The APU is one of five major component groups which form a large portion of total aircraft maintenance costs. Most airlines subcontract APU maintenance and have little knowledge of what affects APU reliability and maintenance costs per aircraft flight hour. Large savings can be made if what affects APU maintenance is understood.

The economics of APU maintenance

Auxiliary power units (APUs) are a major aircraft component, and this has an effect on total maintenance costs. In the past decade most airlines have taken the decision to sub-contract APU repair and overhaul for the sake of simplicity. This has meant that little attention was paid to maintenance costs.

A close examination of what affects maintenance charges reveals how airlines can make savings of literally millions of dollars annually. This is only possible if an airline has an understanding of what influences APU maintenance costs.

APU function & design

The APU, normally situated in the tailcone, is a gas turbine generator that provides electrical and pneumatic power. The APU is used on the ground as an alternative to a ground power unit (GPU). The APU's function is to provide pneumatic power for cabin air conditioning and air pressure to power main engine pneumatic starter motors. The APU also generates electricity and heat while main engines are not running, as well as de-icing.

Older-generation APUs generally consist of two modules. The main module is a gas turbine or core engine. The structure is based on a small jet engine and consists of a centrifugal compressor and two to four turbine wheels. The air intake is through the side, rather than frontal as with main engines.

The second module is the generator, which takes rotary power via a connecting shaft from the core engine. The generator has several line replaceable units (LRUs) and accessories, each of which generates power for the APU's various functions.

Modern generation APUs have a more modular construction for ease of maintenance. They also have a third module, the load compressor, which is based on a centrifugal compressor. It derives power from the core compressor's shaft, and uses a centrifugal compressor to generate pneumatic power.

The APU uses the same fuel supply as the main engines, and APU exhaust from the turbine in most aircraft is passed out through the tailcone pipe. The disadvantages of the APU are that it is noisier and has a higher level of emissions than a GPU.

The APU's air inlet in many aircraft is on the top of the aircraft fuselage. In others it is placed lower down. All APUs are still susceptible to material and foreign object damage (FOD), as are main engines.

APU operation

Except in a few cases, the APU is used to start the main engines as an aircraft is pushed back from the gate at departure. This means the APU has to be switched on up to 45 minutes prior to departure, and so takes over power generation from the GPU, if being used, at this stage.

Once the APU has started the main engines and they are supplying full power to the systems, the APU can be turned off. Depending on airline procedure, the APU is switched off shortly after engine start during taxi out, or in some cases after take-off.

The APU has to be on after landing, so there is a power source after the main engines have been shut down and before the aircraft can draw power from the GPU. Some airlines start the APU during approach to landing, while others wait until taxi in. The decision on when to start the APU also depends on environmental conditions, aircraft type, airline procedure, and airport regulations.

The MD-80 is an example of an aircraft with the APU intake situated on the underside of the aircraft. "This increases the risk of FOD," explains Jorma Klemola, manager small engine powerplant department at Finnair. "We therefore do not start the APU until after landing. There is no need, however, to even start the APU in winter, because air conditioning is not required at our base in Helsinki, and we can get the other power requirements from the GPU immediately after landing. In this case we only start the APU prior to

The PW901A powering the 747-400 is one of the most reliable APUs on the market. It is capable of starting four main engines simultaneously and has one of the highest shop visit intervals.

departure, and so get one APU cycle for each aircraft flight cycle (FC).

"The procedures are different at various outstations. In mid-Europe there are airport restrictions on noise, so we cannot run the APU in many cases. There can also be time limits imposed of only 10-15 minutes for an APU run prior to engine start," continues Klemola. "In south Europe, in warmer climates, we have to start the APU before shutting down the main engines to provide air conditioning during taxi in. We then shut down the APU after connecting to the GPU, and then start the APU before departure. This means short-haul operations can have either one or two APU cycles per FC".

During a short turn time at the gate, most airlines will keep the APU on for starting the main engines, so dispensing with the need for GPU power. "We aim to get turn times of 30 minutes between short-haul flights," says Peter Gille, APU workshop manager at Sabena Technics. "This is not possible on some short-haul flights, because of airport congestion. Turn times can exceed one hour. Long-haul flights have even longer times at the gate, and reach up to two hours with some operators. This means most long-haul operations will have two APU cycles per FC".

The type of APU operation is important in relation to maintenance costs, since APU reliability, and the need for a shop visit, is sensitive to cycles rather than operating hours.

"It is better to have an APU operating one cycle per FC, so as to preserve reliability and to increase APU on-wing times and removal intervals in terms of aircraft flight hours (FH)," explains Klemola. "Having two APU cycles per FC is not such a big deal for long-haul aircraft, since aircraft FH is high in relation to APU cycles and hours, and so APU maintenance costs per aircraft FH are kept low. A few of our long-haul flights, with the MD-11, manage to keep the APU on during the entire ground time, and so some flights have one APU cycle per FC".

Turn times in long-haul operations tend to be longer, up to four hours, for ultra-long-range missions. The 747-400 and A340 will be the main types operating these longest flights. "The PW901A on the 747-400 operates two APU cycles per flight," explains Michael Struck, deputy section manager marketing at Lufthansa Aero.

Besides APU cycles in relation to aircraft FC and FH, other economic issues of operation should be considered. Some airports have time limits for an APU run. APU fuel burn must also be compared with the cost of GPU power.

APU utilisation

APU utilisation in relation to aircraft utilisation will affect APU maintenance costs per aircraft FH. Like main aircraft engines, APU maintenance cost efficiency is increased with longer removal intervals. The more aircraft FH in relation to APU hours and cycles, the lower the APU maintenance cost per aircraft FH.

APU reliability is sensitive to cycles, so APU and maintenance cost efficiency is dependent on average APU cycle length.

Short-haul operations, where the APU is kept on during ground time, will have an average APU cycle time equal to the average turn time plus the few minutes the APU is on during taxi in and during engine start and taxi out. This will be the turn time plus 20-25 minutes. Turn times of 30-60 minutes will thus result in APU cycles of 50-85 minutes.

Short-haul operations with two APU cycles per FC will have an APU cycle of about 10 minutes during taxi in and another of 15-25 minutes prior to departure and engine start.

Long-haul operations will have two APU cycles: the first of 10-15 minutes, but the second a longer cycle of up to one hour.

Examination of typical short-haul and long-haul operations reveals the average APU cycle time, and number of APU cycles per aircraft FC.

Sabena operates A320s and 737s on its short-haul network and A330s and A340s on its long-haul operation. The airline's average APU cycle time for its short-haul fleet is 28 minutes, and it uses 1,300APU hours per year. Its short-haul fleet has annual utilisation of 2,850FH. Sabena's short-haul fleet uses 28APU minutes per aircraft FH.

Finnair has a mixed short-haul fleet of 757s, A321/19s, MD-80s and DC-9s. Its 757s have APU cycles averaging 46 minutes, have 1.5APU cycles per FC and use about 20 minutes per aircraft FH.

The MD-80s run APUs for about 28 minutes, use about 1.25APU cycles per FC and 20 minutes per FH.

Sabena's widebody fleet have APU cycles averaging one hour, and use about 22APU minutes per FH.

Finnair's MD-11 operation runs APU for about 50 minutes, and about 1.7APU

REMOVAL INTERVALS OF APU'S POWERING MAJOR AIRCRAFT TYPES

APU model	Aircraft type	MTBR (APU hours)
GTCP 660	747-200/-300	2,650
GTCP 331-350	A330/340	3,300
GTCP 700-4E	MD-11	1,700
GTCP 700-4B	DC-10	1,500
GTCP 331-250	A310	2,500
GTCP 331-200ER	767	2,700
GTCP 331-200	757	3,800
APS 3200	A320	5,700
GTCP 85-98	MD-80	2,700
GTCP 85-129	737-200	2,200

cycles on average per flight. This long APU cycle time is diluted by the long flight distance of its long-haul operation to about 20APU minutes per FH.

These two examples show that most short-haul operations use 20-30APU minutes per FH, while long-haul operations have similar ratios of 18-20 minutes. This similarity in APU minutes per aircraft FH is explained by long-haul operations running APUs longer prior to engine start, and having more APU cycles per flight.

Utilisations are similar on ultra-long-range missions. "The APU on the 747-400 can run for about two hours each time, and so four hours per flight," says Struck. Average flight times of 10 hours mean that APU utilisation is about 24 minutes per FH.

APU reliability

The rate of APU utilisation in relation to aircraft utilisation has a large impact on APU maintenance costs per aircraft FH. APU hours between removal are low compared with main engine removal intervals.

There are various parameters for measuring APU reliability. "The most important is mean time between removal (MTBR), which is the average time between all removals for all removal causes," explains Gille. "This is because a shop visit is required at each of these removals".

There is also mean time between unscheduled removal (MTBUR), or the interval between installation and a defect occurring, resulting in a shop visit. "This is an important parameter, since APU removals and maintenance are performed on an 'on-condition basis'," says Gille. "Modern APUs do not have life limited parts (LLPs), and so all maintenance is done on-condition. No removals have to be scheduled around LLP replacement".

Since the largest module is the core engine, there is also a record of mean time between core removals (MTBCR), a measure of the interval between removals for a shop visit on the core section, rather than the whole APU unit. "We have actually managed to establish a soft time or maintenance threshold (MT) for core engine shop visits for the GTCP 331-350 which powers our A330 fleet," says Gille. "The problem with this is that different modules fail at different intervals. So, the load compressor could fail another 500 or 1,000APU hours after the core engine workscope. The established soft time between removals then has to be considered against all modules and the workscope they require to last another soft time interval".

Unscheduled removals and FOD will reduce the average removal interval. MTBR, the most important measure for maintenance, will be smaller than MTBUR and MTBCR.

While on-wing times for modern engines are 7,000-12,000 hours in most cases, APU MTBRs are in the order of 1,500-4,000 hours. "Many airlines do not actually report APU hours between removals," says Klemola, "but report aircraft FH between APU removals instead. A 10,000-hour interval can then really mean an APU interval of something like 3,500 hours".

MTBRs for APUs vary by generation, as do reliability rates. Some modern APUs have poor MTBR rates. "The GTCP 85-98 powering the MD-80 has a MTBR of about 2,700 hours. It also has a hard time for a hot section, or core engine, inspection, at 3,000 cycles, which is the most economic. The rest of the APU is on-condition," says Klemola. "The turbine is the most critical part, and must last 3,000 cycles".

The MTBR rates of APUs powering major aircraft types are shown *(see table, this page)*. High MTBRs are 2,500 hours or more.

The GTCP 331-200 for the 757, for example, has an MTBR of 3,800 hours and an MTBCR of 7,400 hours.

APUs with poorer reliability have MTBRs of less than 2,000 hours. One example is the GTCP 700-4B, -4E and -5 used on the DC-10, MD-11 and A300. MTBR is about 1,700 hours and MTBCR 2,600 hours. "This model has several reliability problems," explains Klemola. "These include parts failures and fast performance deterioration".

Although condition monitoring is available, Struck says the PW901A's reliability is good enough for most operators not to bother, and to keep it in operation until serious damage has occurred. Workscopes at removal are either a repair or a major refurbishment. The average interval between major refurbishments is about 9,500APU hours. Its MTBR is less than 9,500 APU hours. Struck claims the PW901A is one of the most reliable APUs in the business. It is even capable of starting all four of the 747-400's engines simultaneously.

Reliability causes

There are several factors which affect reliability. "The run for a new APU to its first removal is the longest," says Gille. "Subsequent runs and MTBR reduce as the fleet ages. A better definition of the reliability of an APU is not to include the run to first removal when calculating MTBR. The average number of runs after first shop visit provide the mean restored life (MRL)".

Major causes of removal include deterioration of rotating parts in the core engine. The most reliable module is generally the gearbox, then the core engine. Like main engines, exhaust gas temperature (EGT) margin erodes and should be monitored. Klemola explains the manufacturer will recommend EGT margins, and an airline will remove the APU for a shop visit if EGT falls to this level. "Part of the shop visit workscope will be to restore EGT margin in relation to expected removal interval and the most economic shop visit workscope," says Klemola. "The removal interval affects the material input level, and material costs increase in proportion to time between removals. It is hard to find an optimum removal interval, especially when a new APU is being operated and the operator has little experience".

Like main engines, the lowest maintenance cost per hour follows a U-curve against removal interval. Airlines require wide experience to have an idea of how shop visit costs can vary.

"If maintenance and removal intervals are managed on a purely on-condition basis," explains Gille "then MTBR is the same as MTBUR and MTBF. This is because all removals are unscheduled. It is not possible to swap modules on the aircraft, so all failures result in a removal and shop visit. This means we need to perform a workscope on the whole of the APU to maintain the same soft interval on the next run. So, if the APU has run for 3,500 hours (the MT), we perform a core workscope if the load compressor requires a shop visit".

Shop visit workscopes

Unlike main engines, APUs have few LLPs. These LLPs also have long lives in relation to typical MTBRs. The need to replace LLPs because of life expiry therefore does not force or influence APU removals.

The APS 3200, for example, has no LLPs, although the issue of an airworthiness directive by the Federal Aviation Administration could change this.

Older APUs have a few LLPs. The GTCP 700 on the DC-10 and MD-11 has disks with life limits of 16,000-30,000 hours. This should be considered against APU utilisations of about 1,500 hours per year. LLPs will therefore only require replacement every 10-20 years.

The younger GTCP 331-200 on the 757 has LLPs with lives of 40,000 cycles, and so are never likely to require replacement.

Gille explains that establishment of a soft removal interval is done using removal and workscope costings. As more shop visits are performed a more accurate workscope can be defined. "This is done using the engine condition monitoring programme. This allows us to anticipate failures. It is even possible to establish that one module has approximately twice the MTBR of the soft time, and so we can take the risk of doing a workscope on the module every second removal. It is possible to establish this with experience from earlier models of an APU," says Gille.

Cost drivers of APU shop visits are similar to those for engines. The cost of labour only counts for about 20%, and material and sub-contract repairs are high. Gille cites load compressor damage, hot section parts and LRU failures as examples of high-cost items in shop visits.

An example of a shop visit cost for the GTCP 331-250, used by the A310, is 150-250 routine man-hours and $30,000-300,000 for parts, materials and sub-contract repairs. This will result in a shop visit cost of $150,000-350,000. The final cost is partially influenced by the level of repairs and parts replacement.

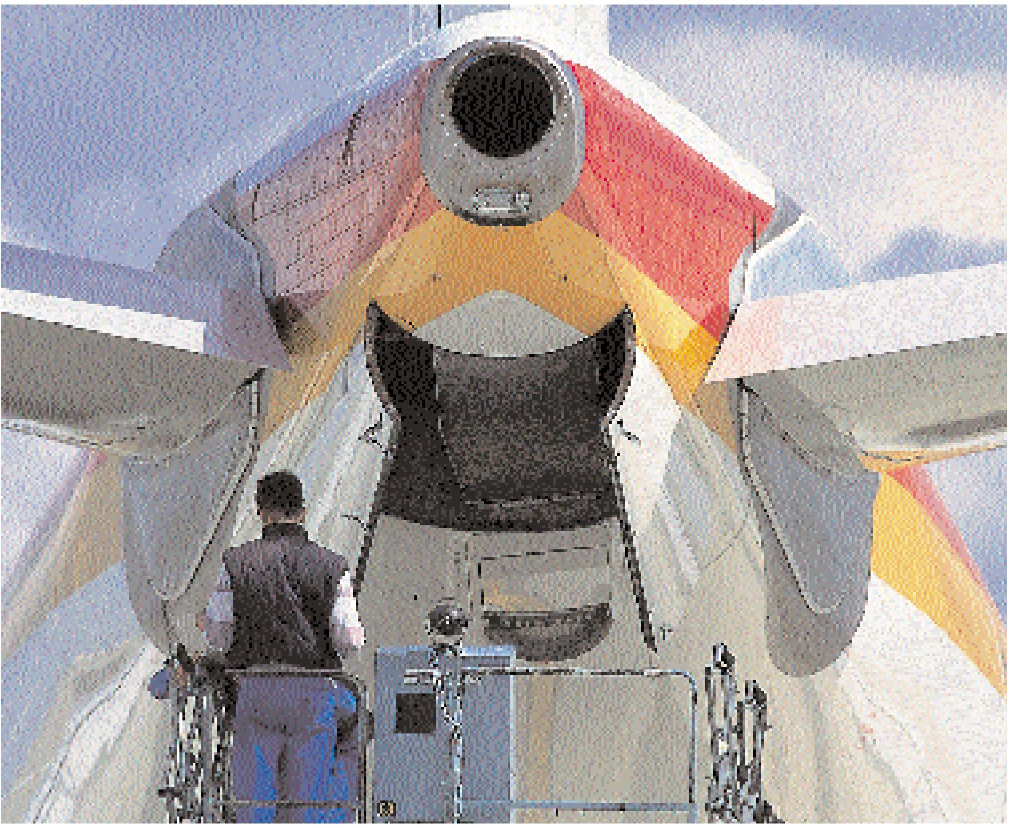
Struck at Lufthansa Aero says an average refurbishment cost for the PW901A, used on the 747-400, is about $360,000.

Reducing maintenance costs

The first main driver in maintenance cost reduction is to improve reliability. This is achieved using trend monitoring, borescoping the APU to check for damage and deterioration and troubleshooting the APU to check for problems. Gille also recommends that airlines establish a soft time for removal, so that optimum costs charged on a time and materials basis can be achieved.

Operators have more ability to control and reduce their costs if they maintain their own APUs.

Gille says developing parts repairs to avoid expensive replacement will reduce costs, and can even improve MTBR reliability. "One problem is that blades have shorter lives than engines. Disks can be repaired a limited number of times, and get replaced eventually. Airlines should still keep records of disk lives, in case service bulletins requiring the



The GTCP331-350 on the A330/340 has one of the higher MTBRs of all APUs. APU maintenance costs per flight hour will be diluted by long average aircraft flight cycles.

tracking of their life history are issued," says Gille. "There are companies within the Triumph Group which specialise in particular parts repairs, and these have reduced costs. The repair or overhaul of parts can cost as little as 50% of new part list price, and subsequent reliability is just as good".

Klemola explains that another major issue of parts and repair costs are material handling charges. "This can be as much as 13-16% of the total shop visit costs. Handling fees are charged at a flat rate per item, irrespective of price or part value. Sub-contracted repairs can be relatively more expensive, since they have profit margins for all parties involved".

Maintenance costs

The final cost of APU maintenance per aircraft FH depends on several factors. Some operators have elected to sub-contract all APU maintenance and have accepted power-by-the-hour (PBH) style deals. These charge the operator a flat rate per FH, giving a predictable cost. "While they make costs predictable, they have a safety margin built in for the supplier," explains Gille. PBH deals tend to be expensive, but remove any requirement by the operator to manage the APUs.

Klemola adds that many PBH deals do not include costs for removals and shop visits caused by FOD. These have additional charges, based on labour and material.

Another method is charging labour and material as incurred. This can result in cost spikes, and puts pressure on the operator to monitor reliability and be more active in APU management.

First, the average shop visit cost and average removal interval, or MTBR, will determine maintenance cost per APU hour. The GTCP 331-250, for example, can have a typical shop visit cost of $150,000-300,000. MTBR is about 3,800 hours, so cost per APU hour will be $40-79. This will decrease to $30-60 if MTBR increases to 5,000 APU hours.

The PW901A, which has some of the best reliability, has a higher shop visit cost of about $360,000. The high MTBR of 9,500 hours reduces cost per APU hour to $38.

Narrowbody APUs' shop visit costs are typically in the range of $75,000-150,000, while widebody APUs incur costs of $150,000-300,000.

Depending on MTBR, costs per APU hour are $20-40 for narrowbodies. Widebody costs are in the range of $25-50 per APU hour.

The ratio of APU hours to aircraft FH then has a major influence. APU utilisation of 20 minutes per aircraft FH will dilute costs of $60 per APU hour to $20 per FH. A utilisation of 30APU minutes will increase costs to $30 per FH.

Finnair compared PBH rates with the labour and material charges it was incurring for its widebody APU maintenance it sub-contracts. "Since PBH deals do not include removals for FOD, I did not include labour and material for FOD removals; which were about 10% of all shop visits," says Klemola.

"The PBH deals available for the APU type were about $60 per FH. In comparison, if we were operating at 0.25APU hours per FH, the costs were $40 per FH. At 0.35APU hours per FH, costs came down to $25 per FH. The true cost is probably about $35 per FH, but still $25 per FH lower than the PBH deal".

Although both cost levels did not include FOD removals, the saving across Finnair's small MD-11 fleet for the majority of removals still meant the airline was saving about $100,000 per aircraft per year. "One way of looking at the savings potential is that airlines can bear a higher number of failures under a time and material contract compared to a PBH deal," argues Klemola.

Overall, the different rates illustrate the possible savings airlines can make with careful APU management and awareness of the effects of APU costs.

Summary

Airlines should consider their APU utilisation carefully, not forgetting the costs of alternative sources, such as GPUs. Careful APU operation will reduce APU hours per aircraft FH by just a few minutes, but can save several dollars per FH.

Airlines should also monitor reliability, removal causes and determine how to improve MTBRs. Repair and maintenance shops which have a high level of repair capability should be used. Airlines should also pay attention to maintenance management, and establish optimum removal intervals which provide the lowest costs per APU hour.