While often overlooked, the maintenance costs of an aircraft APU will be equal to as much as $100 per flight hour unless managed well. The technical issues affecting APU operation, their management, and maintenance drivers and requirements are examined.

APU maintenance & management

The auxiliary power unit (APU) is one of four heavy components on an aircraft. The other three are the landing gear, wheels and brakes, and the thrust reversers. The APU is classed as rotable component, while there are also several hundred other types of rotable components on an aircraft that are classed as line replaceable unit (LRU) components.

The APU contributes significantly to overall aircraft maintenance costs, as well as aircraft operation.

APU function

The APU is a gas turbine, located in the tailcone of most aircraft types. Like the main engines, the APU provides compressed air and also operates as an electrical power generator. Its three main functions are to: provide electrical power for lighting, avionic and system electrical power while the aircraft is on the ground; provide compressed air for air conditioning when the aircraft is on the ground; and start the aircraft's main engines via their associated pneumatic starter motors.

The APU can be started simply via a switch on the overhead panel on the flightdeck, and its exhaust gas temperature (EGT) is monitored via a simple gauge. The APU is started with an electric starter motor, and consumes the same fuel used to power the main engines. The APU's exhaust is via a pipe in the aircraft's aft tailcone in most aircraft types.

The APU is generally started shortly after landing and while the aircraft taxis to its parking stand. It can then be run during the entire turnaround period, and extinguished after the main engines have been started, and then stabilised during taxi out. It is generally economic to keep the APU running during a short turnaround period, but APU operating costs are high when it is run consistently for the three- or four-hour turnaround process that is typical for long-haul operations.

The electrical and pneumatic power provided by the APU can instead be provided by a ground power unit (GPU), or a simple electrical connection from the airport terminal. This will save fuel consumption, and cancel the APU's noise emissions. It will also save the APU's running time. APU hardware deterioration is similar to that of jet engines, and the removal intervals for maintenance are related in terms of accumulated APU hours (APUH) and cycles (APUC). Saving accumulated APUH/APUC will prolong maintenance shop visit intervals, and so reduce overall APU-related maintenance costs on a per aircraft flight hour (FH) basis.

APU configuration

There are two basic configurations for an APU: radial and axial designs.

The radial APU is a simple single-shaft gas turbine. Air intake is through a side inlet, and air flows into a plenum chamber forward of the gas turbine generating hardware. Intake air passes through a centrifugal compressor, and along the direction of the shaft. This centrifugal compressor, known as the engine compressor, is mounted on the same shaft as the turbine, which is downstream and aft of the compressor. Combustion chambers are located between the centrifugal compressor and turbine. Exhaust air passing from the turbine flows directly into the exhaust pipe, usually located in the aircraft's tailcone. These components form the main hardware sections of the gas turbine.

The APU also has components and hardware related to its electrical and compressed air generating functions. The gas turbine shaft extends forward of the centrifugal compressor and through the plenum chamber and to a second centrifugal compressor, referred to as a load compressor; a gearbox and oil pump; and an electrical generator. This second centrifugal compressor, or load compressor, provides the compressed air for cabin air conditioning via an APU bleed valve, while the shaft's rotary power generates electrical power in the APU generator via the gearbox. The APU bleed valve regulates the pressure of air being passed to the cabin, with any excess pressure being dumped into the APU's exhaust pipe.

In most respects an axial-configured APU is the same as a radial APU. The main difference is that an axial APU in most cases has three, instead of four, compressor stages, and these are the same configuration as a jet engine.

One example of where an axial APU was first used was the Garrett GTCP 660-4 built for the 747-100/-200/-300. This has a four-stage compressor, and was required to provide enough power to start the 747's large turbofans. The APUs used on the 747-400, 747-8 and A380 are all axial-style units.

The turbine disks and compressors are life-limited parts (LLPs) in some APU types. In the case of most of the GTCP family of APUs, all three LLPs in all variants had life limits of 20,000APUC. One exception to this is the third stage turbine rotor which had a life limit of 25,000APUC. A second exception is the two GTCP 131-9 models used on the A320 and 737NG families, which have four LLPs, and have life limits of 30,000APUC. Some part numbers (P/Ns)

APU TYPES FOR MAIN AIRCRAFT TYPES

Aircraft type	APU Manufacturer	APU type	Output shaft power - SHP	Max EGT	LLP quantity	LLP life limits - APUC
Narrowbodies						
CRJ-700	Honeywell	RE220				
CRJ-900	Honeywell	RE221				
CRJ-1000						
ERJ-135/-140/-145	Hamilton Sundstrand	APS 500				
E-175/-190/-195	Pratt & Whitney Canada	APS2300			3	35,000/50,000/60,000
DC-9	Garrett	GTCP 85				
737-200	Garrett	GTCP 85-129	25	1,200	N/A	N/A
MD-80	Garrett	GTCP 85-98D				
737-300/-400	Garrett	GTCP 85-129 (E)	30	1,150	N/A	N/A
	Garrett	GTCP 36-280 (B)				
	Sundstrand	APS 2000				
737NG	Allied Signal	GTCP 131-9B	131	1,170	4	30,000
757	Honeywell	GTCP 331-200	143	1,085	3	20,000
A319/20/21	Sundstrand	APS 3200			4	32,000/50,000
	Honeywell	GTCP 131-9A	131	1,185	4	30,000
717	Sundstrand	APS 2100				
Widebodies						
DC-10/MD-11	Garrett	TSCP 700-4				
747-200/-300	Allied Signal	GTCP 660-4				
767-200/-300	Honeywell	GTCP 331-200ER	143	1,085	3	20,000/25,000
767-400	Honeywell	GTCP 331-400				
747-400	Pratt & Whitney Canada	PW901A				
777	Honeywell	GTCP 331-500B			6	27,000
787	Pratt & Whitney Canada	APS5000			3	24,000/41,000/44,000
747-8	Pratt & Whitney Canada	PW901C				
A300-600R	Honeywell	GTCP 331-250	170	1,085	3	20,000/25,000
A330	Honeywell	GTCP 331-350	166	1,150	N/A	N/A
A340-300	Honeywell	GTCP 331-350	166	1,150	N/A	N/A
A340-500/-600	Honeywell	GTCP 331-600(A)				
A350	Honeywell	HGT 1700				
A380	Pratt & Whitney Canada	PW980				

for the second stage turbine rotors had limits of 10,000APUC due to a manufacturing defect.

The turbine disks in the GTCP 129 family for the 737 family and the GTCP 331-350C for the A330/A340-300 are not life-limited, and so do not have any APUC limits *(see table, this page)*.

Although some APU types did not originally have compressor and turbine disks with life limits expressed in cycles, regulatory authorities have changed this and are imposing cycle limits on these parts for safety reasons. An example is the Pratt & Whitney Canada (P&WC) APS 2300 used for the Embraer E-Jets. This does not currently have any parts with cyclic life limits, but this is due to change.

Unlike jet engines, there are no certified thrust ratings for APUs. The two important operating parameters are the EGT and the AC electrical output, both of which are displayed and monitored via

The configuration of APUs is relatively simple. Most have a centrifugal engine compressor, a combustion chamber, a two- or three-stage turbine, and an exhaust. This small gas turbine drives a shaft to power a load compressor and electrical power generator.

a simple gauge.

An APU's power rating can be expressed or gauged in terms of output shaft power and shaft speed. The early GTCP models for the 737 Classics, for example, have output shaft power ratings of 25-87 shaft horse power (SHP).

Another parameter that has to be followed is EGT, which has a maximum limit, varying from 1,085 degrees to1,200 degrees Fahrenheit *(see table, page 56)*.

Factors that determine the power required by the APU include: the air pressure and volume required to start the turbofan engines on the aircraft; the air pressure required for air conditioning; and the electrical power required for the aircraft while on the ground.

APU types

There are three main manufacturers of APUs. Honeywell's Gas Turbine Compressor Power (GTCP) family is produced in the largest numbers. The GTCP family of APUs was the sole unit for the first generation narrowbodies that included the DC-9, 727 and 737-200; as well as for later generation narrowbodies including the MD-80 and 737-300/-400. They also include the 757, 737NG family, and the A320 family.

Larger and more powerful members of the GTCP family APUs are used for the DC-10, MD-11, 747-200/-300, 767 family, the 777, the A330/340-300, the A340-500/-600, and the A350.

Some of the earlier models of the GTCP family include: the GTCP 85 for the DC-9; the GTCP 85-98 for the 727-100/-200; and the GTCP 85-129 family for the 737-100/-200 and 737-300/-400/-500.

The GTCP 85-129 has output shaft power of 25 SHP for the earliest -129, -129A, -129B and -129D models. This rises to 30 SHP for the -129C, -129E, -129F, and -129G models. The 737-300/-400/-500 also have a higher powered variant: the -129H/J/K rated at 87 SHP *(see table, page 56)*.

The next generation was the GTCP 85-98D for the MD-80 family, coming into operation in the late 1970s. Since there are few 727s and MD-80s left in operation, and almost no DC-9s and 737-200s left in active service, there are only a small number of the earlier generation GTCP APUs left in operation.

The further later generation GTCP 131-9BA was used on the A320 family from the late 1980s, and the GTCP 131-9B was used on the 737NG family.

The -131A has a higher power rating than the models used for the 737-300/-400/-500, and is rated at 131 SHP *(see table, page 56)*. The same model, the -131B, has the same configuration and power rating, and is used for the 737NG family.

A higher rated version of the GTCP 331-200, the 331-200ER, was fitted to the 767 family. Higher-rated models were used for larger and later generation widebodies that entered service from the early 1990s. These are rated at 143 SHP *(see table, page 56)*.

There were then the GTCP 331-350 for the A330 family and A340-200/-300 rated at 166 SHP.

The most recent variant is the GTCP 331-600 (A) for the A340-500/-600, and the HGT 1700 for the A350.

The two other main APU manufacturers are Pratt & Whitney Canada (P&WC) and Sundstrand.

P&WC's first APU type was the PW901A for the 747-400. This was followed by the PW901C for the 747-8, and the PW980 for the A380. These three APUs are all axial-configured units.

Hamilton Sundstrand entered the APU market in the 1990s with the radial-configured APS 2000 for the 737-300/-400, otherwise referred to as the 737 Classics; and the axial-configured APS 3200 for the A320 family. Hamilton Sundstrand was merged with Goodrich Corp to form UTC Aerospace systems.

Pratt & Whitney (PW) commercial engine division has since taken over the production of these APU types. It no longer manufactures the APS 2000 for the 737 Classics. It did manufacture the radial-configured APS 2100 for the 717.

PW also manufactures the axial-configured APS 2300 for the Embraer E-Jets, and the APS 5000 for the 787. The APS 5000 is unique because it has no load compressor. The forward shaft drives two power generators, and this configuration is explained by the 787 being an all-electric aircraft. Compressed air is therefore not required to start engines or provide air conditioning, but higher electrical output is required for electric starter motors for engine start and electrically powered air conditioning units.

APU in operation

The operation of the APU in service has been briefly described. For some aircraft types and styles of operation, the unit is usually started after landing and kept running at least until the aircraft has reached its terminal parking stand. It may be kept running during the entire turnaround period. It will often be used for engine start at departure, and in the case of some engine types and styles of operation, will be kept operating until engine power has stabilised.

The APU is either run during the complete turnaround cycle, or twice at both ends of the turnaround cycle.

In the case of all Airbus types the APU has to be operating during landing and take-off, so it has to be started during the descent or approach, and stopped after the aircraft has become airborne.

The APU also has to be operating permanently for extended range twin-engine operations (ETOPS) missions where smaller aircraft types are used. The

The centrifugal compressor of a radial-configured APU is a core component. Deterioration of this and the turbine disk stages are key drivers of removal for shop visit maintenance.

larger types have to be able to start in flight and are tested on a monthly basis.

The ratio of APUC to aircraft flight cycles (FC) is either 2:1 or 1:1. Given that short-haul aircraft will typically operate at annual rates of 1,700-2,300FC, APU utilisation will be 1,800-4,000APUC per year. Moreover, typical APUC times in short-haul operations range from 30 to 85 minutes, depending on the number of APU cycles per turnaround and the style of operation. Low-cost carriers (LCCs) tend to have shorter cycle times of 15-20 minutes.

Aircraft operated for medium- and long-haul operations typically accumulate 500-1,000FC per year. Annual APU utilisation will therefore be 1,000-2,000APUC for most airlines, if the APU is run twice per turnaround. In this case, the typical APUC time or length is about 60 minutes. A shorter APU cycle will be used for the landing and taxi phases, but a longer cycle will be used for the passenger boarding, pushback, engine start, taxi out, and take-off phases.

As with the main engines, the APU's turbomachinery hardware will deteriorate, especially the airfoils in the compressor and turbine disks. This will result in a steady increase of the APU's EGT.

The APU's hardware condition will therefore decline to the point that it is necessary to remove the APU for a shop visit. This deterioration, and the subsequent increase in EGT and decline in the unit's performance, is the main reason for removal for shop visit maintenance. "A key factor on the rate of decline of APU performance is the unit's average cycle length, combined with the annual rate of APU utilisation," says Dennis Wetjens, EPCOR managing director at KLM Engineering & Maintenance. "There is also the issue of foreign object damage, as well as the deterioration of other associated hardware." These are items such as the load compressor, which generates the compressed air, and the electrical power generator and its associated components.

The key driver for APU removals is therefore hardware deterioration leading to rising EGT. The unit's EGT therefore has to be monitored to accurately assess the need for removals for shop visit maintenance.

Additional causes of removal for shop visit maintenance are: hot section distress, which is driven by accumulated APUH and APUC in operation; vibration, usually as a result of wear of a bearing; distress of various parts and components; the expiry of LLPs; and foreign object damage or damage due to ingestion of ice.

Most APUs are maintained on a third-party basis, so their associated management is also carried out by maintenance, repair and overhaul (MRO) providers. Many MROs include an APU EGT monitoring and maintenance management service in addition to the shop visit activities. Revima of France, for example, provides a dedicated fleet management programme to airlines, which includes development of a customised APU health monitoring system. The Revima APU management system operates via web-based access to health monitoring, and includes real-time data analysis, and APU and LRU reliability management. Health monitoring data and parameters can be visualised graphically on screen, and health data trends followed. Overall, airlines can rank their own fleets, and predictions for remaining useful life of time on-wing can be provided through the service.

Air France Industries and KLM Engineering & Maintenance also provide an APU monitoring and management service through EPCOR, a wholly-owned subsidiary of KLM Engineering & Maintenance. EPCOR provides maintenance support for APUs and pneumatic system components for a wide range of aircraft types. These include the 737NG, the 777, both APU types for the A320, the A330, the A340, the Embraer E-Jets, and the 787.

As part of its service offering, EPCOR provides a health monitoring and APU maintenance management service. The health monitoring service provided is EPCOR Trend Monitoring (ETM). This is an on-line accessible service for APU health data, diagnostics and prognostics. The ETM service is accessed via an on-line web system, 24 hours per day and 365 days per year. In addition to APU on-wing data, EPCOR also provides fleet management and warnings of upcoming events and possible failures. EPCOR also includes a management service with respect to removal and shop visit planning.

LLP lives

"The longer-term issue driving the need for APU removals for maintenance shop visits is the expiry of LLPs," says Martin Matthews, program manager at AerFin Limited. "All APU types generally have very high LLP lives of 20,000-40,000 APU cycles (APUC). APUs are usually considered as on-condition components, so they are normally removed due to internal stress and deterioration. They are rarely removed due to LLP life."

These life limits are illustrated in more detail *(see table, page 56)*, and exert a life limit or fixed heavy shop visit workscope and overhaul limit on the APU. The APU will require a shop visit workscope involving a full disassembly for LLP life replacement when the parts come close to life expiry.

These LLP life limits must be considered in relation to aircraft and APU utilisation.

At typical rates of utilisation in short-haul operations, the LLPs in APUs of short-haul aircraft will expire every six to

Inspection criteria for APU parts and components are continue-time and zero-time, the latter having higher inspection criteria. A shop visit is classed as an overhaul if all parts pass the zero-time criteria, or they are replaced with new items.

16 years, depending on part life and rate of aircraft and APU utilisation. Some will have to be replaced several times during the aircraft's operational life, while those with the longest life limits may only need to be replaced once.

In the case of medium- and long-haul operations, given rates of utilisation and APU life limits, parts with the shortest lives may face life expiry after 13 years, but up to as many as 30 years, which is the operational life of the aircraft. Parts with the shortest lives may therefore only need to be replaced once.

APU reliability

Like the main jet engines, APUs are removed for maintenance primarily on an on-condition basis, so most parts are maintained on this basis. These include the turbomachinery, combustion chambers, line replaceable units (LRUs), and accessories. The only items which have fixed maintenance intervals are the disks and shafts in the APUs where these items are classed as LLPs. The disks and shafts in APUs do not experience the same variation in temperatures and rotating speeds as those in jet engines.

The removal intervals of APUs can be measured by several parameters, including: the mean time between removals (MTBR), which is a measure of the average interval for all shop visit inputs; and the mean time between core removals (MTBCR), which is the mean time between shop visits for the core module with the turbomachinery of the compressor and turbine.

The MTBCR is an important parameter, since it indicates when the more stressed parts or modules of the APU unit require maintenance. The turbine is the most critical part of the core. Many operators use the MTBCR as a soft removal interval for maintenance management.

There are various levels of APU shop visit, and some are classed as line or light maintenance. Only the heavier levels of maintenance would be regarded as shop visit maintenance. The two levels of shop visit that require a significant degree of maintenance are a repair shop visit, which is similar to a performance restoration for a jet engine; and an overhaul.

"As with an aircraft's main jet engines, the first removal interval is usually longer than the subsequent and mature removal interval," says Richard Lynch, powerplant engineer at Dublin Aerospace.

APU removal intervals are usually recorded in terms of APUH, and the removal to the first shop visit averages about 1,000APUH more than the mature average interval.

First removal and mature average intervals tend to be considerably shorter than for the main jet engines at 5,000-7,500APUH for most engine types. They have been shorter for some APU types in the past, but in-service experience and improvements in operational reliability through modifications have gradually extended these average intervals.

It can be preferable to express the average shop visit intervals for APUs by excluding the first removal interval. This mature interval may be referred to as the mean restored life (MRL). "Mature intervals do vary by type, but the shorter average MTBR are for the GTCP 331-200, -200ER and -350 that equip the 757, 767-200/-300 and A330/A340-300," says Lynch. "In the worst case scenario, these are 3,500APUH, but edge up to 5,000APUH in the better cases *(see table, page 56)*." Given typical ratios in operation, the 4,500-5,000APUH for the GTCP 331-200 on the 757 is equal to 3,500-5,000APUC *(see table, page 56)*. On this basis, the LLP with a life limit of 20,000EFC would come due for replacement at the fourth shop visit.

A shorter interval of 3,500-4,500APUH for the GTCP 331-350 on the A330/A340-300 *(see table, page 56)* is equal to a similar number of APUC when the aircraft are used for medium- and long-haul operations. The GTCP 331-350, however, does not have any LLPs, so LLP replacement does not have to be taken into account when managing removals and shop visits.

Longer average MTBR and shop visit intervals are demonstrated for the APS 3200, which equips the A320 family, with MTBR at 6,000-7,000APUH. This will be equal to 5,000-11,000APUC depending on the average APUC time. This APU has LLPs with lives of 30,000APUC, so these will have to replaced at some point between the third and sixth shop visits.

Similar average MTBRs are recorded for the GTCP 131-9A for the A320 family, and the GTCP 131-9B for the 737NG family.

The APU type with one of the longest average MTBRs is the PW901A at 9,000APUH. An average APUC time of 60 minutes for most long-haul operations will be equal to a similar number of APUC between removals.

Data from Honeywell shows that the average removal interval and MTBR for the GTCP 331-500B, which equips the 777 family is 7,400APUH. Given an average APUC time of 60 minutes, the APUC removal interval will be similar. Given that the APU's shortest LLP life limit is 27,000APUC, the APU will have to undergo an overhaul and full disassembly at the third shop visit. This is likely to be after about 15 years of operational service.

Another significant APU type in operation in relatively large numbers is the APS5000, used on the 787 family. The APS 5000's configuration of two power generators, and the high power output it is required to produce have

The majority of APUs are managed under MSP- or PBH-style management programmes. A small portion of airlines use time and material contracts.

resulted in relatively poor levels of reliability. Removal intervals have averaged in the region of 2,000APUH.

APU maintenance process

There are several levels of light maintenance for APUs.

"One of the lightest workscope where actual regular maintenance is performed on an APU is the borescope inspection of the high temperature modules of the combustion chamber and turbine disks," sayss Lynch. "The APU's core is inspected without any disassembly. This is usually performed after an APU test, so it is not performed together with a shop visit workscope."

The only information to be gained from the borescope inspection will relate to the physical condition of the combustion chambers and turbine disks."

The first level of APU maintenance that comprises some shop visit work is a hot section inspection (HSI). "This is not the same level of maintenance as an HSI on a main jet engine. The main issue here will be the leaks of turbine seals." explains Lynch. "This really only involves changing the bearings and seals following an oil leak, for example from the turbine bearing seal. This does not affect the rest of the APU, and is actually a minor repair."

The first level of shop visit that involves a disassembly and work on turbomachinery in the APU is a repair level workscope. "This is similar to a performance restoration performed on a jet engine. It involves disassembly, and checking of exposed parts at a continue-time level as per the inspection repair manual (IRM)," says Lynch.

The continue-time inspection criteria are light or medium, and if the part inspection passes these criteria it can be reinstalled in the APU. If the part fails then it may be sent for repair, and then reinstalled. If parts that are inspected generally pass the continue-time criteria then the shop visit is generally classed as a repair.

"The overhaul is the highest level of shop visit," says Lynch. "There are five main parts to an overhaul. The first involves fully disassembling the load compressor, engine compressor and turbine section. The compressor rotors, turbine disks and rotors, and tie shaft are inspected as per the inspection repair manual (IRM) to a zero-time inspection. It is more difficult for a part to pass this inspection because the zero-time criteria are more stringent. Zero-time inspections involve more detailed dimensional checks, more parts require a non-destructive test (NDT), and parts are inspected using magnification of up to 10 times their size.

"The gearbox is also inspected and repaired as necessary," continues Lynch. "The LRUs and accessories are also repaired as required, and following reassembly the APU is tested to the highest performance standard."

If all parts pass the zero-time inspection criteria then the shop visit can be classed as an overhaul. The parts can be reinstalled without any further repairs or inspections, or parts that fail the criteria are replaced.

If parts that fail the stringent inspection criteria then they can be inspected at the lighter continue-time criteria. If these are reinstalled then the shop visit can only be classed as a repair.

Removals for shop visits will be caused by the deterioration of rotating parts in the core and of the combustion chambers, and an increase in EGT to close to the maximum allowable limit. Findings made in borescope inspections can reveal some of these.

Airlines may try to establish soft removal intervals, which may be close to the MRL for each engine type. Some of the APU modules may have intervals that are twice the soft shop visit interval. Operators and maintenance shops may therefore be able to establish a shop visit pattern of alternating repair and overhaul workscopes.

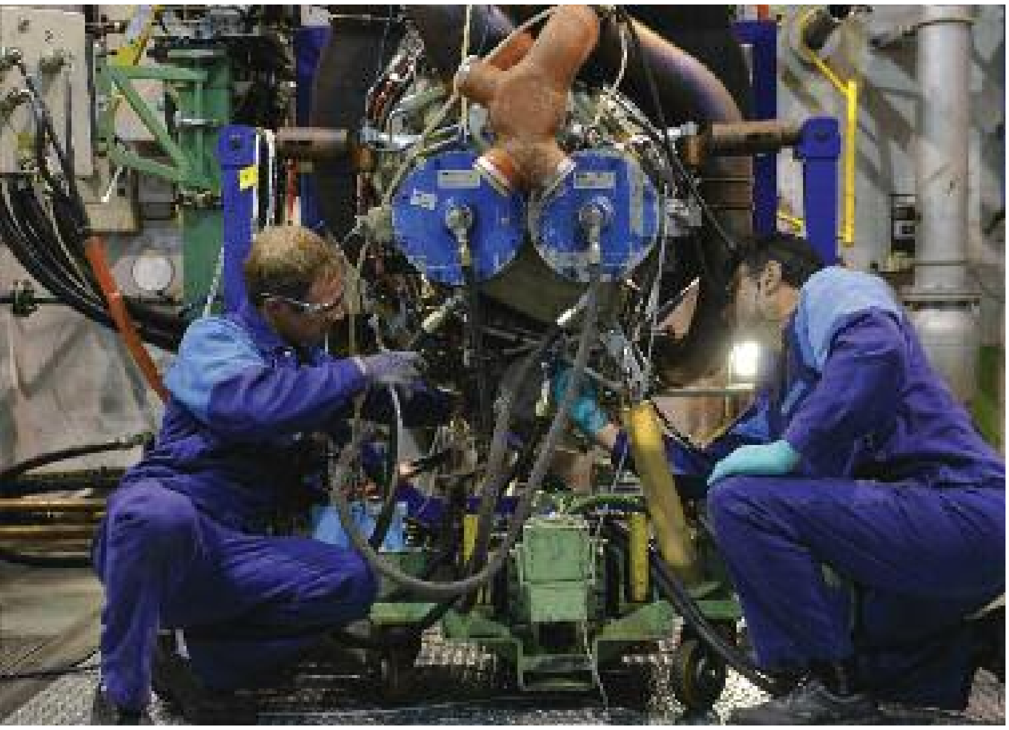
Shop visit costs

The main APU types in service are the GTCP 131-9A/B for the A320 and 737NG families, the GTCP 331-200/-200ER for the 757 and 767 families, the GTCP 331-350 for the A330/A340, the GTCP 331-500 for the 777 family, and the PW901 for the 747-400. There is also a fairly large fleet of PW980s for the A380 in operation, and limited numbers of the APS5000 for the 787, and HGT 1700 for the A350.

A large number of airlines now use fixed-cost-per-hour maintenance and management programmes. These are programmes that include power-by-the-hour (PBH) offered by Honeywell, and maintenance service programmes (MSP) offered by Pratt & Whitney.

A smaller number of airlines still use traditional third-party time-and-material maintenance contracts. Some airlines have retained their in-house APU capability, and there are still some independent shops such as Dublin Aerospace and The Triumph Group.

"Removal intervals can be up to 10,000APUH if the APU is managed well and operates in a better environment," says Mike Redmond, chief executive officer at Aerospace Industries Auxiliary Power, Ireland. "The GTCP 331-131B (on the 737NG) can regularly achieve this removal interval. The 131-9A (for the A320 family) does not achieve such long intervals. This may be because it is the same APU as the -131-9B, but the -9A has to power a larger aircraft. It may also be partially explained by the air intake on Airbus aircraft being on the ventral side of the fuselage, making it prone to ingesting foreign objects."



Following a repair or overhaul shop visit, an APU has to go through a performance test. It then has a borescope inspection. This provides information relating to the status of core turbomachinery parts and components.

A heavier shop visit for the GTCP 131-9A/B is likely to incur a shop visit cost in the region of $350,000, depending on LLP replacement. One factor affecting the final cost will be the cause of failure and removal.

Historically, there are two main issues triggering early removal. The first is failure of the compressor bearing, although this has now significantly improved with a modification to a duplex bearing. The second main removal cause is the detachment of blades in the first stage turbine disks, or 'blade walk'. The effect of this could be quite destructive, and led to short removal intervals especially in early modifications. "This problem was finally solved by replacing disks and the inserted blades with a single-unit blisk," says Redmond.

If these main parts suffer a certain level of deterioration, due to erosion for example, that the first and second turbine disks may have to be scrapped. The cost of these replacement parts alone can be about $200,000, and so increase the overall cost of the shop visit.

The APS 3200 for the A320 family has historically been maintained and managed on MSPs for the majority of units. The APS 3200 usually achieves 6,000-7,000APUH between removals. Redmond explains that due to OEM control over the aftermarket there is little serviceable material available. A heavier shop visit workscope can therefore be quite expensive.

"In the case of the GTCP 131-9 series, Honeywell has developed some repairs, and the availability of these affects shop visit costs, since it reduces the parts replacement rate," explains Redmond. "In the case of the APS 3200, the first and second turbine stages are bladed, and replacing blades adds to shop visit costs. Both sets can often require replacing on a heavy shop visit."

Of the main widebody fleets, a large number of 747-400s, A340-300s, and 767s have been retired and parted out. A large number of 757s have also been removed from service. This has resulted in a surplus of PW901, GTCP 331-350, and GTCP 331-200/-200ER units on the market.

"The problem with this is that market values for time-continued or 'green time' units have now fallen to the level where, for instance, for a GTCP 331-200ER, it can be more economic to use these unless the quoted shop visit cost is less than $250,000," says Redmond. "That is, a shop visit of more than about $250,000 makes the APU beyond economic repair (BER). Some airlines are prepared to take advantage of the low value of used units available in the market, while other operators are continuing to fully maintain their own units. One factor affecting an airline's decision is the aircraft's ownership status. Lessors may stipulate that the APU is fully maintained to preserve asset value. Aircraft age and likely secondary market opportunities also has an influence."

The shop visit costs for a full refurbishment on these larger APUs is $500,000-700,000. This compares to depressed aftermarket values for time-continued units. "APUs for the 747-400 and A340-300 were $700,000-800,000 about seven years ago," says Redmond. "The large number of aircraft that have been parted out has seen these values drop to about $250,000-350,000. There is the possibility that some of the surplus will dry up, since most A340-300s have now been parted out and there are about four times as many A330s in operation.

"As another example, there are several repair shops that are making greater use of serviceable material and repaired parts, rather than replacing parts, to reduce shop visit costs and get them down to a level that is commensurate with used market values," adds Redmond. "The large number of PW901s on the market, however, means they are BER, and most operators and owners are not approving the shop visit costs."

The major providers of APU maintenance and engineering management include the OEMs, large independent shops, and large airline maintenance and engineering departments. Honeywell is naturally is the largest provider, and has shops in Raunheim, Germany; Phoenix, Arizona; and Singapore. Pratt & Whitney provides services for all PW900 series and APS models of APU, together with its broad range of regional and corporate jet engines.

Revima of France is one of the largest independent shops. It has capability for all APS types, a wide range of GTCP models and all PW900 series models. It performs more than 500 shop visits per year.

Dublin Aerospace is an example of a small independent shop. It has capability for the GTCP 85 (737 Classics), GTCP 131-9A/B (A320/737NG), GTCP 331-200 (757/767), and the GTCP 331-350 (A330/A340).

The large airline maintenance and engineering department providers are Air France Industries (AFI) KLM Engineering & Maintenance (AFI KLM E&M), Lufthansa Technik, and Turkish Technic.

AFI KLM E&M has capability for the APS 2300, 3200, 5000; and GTCP 131-9A, -9B, 331-350, and 331-500. It performs about 200 shop visits per year.

Lufthansa Technik has capability for the APS 2000, 2100, 2300, and 3200; and the HGT 1700. It performed about 125 shop visits in 2016, and expects this to reach about 190 annually by 2018.

Turkish Technic specialises in the APS 3200, GTCP 131-9B, and the GTCP 331-350C. It performs about 70 shop visits per annum. *-CHW* AC