Rolls-Royce Trent family maintenance costs

Removal intervals,shop visit workscopes, shop visit costs, and LLP lives and list prices give an indication of maintenance reserves for the Trent 700, 800, 900 & 500 series.

Reserves for maintenance costs are affected by several variables. The most important are interval to shop visit, shop visit workscope and cost, life-limited part (LLP) lives and utilisation, and LLP costs. These elements can be examined to get a reserve per engine flight hour (EFH) and per engine flight cycle (EFC) for the two main elements of engine maintenance.

Total care packages

Most Rolls-Royce (RR) engines are maintained under total care packages (TCP). Engine shop visits are performed through facilities that are either owned by RR, or are a joint venture between RR and a major maintenance provider. These include TAESL in Texas, SAESL in Singapore, HAESL in Hong Kong, and N3 in Germany. RR therefore maintains control of most RB11 and Trent engines in operation.

In addition to the shop-visit maintenance of engines and the replacement of LLPs, the TCP packages offered by RR provide a wide variety of services related to the management of engines, and which airline engineering and maintenance departments have traditionally organised themselves.

The services provided under TCP can be selected by airlines from a menu, and paid for on a cost per EFH basis. The aim is to provide airlines with a predictable and stable cost, and remove the need to arrange and perform the function.

A key element of RR's TCP packages is comprehensive engine health monitoring (EHM). This is provided by RR's subsidiary optimised systems and solutions (Osys). This service analyses engine health and performance data sent from the aircraft in real-time. It is part of the engine management traditionally carried out by airlines, but needs specialist equipment and trained staff.

In hand with health monitoring, RR provides TotalCare workscope, which defines the appropriate shop-visit workscope to allow the engine to achieve the optimum time on-wing to the subsequent removal and shop visit.

RR also offers a reliability improvement service through selection of appropriate modifications to improve on-wing reliability. RR can also offer specialist line maintenance for aircraft-on-ground (AOG) situations. These occur randomly, and can be expensive, especially when aircraft are grounded for long periods and replacement engines have to be sent long distances.

Another element of line maintenance is managing and provisioning engine line replaceable units (LRUs) and accessories. Since these components fail, and require replacement, at random this requires a logistics service and organisation. RR provides this as an element of TCP on a flat-rate cost basis. As part of this, RR also monitors the component configuration of engines as an engineering management service for airlines.

Technical records of all maintenance performed also have to be kept. RR provides a technical records service by capturing, storing and retrieving records as required. This can also be added for creating work documents and continuing airworthiness management.

RR also provides spare engines, on a long- or short-term basis, through its subsidiary Rolls-Royce Partners Finance Ltd. RRPF has a portfolio of 290 engines, including the Trent family, available to airlines and lessors globally. RR also offers a lease return conditions management service. This ensures that leased engines are returned in the right maintenance condition and LLP life status.

Shop-visit maintenance

With shop-visit removal intervals, workscopes, shop-visit costs, and LLP replacement timings and costs it is possible to get approximate reserves for engines on a $ per EFH or per EFC basis.

LLPs in Trent engines are sub-divided between Group A parts, the disks and shafts; and Group B parts, the fan blades and annulus fillers that are placed between the fan blades. The list price of a shipset of Group A parts for the Trent 700 is $4.1 million, and the list price of Group B parts is about $2.0 million.

For the Trent 800, the list price of Group A parts is $4.9 million, and Group B parts have a list price of $2.7 million.

The Trent 500 has list prices of $4.6 million and $2.0 million for Group A and B parts. The Trent 900 has list prices of $4.9 million and $1.9 million for Group A and B parts.

The life limits of LLPs are an important factor in engine management. Each Trent family member has a target life for LLPs, and actual certified lives. Target lives are either 10,000EFC or 15,000EFC, depending on engine variant and thrust rating.

Actual certified lives are the lives of different part numbers for LLPs installed in the engine. These can be as low as 1,000EFC or as high as 15,000EFC at service entry. Certified lives can be extended for a part number while in service, as a result of testing by RR. When these parts are removed at a shop visit, they can be replaced with part numbers that have a higher certified life. The certified lives of replacement parts can be target lives, or just a longer life compared to the life of the original part.

RR's stated intention is for certified lives to be gradually extended to target lives. The lives to which parts get extended ultimately depends on the amount of testing done by RR.

The short or 'stub' certified life limits of individual parts can force early engine removals, or compromise removal intervals. LLP reserves account for a large portion of total maintenance costs. If the cost of a replacement part were amortised over the short certified life of the original part, then LLP reserves would be excessively high. It may be possible for operators to be compensated for short lives of individual parts through various mechanisms. One possible mechanism is for the operator to not pay full price for the replacement LLP, but pay a pro-rated price in proportion with its certified life. For example, a cost of $100,000 may only be charged for a part with a list price of $300,000 and a target life of 15,000EFC, but which had a certified life of 5,000EFC. This way LLP reserves per EFC would be kept to a level that is equivalent to list prices amortised over an interval equal to target lives.

The Trent 700 has a target life of 15,000EFC for all Group A LLPs. This is different to an earlier target life of 10,000EFC in its high pressure (HP) modules, and 15,000EFC for the

Fan blades and annulus fillers are life-limited parts in Trent engines. These are termed Group B LLPs, and their life limits are at the target lives of Group A parts, the disks and shafts. Fan blades and annulus fillers are removed relatively easily.

intermediate pressure (IP) and low pressure (LP) modules.

The lives of Group B parts are 20,000EFC, but Group A parts have varying certified lives of 4,200-15,000EFC.

Trent 800 engines fall into two groups. The Trent 875, 877, 890 and 892 engines all have LLP target lives of 15,000EFC. The Group B fan blades and annulus fillers have lives of 15,000EFC, while Group A parts have varying lives of between 4,500EFC and 15,000EFC.

The highest-rated Trent 895 has a target life of 10,000EFC. This is the limit of Group A parts, while Group B parts again have varied lives.

The target life for Trent 500 LLPs is 10,000EFC, and is the life limit of Group B parts. Group A disk and shaft parts have varying lives from 2,600EFC to 10,000EFC.

The Trent 900 has an LLP target life of 15,000EFC . Group A parts vary between 1,000EFC and 4,000EFC in the HP modules, and 3,200-12,500EFC in the IP and LP modules.

The uniform target lives for LLPs are intended to make managing engine shop-visit intervals and workscopes relatively easy. This is especially the case with engines operated on long-haul operations where EFH:EFC ratios are 6-7EFH per EFC. Engines therefore operate at utilisations of up to 750EFC per year.

In this case LLPs are only likely to be replaced either after 9,000EFC and 12-30 years of operation; or after 13,500-14,000EFC and 18 or more years of operation. Engines would therefore only likely have their LLPs replaced once in their operating life. Engines operated on medium-haul operations may only need to have their LLPs replaced twice.

LLP reserves, theoretically, not need be paid for the remainder of the engine's operational life after the LLPs have been replaced for the first or second time.

Based on current LLP list prices, and no allowances for annual price increases, LLP reserves for parts amortised over their target lives would be $454-507 per EFC for parts with a uniform life of 15,000EFC. They would be up to $660-760 per EFC for parts with uniform lives of 10,000EFC.

The actual lives of LLPs initially installed in the Trent 500, 700, 800 and 900 were not uniform for the earlier-built engines. These were staggered, with some parts having limits as low as 1,000EFC.

Staggered LLP lives complicate shop-visit management and raise LLP reserves. Parts with short lives force early removals for shop visits, which can increase the reserves per EFH for shop visits.

The replacement of these stub life or limited LLPs at the first shop visit then may either be with a part that has the same or a different restriction on its life limit, or may be a part with a full target life limit of 15,000EFC. In either scenario, the engine has a shipset of LLPs in the engine with staggered lives following the shop visit. This means subsequent removal intervals may be compromised, and some LLPs will have to be replaced early. This could raise both shop visit reserves. Engine removals need to be managed around LLP lives.

LLPs with uniform lives of 15,000EFC became available with later-build engines. These LLPs can be used to replace the earlier parts with restricted lives as they come due. Shop-visit intervals will not be so compromised, and engine management and LLP replacement will be made simpler.

Another main issue is shop-visit intervals. Besides being influenced by LLPs with restricted lives, they can be affected by the erosion of the turbine gas temperature (TGT) margin. Most Trent models and variants have a steady rate of mature TGT margin erosion, and few engines tend to be removed for TGT margin loss. The notable exception to this is the Trent 895; the highest-rated variant of the Trent family.

With the exception of some Trent 700s and 800s that operate on short- and medium-haul operations, all Trent models operate at EFC times of at least 6.0EFH. Some operate on EFC times as long as 11.0EFH. TGT margin erosion is not a major cause of engine removals for engines operated on long-haul services. Engines are more often removed due to hardware deterioration after long intervals of accumulated EFH.

Trent 700

The Trent 700 was the first Trent family member into service in 1994. It operates on the A330-300 on a mixture of medium- and long-haul operations, while the A330-200 is confined mainly to long-haul services.

Medium-haul operations have EFC times of 2.5-3.5EFH, while long-haul operations have EFC times of 6-7EFH.

The LLPs in the earlier-built Trent 700s had lives of 4,200EFC to

15,000EFC. The three parts with the shortest lives are the high pressure turbine (HPT) shaft at 4,200EFC, the high pressure compressor (HPC) rotor at 6,000EFC, and the HPT disk at 9,000EFC. These parts forced early removals in the earlier-built Trent 700s.

The target lives of Group A parts in the high pressure (HP) module were 10,000EFC, but were later increased to 15,000EFC. All Group A parts now have target lives of 15,000EFC. The fan disk and intermediate pressure compressor (IPC) drum had initial lives of 13,000EFC and 12,600EFC. These also compromised removal intervals.

The Trent 700 has a reputation for good TGT margin, and operators report that earlier-built engines get removed for their first shop visit because of the HPT shaft life limit of 4,200EFC.

Even engines operated at 2.5-3.5EFH per EFC have enough TGT margin retention to remain on-wing for up to 5,000EFC. The Trent 700 is generally capable of achieving longer removal intervals than the other A330 engine choices: the PW4000-100 and CF6-80E1.

The range of first removal intervals is 2,500-4,200EFC, the higher interval being imposed by the LLP limit. British Midland, for example, operated the A330-200 at 7.1 flight hours (FH) per flight cycle (FC). The Trent 700 in this case remained on-wing up to its first LLP limit of 4,200EFC.

Air Canada, which operates the 772B on its A330-300 fleet at 6-7EFH per EFC, says the cause of the engine's first removals were HPT disk and HPC drum life limit restrictions.

The HPC drum's or rotor's life limit of 6,000EFC could reduce the second removal to just 1,800EFC if not removed and replaced at the first shop visit.

Since the Trent 700 has sufficient TGT margin to remain on-wing for a longer first interval, the engine can be expected to stay on-wing for up to 4,200EFC for EFC times of 2.5-7.0EFH. This would be equal to 10,500EFH to 29,400EFH *(see table, page 20)*.

The first shop visit would at least include full disassembly of the HP rotor, as well as disassembly of the intermediate pressure (IP) rotor. A level 3 workscope involves the full disassembly of the HP system and combustor. A level 4 workscope also includes a full disassembly of the IP system and the low pressure (LP) system. The need to disassemble both the HP and IP systems means the workscope will be larger than a level 3 shop visit.

The second interval could be up to a maximum of 4,800EFC, given the 9,000EFC limit of its HPT disk. Second run intervals are about 80% of first run intervals. Leaving the HPT disk in place at the first shop visit should therefore not compromise the second interval.

Second removal intervals would be: 3,400EFC for those operated at 2.5EFH per EFC; 3,300EFC for those at 3.5EFH; 2,800EFC for those at 6.0EFH; and 2,500EFC for those at 7.0EFH. This is equal to 8,500EFH, 11,500EFH, 16,800EFH and 17,500EFH.

The workscope at this interval could include a full engine disassembly that includes the fan or low pressure compressor (LPC), low pressure turbine (LPT) and gearboxes. The HPT disk would also have to be replaced. This would be a level 4 workscope.

The third removal interval would likely be reduced to a mature level closer to 3,000-3,400EFC for engines operated on medium-haul operations, and to 2,400-2,600EFC for those operated at 6-7EFH per EFC.

LLPs with lives restricted at up to 12,000EFC, which include the fan disk and IPC drum, would have to be replaced at this third shop visit. The engine would therefore undergo a high level of disassembly - a level 4 workscope.

Mature intervals mean the remaining LLPs with lives of 15,000EFC would have to be replaced at the fourth shop visit in engines operated on medium-haul operations, and more likely at the fifth shop visit for engines operated on long-haul services. Replacing remaining LLPs would mean a third level 4 workscope in

TRENT 700 MAINTENANCE RESERVES

	Engines with old LLPs				Engines with full-life LLPs			
EFH:EFC	**2.5**	**3.5**	**6.0**	**7.0**	**2.5**	**3.5**	**6.0**	**7.0**
1st interval								
EFC	4,200	4,200	4,200	4,200	4,800	4,600	4,400	4,300
EFH	10,500	14,700	25,200	29,400	12,000	16,100	26,400	30,100
LLP replacement:	HPT shaft & HPC rotor				None	None	None	None
LLP reserve-$/EFC	374	374	374	374	436	448	395	411
S-V workscope level	3	3	3	3	3	3	3	3
1st S-V -$	4.25m	4.4m	4.6m	4.7m	4.3m	4.45m	4.65m	4.75m
S-V reserve -$/EFH	405	299	183	160	358	276	176	158
Total reserve-$/EFH	**554**	**406**	**245**	**213**	**533**	**404**	**242**	**217**
2nd interval								
EFC	3,400	3,300	2,800	2,500	3,800	3,700	3,500	3,300
EFH	8,500	11,550	16,800	17,500	9,500	12,950	21,000	23,100
LLP replacement:	HPT disk @ 9,000EFC				None	None	None	None
LLP reserve-$/EFC	374	374	374	374	436	448	395	411
S-V workscope level	4	4	4	4	3/4	3/4	4	4
2nd S-V -$	5.0m	5.2m	5.4m	5.5m	4.7m	4.7m	5.5m	5.6m
S-V reserve -$/EFH	588	450	321	314	495	363	262	242
Total reserve-$/EFH	**738**	**557**	**384**	**368**	**669**	**491**	**328**	**301**
3rd interval								
EFC	3,300	3,100	2,600	2,400	3,600	3,500	3,300	3,200
EFH	8,250	10,850	15,600	16,800	9,000	12,250	19,800	22,400
LLP replacement:	Parts with lives of 12,000EFC				All Gp A	All Gp A	None	None
LLP reserve-$/EFC	374	374	374	374	436	448	395	411
S-V workscope level	4	4	4	4	4	4	3	3
3rd S-V -$	5.0m	5.2m	5.4m	5.5m	5.1m	5.3m	4.6m	4.7m
S-V reserve -$/EFH	606	479	346	327	567	433	232	210
Total reserve-$/EFH	**756**	**586**	**408**	**381**	**741**	**561**	**298**	**269**
4th interval								
EFC	3,300	3,100	2,600	2,400	3,600	3,500	3,300	3,200
EFH	8,250	10,850	15,600	16,800	9,000	12,250	19,800	22,400
LLP replacement:	All remaining original parts		None	None	None	None	All Gp A	All Gp A
LLP reserve-$/EFC	374	374	374	374	393	395	395	411
S-V workscope level	4	4	3	3	3	3	4	4
4th S-V -$	5.0m	5.2m	5.4m	5.5m	4.5m	4.5m	5.5m	5.6m
S-V reserve -$/EFH	606	479	346	327	500	367	278	250
Total reserve-$/EFH	**756**	**586**	**408**	**381**	**657**	**480**	**344**	**309**

succession could be required.

The replacement of Group A life-restricted LLPs at the first, second and third shop visits means the engine would have LLPs with staggered lives.

Mature shop visit intervals of 3,000-3,400EFC for medium-haul engines mean Group A LLPs would be replaced every fourth or fifth shop visit after 13,000-15,000EFC if managed well. Engines operating at 6-7EFH may have LLPs replaced every five or six shop visits.

Group B parts, with lives of 20,000EFC, would likely be replaced at the fifth or sixth shop visit.

Reserves for Group A parts would be $274 per EFC, on the basis that the list price is amortised over the full target life, 15,000EFC. Reserves for Group B parts, fan blades and annulus fillers, would be $100 per EFC, taking total LLP reserves to $374 per EFC *(see table, this page)*. This reserve is based on the assumption that the cost of new LLPs have their list prices pro-rated to compensate for the stub life of parts they are replacing.

Costs for the first workscope after the first removal would be $4.25-4.5 million for engines operated at 2.5-3.5EFH, and marginally higher at $4.6-4.8 million for engines at 6-7EFH. This cost excludes the replacement of LLPs. The shop visit costs result in reserves of $405 per EFH for engines operated at 2.5EFH; $299 per EFH for those operated at 3.5EFH; $183 per EFH for those at 6EFH; and $160 per EFH for those at 7EFH *(see table, this page)*.

With LLP reserves converted to rates per EFH, total reserves are: $554 per EFH for engines operated at 2.5EFH; $406 per EFH for those operated at 3.5EFH; $245 per EFH for those at 6EFH; and $213 per EFH for those at 7EFH *(see table, this page)*.

The second shop-visit workscope would either be close to an overhaul or a full overhaul, and cost $5.0-5.5 million, depending on the total number of accumulated EFC and EFH on-wing.

These shop visit inputs will have reserves of $588 per EFH for engines operated at 2.5EFH; $450 per EFH for those operated at 3.5EFH; $321 per EFH for those at 6EFH; and $314 per EFH for those at 7EFH *(see table, this page)*.

With LLP reserves converted to rates per EFH, total reserves are: $738 per EFH for engines operated at 2.5EFH; $557 per EFH for those operated at 3.5EFH; $384 per EFH for those at 6EFH; and $368 per EFH for those at 7EFH *(see table, this page)*.

Engines with LLPs with lives of 15,000EFC would have a simpler shop-visit pattern and be easier to manage.

Removal intervals may be longer, since LLPs with restricted lives would not be a removal cause.

The main difference is that engine shop visit workscopes would follow a more simple pattern. This is because a level 4 workscope would not be required at so many removals because LLPs with stub lives would not have to be replaced. This is especially the case with engines operated on longer EFC times.

For engines operating at 2.5-3.5EFH per EFC, the first, second and third removals would be 4,600-4,800EFC, 3,700-3,800EFC and 3,500-3,600EFC. By the third removal, total accumulated time on-wing would be about 12,000EFC. All Group A LLPs would have to be replaced at this stage. A level 4 workscope would therefore be required. A level 3 workscope may therefore only be required at the second shop visit, although this is not certain.

The LLP reserves for Group A parts up to this third shop visit would be $336-348 per EFC. With reserves for Group B parts added, total LLP reserves to the third shop visit would be $436-448 per EFC *(see table, this page)*.

The first two shop visit inputs would incur similar costs to engines with restricted LLP lives, removal intervals being up to 2,000 EFH longer.

The first shop-visit costs result in reserves of $358 per EFH for engines operated at 2.5EFH; $276 per EFH for those operated at 3.5EFH.

With LLP reserves converted to rates per EFH, total reserves would be: $533 per EFH for engines operated at 2.5EFH,

The stub lives of many LLPs in the HP, IP and LP modules of different Trent family members can force heavy workscopes earlier than would otherwise be required if the LLPs had certified lives equal to their target lives.

and $404 per EFH for those operated at 3.5EFH *(see table, page 20)*.

The second shop-visit cost will depend on whether a level 3 or level 4 workscope is required. An average shop visit cost of $4.7 million will result in reserves of $495 per EFH for engines operated at 2.5EFH, and $363 per EFH for those operated at 3.5EFH.

With LLP reserves converted to rates per EFH, total reserves would be: $669 per EFH for engines operated at 2.5EFH, and $491 per EFH for those operated at 3.5EFH *(see table, page 20)*.

The level 4 workscope required at the third shop visit, and shorter corresponding removal interval, will result in a higher overall reserve of $741 per EFH for engines operated at 2.5EFH, and $561 per EFH for engines operated at 3.5EFH *(see table, page 20)*.

Reserves to the fourth shop visit should be lower; a level 3 workscope will be required at the shop visit.

Engines operating at 6.0EFH and 7.0EFH per EFC, the first, second and third intervals would be 4,300-4,400EFC, 3,300-3,500EFC, and 3,200-3,300EFC. These intervals mean it would be possible to removal Group A LLPs at the fourth shop visit, after a total time of about 14,000EFC *(see table, page 20)*. This would allow the engine to follow an alternating pattern of level 3 and level 4 shop visit workscopes.

The reserves for Group A parts would be $283-293 per EFC. Group B parts would have a reserve of $112-118 per EFC; taking the total LLP reserves to $395-411 per EFC *(see table, page 20)*.

The first and third shop visits would thus have costs of $4.6-4.8 million, and second and fourth shop visits would have costs in the region of $5.5-5.6 million.

With LLP reserves converted to rates per EFH, total reserves would be: $242 per EFH for those at 6EFH; and $217 per EFH for those at 7EFH to the first shop visit *(see table, page 20)*.

These would increase to $328 per EFH for those at 6EFH; and $301 per EFH for those at 7EFH for the second shop visit *(see table, page 20)*.

Reserves for the subsequent third and fourth shop visit inputs would be higher than this due to shorter, mature removal intervals *(see table, page 20)*.

Trent 800

The Trent 800 variants in operation can be divided into three groups. The first of these are the 875 and 877 engines powering the 777-200s; which are operated on medium-haul operations with EFC times of 2.5-4.0EFH.

The second group are the 884, 890 and 892 engines powering the 777-200ERs on long-haul operations with EFC times of 7.0-10.0EFH. The 892 engines also power 777-300s, which are used on a variety of mission types.

A third group is the 895 engines powering 777-200ERs; and which generally operate at the longest EFC times of 8.0-10.0EFH.

Most Trent variants have enough TGT margin, and a slow enough rate of TGT margin erosion, for loss of margin and engine performance not to be a main removal cause for shop visits. The exception to this is the Trent 895, which in some cases has TGT margin loss as a main removal cause.

The initial Trent 800s from the production line had LLPs with varying, certified lives for individual parts.

Parts with the shortest lives are in the HP spool, and include the HPC 1-4 and HPC 5-6 drums, and the HPT disk. These parts had some part numbers with lives as short as 4,500EFC, but the shortest life of most parts is about 5,000EFC.

Other HP and IP parts have lives of 6,000-8,500EFC. Most other LLPs in the 875, 877, 890 and 892 engines have lives of 12,000-15,000EFC.

The highest life limit for Group A parts in the Trent 895 is 10,000EFC.

As described, different Trent models operate on different route networks and mission lengths. Trent 875s and 877s on low-gross-weight 777-200s and 892s on 777-300s mainly operate on medium-haul missions of 2.5-4.0EFH per EFC. Some 777-300s are used by Thai International and Cathay Pacific to operate medium-haul routes in the Asia Pacific. Other -300s are operated by Emirates on longer sectors.

The Trent 884s, 895s and most 892s are all operated on 777-200ERs on long-haul operations. EFC times are 7.0-10.0EFH in most cases. Most engines are 892s, operated by American, Delta, Thai, Singapore Airlines, and Malaysian.

Smaller numbers of 884s are operated by Singapore Airlines, Cathay Pacific and Emirates. Trent 895s are operated British Airways, Air New Zealand and El Al.

Trent 875, 877 & 892

The 875, 877 and 892 engines operated on medium-haul operations, with an average EFC time of 3.5EFH, can operate up to 5,000-5,500EFC before their first removal. This can be limited to a shorter life if the engine has some HP LLPs with shorter life limits. An example is airworthiness directive (AD) 2011-10-04 which limits the HPC stage 1-4 drum part number FK32580 to an SDC life of 5,580-7,780EFC.

An interval of 5,000-5,500EFC is equal to 17,500-19,250EFH. The first shop visit will require the replacement of LLPs with the shortest lives.

The second removal interval can be up to about 4,500EFC, so total accumulated engine life will be up to 10,000EFC. The second removal interval will depend, however, on which LLPs with restricted lives are left in the engine at the first shop visit. The second removal will be less than 4,500EFC if some of the

IP spool parts with lives of 8,000-9,000EFC are not replaced at the first shop visit.

Given that the third removal interval could be up to 4,250EFC and a total accumulated time of 14,000-14,500EFC, most LLPs with restricted lives will have to be removed and replaced at the first shop visit. Only those with lives of 9,000-10,000EFC can be left in until the second shop visit to prevent compromising the second removal interval.

All parts with lives of up to 14,000EFC should be removed and replaced at the second shop visit to prevent limiting the third interval.

All other original Group A LLPs will have to be removed and replaced at the third shop visit.

A full shipset of LLPs with no life restrictions has a current list price of $7.6 million. The reserve for the cost of the shipset amortised over the accumulated time of about 14,500EFC at the third shop visit results in a reserve of about $524 per EFC *(see table, this page)*.

The first shop visit will therefore have to be higher than a level 3 workscope. This will be full disassembly to piece-part level of the HP modules and combustor section, as well as a full disassembly on the IP modules. The need to fully disassemble the IP modules to allow LLP replacement means the cost of this shop visit will be high. A level 3 shop visit on the Trent 800 can cost $4.7-5.5 million;, but adding of the IP spool means the cost is likely to be higher *(see table, this page)*.

The second shop visit could be with a level 3 workscope again if the LP modules are in good condition, but the engine worked at short cycles. A level 4 workscope, which involves a full disassembly of all modules, will cost $6.5-7.0 million *(see table, this page)*.

The third shop visit will have to be a level 4 workscope so that all remaining LLPs, including all parts in the LP modules, will be replaced. A full workscope costs about $7.0 million.

The reserves for these shop visit costs are about $300 per EFH up to the first workscope, $395 per EFH up to the second, and $471 per EFH up to the third *(see table, this page)*. Total reserves that include LLPs will, therefore, be $446 per EFH up to the first removal, $545 per EFH up to the second, and $620 per EFH up to the third *(see table, this page)*.

TRENT 800 & 500 MAINTENANCE RESERVES

	Trent 800			Trent 500	
Engine Variant	**875/877**	**884/890/892**	**895**	**556**	**553**
EFH:EFC	**3.5**	**7.0**	**9.0**	**8.5**	**10.75**
1st interval					
EFC	5,300	3,500	2,500	2,600	2,600
EFH	18,550	24,500	22,500	22,100	28,000
LLP replacement:	HP parts, IPC	HPTD	HPTD	HPT Disk, Plate	HPT Disk, Plate
LLP reserve-$/EFC	524	596	844	710	710
S-V Workscope level					
1st S-V -$	5.5m	5.1m	5.6m	5.4m	5.7m
S-V reserve -$/EFH	296	208	249	244	204
Total reserve-$/EFH	**446**	**293**	**343**	**328**	**270**
2nd interval					
EFC	4,700	2,500	2,300	2,300	2,300
EFH	16,450	17,500	20,700	19,550	24,725
LLP replacement:	None	Other HP/IP	Other HP/IP	HPC1-4, IPT Disk	HPC1-4, IPT Disk
LLP reserve-$/EFC	524	596	844	710	710
S-V Workscope level					
2nd S-V -$	6.5m	6.75m	7.0m	6.0m	6.4m
S-V reserve -$/EFH	395	386	338	307	259
Total reserve-$/EFH	**545**	**471**	**432**	**390**	**325**
3rd interval					
EFC	4,250	2,250	2,150	2,200	2,200
EFH	14,875	15,750	19,350	18,700	23,650
LLP replacement:	Remainder	Remainder	None	None	None
LLP reserve-$/EFC	524	596	844	710	710
S-V Workscope level					
3rd S-V -$	7.0m	7.0m	5.7m	5.4m	5.7m
S-V reserve -$/EFH	471	444	295	289	241
Total reserve-$/EFH	**620**	**530**	**388**	**372**	**307**
4th interval					
EFC			2,150	2,200	2,200
EFH			19,350	18,700	23,650
LLP replacement:			Remainder	Remainder	Remainder
LLP reserve-$/EFC			844	710	710
S-V Workscope level					
3rd S-V -$			7.0m	6.0m	6.4m
S-V reserve -$/EFH			362	321	271
Total reserve-$/EFH			**456**	**404**	**337**

Trent 884 & 892

The 884 and 892 and variants operated on EFC times of 7-10EFH will have to be managed differently. American Airlines, for example, operates the largest fleet of Trent 892s for its 777-200ERs. It has an average EFC time of 9.0EFH. E Al operates 895s on 777-200ERs at an average of 10EFH per EFC.

American achieved first removal intervals of 3,000-3,500EFCs with its 892s. Removals were not caused by TGT margin loss, but by other issues.

American says it has a planned for a similar second removal interval, given the engine's ability to retain TGT margin and its durability. A shorter interval of about 2,500EFC should be planned for.

A mature or third interval will about 2,250EFC, equal to an accumulated total time of 8,250EFC. To avoid compromising later removal intervals, the HPT disk should be removed and replaced at the first shop visit.

The remaining HP and IP parts with restricted lives should be removed and replaced at the second shop visit.

Similar subsequent intervals will mean LLPs will have to be replaced at the fourth or fifth shop visits, given the lives of up to 15,000EFC life limit of these remaining parts.

The first shop visit can be a level 3 workscope. This will be smaller than the workscope required by the engines operating on shorter cycles. The cost of this will be $5.1 million. Amortised over the interval, it is equal to a reserve of $208 per EFH *(see table, this page)*.

The second shop visit would include the replacement of other HP and IP LLPs with restricted lives. A larger workscope would be required. With a total on-wing

TRENT 900 MAINTENANCE RESERVES

Engine Variant	Trent 900	Trent 900
EFH:EFC	8.5	10.75
1st interval		
EFC	2,700	2,600
EFH	23,000	28,000
LLP replacement:	All HP, some IP & LP rotor shaft	All HP, some IP & LP rotor shaft
LLP reserve-$/EFC	618	618
S-V Workscope level	Level 3, high	Level 3, high
1st S-V -$	$5.0m	$5.25m
S-V reserve -$/EFH	218	188
Total reserve-$/EFH	**291**	**245**
2nd interval		
EFC	2,200	2,300
EFH	19,000	15,000
LLP replacement:	None	None
LLP reserve-$/EFC	618	618
S-V Workscope level	Level 4	Level 4
2nd S-V -$	$6.3m	$6.5m
S-V reserve -$/EFH	334	263
Total reserve-$/EFH	**407**	**320**

time of 42,000EFH it is possible a level 4 workscope might be needed. An average workscope cost will be $6.75 million, with a corresponding reserve of $386 per EFH *(see table, page 23)*.

The third shop visit would replace all remaining LLPs in all modules. A level 4 workscope would therefore be required. This would cost $7 million, so the reserve for this would be $444 per EFH *(see table, page 23)*.

With reserves for LLPs added, total costs per EFH would be $293 per EFH for the first interval, $471 per EFH for the second and $530 per EFH for the third *(see table, page 23)*.

Trent 895

Trent 895 engines, which are generally operated on longer EFCs of 9-10EFH, have a reputation for being one of the few Trent variants that sometimes have to be removed due to loss of performance and TGT margin.

Air New Zealand, for example, operates the engines at a rate of about 8.5EFH per EFC. It states the engine had an initial TGT margin of 30-40 degrees centigrade. Air New Zealand gives the problem of suspect bearings and LPT Stage 1 damper wire as the main cause for the first removals at an interval of about 22,000EFH, equal to about 2,600EFC. Second removal intervals of about 2,300EFC, and mature intervals of 2,000-2,200EFC can be expected.

The 10,000EFC limit of Group A parts means the engine could follow an alternating shop visit pattern of level 3 and level 4 workscopes, and then have parts with the longest lives replaced at the fourth shop visit. This would be at an accumulated total on-wing time of about 9,000EFC *(see table, page 23)*.

On this basis, LLP reserves would be about $844 per EFC *(see table, page 23)*. The alternating level 3 and level 4 workscopes would mean that shop visit reserves for the first two shop visits would be $249 per EFH and $338 per EFH *(see table, page 23)*. With LLP reserves added, total reserves would be $343 per EFH and $432 per EFH for the first two shop visits *(see table, page 23)*.

Shorter mature removal intervals means total reserves would increase to $388 per EFH and $456 per EFH for the third and fourth removal intervals *(see table, page 23)*.

Trent 500

The Trent 500 powering the A340-500 and -600 operate at some of the longest EFC times of all engine types.

The Trent 553 powering the A340-500 operates on the longest cycles, the aircraft having a longer-range capability. Typical EFC times are 10-11EFH. Operators include Emirates, Etihad, SIA and Thai International.

The Trent 556 powering the A340-600 is in more widespread use. These aircraft are operated on typical long-haul routes, as well as some ultra-long-range missions. Operators include Lufthansa, China Eastern, Thai International, Virgin Atlantic, and South African Airways.

EFC times for the Trent 556 vary from 7.0EFH to 9.5EFH for most operators' fleets, and average 8.50EFH.

All LLPs in the fan, IPC and LPT modules have uniform lives of 10,000EFC. The HPC has four parts, three of which have lives of 10,000EFC but a fourth part has a restricted life of 5,000EFC. The IPT disk is also limited to 5,000EFC, while the IP rotor shaft has a life of 10,000EFC. The HPT has the most restricted parts, with the HPT disk at 2,600EFC and the HPT front cover plate at 4,000EFC.

The HPT disk and HPT front cover plate will therefore limit the first shop visit to 2,600EFC, although this will be about 28,000EFH for the 553 engines operating at almost 11EFH, and 22,000EFH for 556 engines operating at shorter cycles of 8.5EFH. Some operators have reported short first removal intervals, however, due to initial in-service problems related to oil leakages.

The removal and replacement of these parts means that a level 3 shop visit workscope will be sufficient. This will leave the IP and LP modules. A level 3 workscope will cost $5.5-5.7 million, equal to a reserve of $204 per EFH for the 553, and $244 per EFH for the 556 *(see table, page 23)*.

Future removals will be limited if the replacement HPT disk part number does not have a longer life limit. Second and subsequent removal intervals are likely to be shorter at 2,000-2,300EFC. HPT disk lives will still not limit intervals, but the LLP reserves will be raised.

The LLPs that will have to be replaced at the second shop visit include the -04 drum and IPT disk.

The remaining LLPs, with full lives of 10,000EFC, could then be removed and replaced at the fourth shop visit after a total time of about 9,300EFC *(see table, page 23)*. The reserve for Group A and Group B parts amortised over this interval will be $710 per EFC. This will be equal to $66 per EFH and $84 per EFH once they have been adjusted for EFC times *(see table, page 23)*.

The need to replace HP and IP system LLPs at the second shop visit will mean that a workscope higher than level 3 will be required. Given that the accumulated time on-wing will be 42,000-53,000EFH, a level 4 workscope will probably be required. This will cost $6.0-6.5 million, depending on degradation of parts due to accumulated EFH.

No LLPs will have to be replaced at the third shop visit, and most parts will have to be replaced at the fourth. It will therefore be prudent to attempt to manage the engine on an alternating pattern of level 3 and level 4 workscopes.

The total reserves up to the first shop visit will thus be $270 per EFH for the 553, and $328 per EFH for the 556. Reserves up to the second removal will be

$325 per EFH for the 553 and $390 per EFH for the 556 *(see table, page 23)*.

Without adjustments for LLP price indexes, reserves per EFH for the third and fourth removals will be higher than those for the first and second removals because of shorter removal intervals.

Trent 900

The Trent 900 has been chosen by 11 A380 customers; only four airlines have selected the GP7200. Another four airlines have yet to make their engine selections. Lufthansa, Qantas and Singapore Airlines (SIA) have the Trent 900-powered A380 in service, and operate at FC times of 9-11FH.

The Trent 900's Group A LLPs total 18 parts: two fan module; two IPC module; three HPC module; two HPT module; three IPT module; and six LPT module parts. The lives of these vary from 1,000EFC to 12,500EFC. These compare to the target lives of 15,000EFC. These have a list price of $4.9 million.

Each module has parts with restricted life limits, except the fan module. The HPT module has parts with the shortest lives. There are four part numbers for the HPT rotor disk, with lives of 1,000EFC to 3,800EFC. The HPT front cover plate has three different part numbers: two with a life of 1,442EFC and one with a life of 3,800EFC.

The module with the next shortest LLP lives is the IPT. The IPT rotor disk has a life of 2,600EFC, while there are two parts numbers for the IPT rear air seal with a life of 3,984EFC.

Operating at similar EFH:EFC ratios as the Trent 500, the Trent 900 should be able to achieve similar removal intervals of 23,000-28,000EFH to its first shop visit, and 19,000-25,000EFH to its second. This is equal to 2,600-2,700EFC and 2,200-2,300EFC. The total accumulated time on-wing by the second shop visit could thus be 4,800-5,000EFC.

Unless the HPT disk installed in the engine is one of the three part numbers with a life limit of 1,000EFC or 1,250EFC, the engine should be able to operate to these removal intervals without being compromised by LLP lives.

The first shop visit would normally be a level 3 workscope. The large number of parts with lives of up to just 4,200EFC in the IPC and LPT also means these modules would have to be disassembled at the first shop visit. The LP rotor shaft would also have to be replaced.

The fan module would be the only module at the first shop visit that would not have to be disassembled.

All LLPs with restricted lives (that is up to 4,357EFC) would have to be replaced with parts with longer lives, or unrestricted lives of 15,000EFC. This would then mean the second and subsequent removal intervals would not be compromised by limited LLP lives.

Mature intervals after the second shop visit could broadly be expected to be 1,900-2,100EFC; equal to 16,500-21,500EFH.

Original LLPs in the fan, IPC, IPT and LPT modules with lives of 11,600-12,500EFC would start to reach their life limits by the fifth shop visit.

Amortising the cost of all LLPs over the accumulated interval to the fifth shop visit generates a LLP reserve of about $618 per EFC.

The first shop visit would be a heavy level 3 workscope, or a level 4 workscope less the cost of the fan module. This could cost $5.0-5.3 million, with reserves of $188-218 per EFH. With LLPs, total reserves are $245 per EFH for engines operated at 10.8EFH per EFC, and $291 per EFH for engines operated at $8.50EFH per EFC *(see table, page 24)*.

The second shop visit could be a level 3 workscope given that all modules had been disassembled at the first shop visit. Given that the engines had a total accumulated time on-wing of 42,000-53,000EFH, a level 4 workscope would, however, probably be required.

The resulting shop visit would have a cost of $6.2-6.5 million, with reserves of $263 per EFH for engines operating at 10.75EFH per EFC, and $334 per EFH for engines operating at 8.50EFH per EFC. With LLPs add, total reserves would be $320 per EFH for engines operating at 10.75EFH per EFC, and $407 per EFH for engines operating at 8.50EFH per EFC *(see table, page 24)*. AC