effect the improvements have made." AC