The operation of the APU, issues that affects its performance, maintenance management and related costs are all examined. The surplus of aircraft has led to a surplus of APUs on the market, making 'green time' units an attractive alternative to conventional management and shop visits.

APU maintenance management and the aftermarket

The auxiliary power unit (APU) is one of four major components in a commercial aircraft, and accounts for maintenance costs of $40-50 per APU cycle (APUC). The APU is a small gas turbine that provides enough air pressure to air condition the passenger cabin when the main powerplants are shut down, while also providing enough pneumatic power to start a single engine. It also generates sufficient electrical power for the required aircraft systems while the aircraft is on the ground during turnaround and the engine starting process. APU configuration, function and style of operation are all examined here, together with maintenance requirements and management.

APU types

The APU is a gas turbine coupled with an air pressure generator and a gearbox. The gearbox is used to generate the correct revolutions to turn the electricity generator to provide electrical power for the aircraft's various systems. There are two main configurations of APU.

The first is an axial APU, which is similar to a jet engine, in that it has two compressor stages and its turbine stages are mounted on a single shaft, with a combustion chamber in between.

The second type of APU configuration is radial. The air intake is at the side, and enters a plenum chamber which surrounds the shaft. The shaft extends rearward to the gas turbine unit. This is configured with a single-stage centrifugal compressor, referred to as the engine compressor. This is followed by a combustion chamber, and a high pressure turbine (HPT). The HPT in most cases has two stages.

The shaft also extends forward from the plenum chamber and turns a second centrifugal compressor, the load compressor, which provides the air conditioning. The shaft then extends further forward to turn the gearbox and to generate electricity via the electrical generators.

The APUs used on the main aircraft types are: the GTCP family, provided by Honeywell; the APS family, provided by Hamilton Sundstrand; and the PW900 series, provided by Pratt & Whitney (PW) Canada. The main types of APU unit are listed *(see table, page 26)*. Most APUs on commercial aircraft types have a radial configuration.

In addition, the APU has several externally mounted accessory components and line replaceable units (LRUs). These include the oil reservoir and lube pump, the fuel control unit, fuel nozzles, electrical starter motor, the fuel control units and electronic control unit, the ignition unit, wiring harness and ignition components.

The smallest APUs for the RE220 on the CRJ-700 have an electrical power-generating capacity of 40 kilo volt amps (kVA), while the largest units that equip the 747-8 and A380 have ratings of 90 kVA and 2 x 120 kVA *(see table, page 26)*. The shaft horsepower (shp) rating of the APU relates to its air conditioning power.

Axial APU units have a small number of life limited parts (LLPs). The Honeywell GTCP 131 for the 737 Classic and NG, and A320 families, has four LLPs: two HPT disks; the engine centrifugal compressor, which is manufactured as a single piece; and the turbine shaft. These all have life limits of 30,000 APUC. Their combined list price is $600,000.

There are also four LLPs in the radial-configured APS 3200: the load compressor; the power compressor; and the two HP disks. The two compressors have life limits of 50,000APUC, while the two compressors have life limits of 30,000APUC. The APS 3200 was fitted to some A320ceo family aircraft.

The GTCP 331-200ER used for the 757 and 767 has a three-stage turbine, and each disk is an LLP. The first two have life limits of 20,000APUC, and the third has a life limit of 25,000APUC.

There are other APU types that do not have any LLPs. Instead their main shaft and disk components are condition-monitored, simply by inspecting their condition at the time of a shop visit (SV), where there is a sufficient level of disassembly to inspect the parts. They can also be inspected via borescope inspections that take place during airframe checks.

The APS 5000 is used on the 787 family, which has an all-electrical configuration, so it does not require a load compressor to generate air conditioning power. The power for this instead originates from the gearbox and the two electrical generators it has, one of which is used to generate the power for air conditioning.

All widebody types since the 1980s and the 757-200/-300 have been certified for extended range twin-engine operations (ETOPS). One of the requirements for certifying an aircraft for ETOPS is that its APU must be configured differently to other APUs, and demonstrate particular levels of reliability. The APU's modification status will include having the latest LRUs and accessory components installed. The

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Aircraft type	APU model	Electrical power	LLP lives - APUC
CRJ-700/-900	RE220	1 X 40 kVA	
Embraer E-Jets	APS 2300	1 x 40 kVA	3 parts, 35,000, 50,000 & 60,000
Embraer E-Jet 2	APS 2600		
737-300/-400/-500	APS 2000	1 x 45 kVA	
737-300/-400/-500	GTCP 85-129H	1 x 45 kVA	None
737NG	GTCP 131-9B	1 x 90 kVA	4 parts, 30,000
A320ceo family	GTCP 131-9A	1 x 90 kVA	4 parts, 30,000
A320ceo family	APS 3200	1 x 90 kVA	4 parts, 32,000, 50,000
A320neo family	GTCP 131-9A	1 x 90 kVA	4 parts, 30,000
757-200/-300 767-200/-300	GTCP 331-200/ -200ER	1 x 90 kVA	3 parts, 20,000 & 25,000
A330/A340	GTCP 331-350		None
777 family	GTCP 331-500B	1 120 kVA	6 parts, 27,000
787 family	APS 5000	1 x 225 kVA	3 parts, 24,000, 41,000 & 44,000
A350	HGT 1700	1 x 150 kVA	6 parts, 27,000
747-400	PW901A	2 x 90 kVA	
747-8	PW901C	2 x 90 kVA	
A380	PW980	2 x 120 kVA	

operator is also required to have a condition monitoring system in place.

APU performance

Unlike jet engines, APUs are not required to operate at a range of thrust ratings, and instead operate at a constant speed or revolutions per minute (RPM). The APU unit is therefore not subject to higher and lower power ratings, so combustion temperatures are more constant than on jet engines, and the only variation is due to the variation of inlet bleed air temperatures according to the outside environment.

APUs nevertheless have an exhaust gas temperature (EGT) margin. This will erode as the engine's hardware deteriorates, especially in the case of the turbine stages. Each APU type's maximum EGT therefore has to be known, while its operating and output performance must be regularly monitored.

EGT values are sometimes set by the APU's full authority digital engine control (FADEC) unit. Bleed air pressure and temperatures and the APU's shp values are monitored to determine if performance parameters are met or exceeded.

The maximum EGTs of several APUs have been monitored by Standard Aero. The Honeywell RE220 used for the CRJ-700/-900 has a maximum EGT of 1,131-1,166 degrees Fahrenheit, and the APS 2300 for the Embraer E-Jet family has a maximum EGT of 1,324 degrees Fahrenheit.

EGT margin erosion, however, is not tracked, but the bleed air pressure and shp are. "This is because an APU's EGT margin is not monitored, and then removed at an appropriate time in the way an engine is managed," says Rob O'Connor, head of APU at Dublin Aerospace. "APUs are often run until there is a loss of electrical or air conditioning power, or until they fail. That is, the electrical power they generate becomes insufficient once the APU's condition and performance has deteriorated to a certain level. Another issue will be insufficient air pressure to start the main engines.

"Health monitoring is only possible for modern APUs, not the older ones," continues O'Connor. "The performance characteristics that are monitored are the bleed air pressure, bleed air flow, and the electrical power it is generating. As the APU's condition and performance deteriorate, it will take longer to start the APU, because of a long-term decline in the HPT section. Once the start time takes up to 60 seconds, the APU has experienced a high level of thermal damage, so a lower air pressure is produced. This results in a longer time to start the main engines."

The bleed air pressure for engine start and electrical output can be monitored by sending data via the flightdeck's various connectivity systems. Readings or performance parameters can also be recorded during line maintenance and lighter hangar checks.

APU operation

The APU's main functions are to provide aircraft cabin air conditioning, electrical power, and air pressure and flow to start the main engines. These are all provided by the main engines during flight. Engines are shut down on arrival at the gate or parking stand after landing, and started during the pushback process before departure, so the APU needs to run during the turnaround period between flights.

The alternative to APU power is ground supplies of electrical and compressed air, which are generally cheaper than operating the APU, because this consumes fuel and incurs maintenance costs. APU fuel consumption rates are 120Kg (40 US Gallons) per hour for narrowbodies, and 230-300Kg (75-100USG) per hour for widebodies. At current fuel prices, this is $100 per hour for narrowbodies, and $190-250 per hour for widebodies. These rates are for the APU providing both air conditioning and electrical power. They will be reduced when the APU is providing just electrical power, and no air conditioning when maintenance is being performed.

Airlines generally consider the total costs per APU hour (APUH) of fuel consumption and maintenance to be higher than using ground power sources.

The standard operating procedure of most airlines is to advise crews to use ground power whenever possible. Ground power sources are commonly available at the gates and airbridges of main airport terminal buildings, but tend to be less available at remote stands, which may use mobile ground power units (GPUs) instead.

Not all destinations, smaller airports and remote stands have ground power sources and GPUs, so the APU must be used during the full turnaround time.

This will be especially necessary during short turnaround times between flights in a short-haul operation, or when operating in a hot or cold environment. In this case the APU utilisation rate will be 1 APUC per aircraft flight cycle (FC). The average APUC time will therefore be close to the turnaround time. Most airlines' standard operating procedures are to start the APU after landing and during taxi-in as part of the after-landing checklist. The APU will therefore start a few minutes before arriving at the terminal gate or remote stand, and keep running throughout the turnaround time, which could be 20-25 minutes in low-cost, quick turn operations.

It will also be used during pushback to start both engines. Once they are running it will be turned off as part of the after-engine start or pre-departure checklist. The APU will therefore run for five to eight minutes after the pushback process starts.

In these cases, therefore, one APUC is used for 30-40 minutes during turnaround.

There are also short-haul operations which have longer turn times, and are more likely to have two APUCs for the cycle. The taxi-in cycle is likely to include passenger disembarkation time, so could be 15-30 minutes in total. The pushback phase will have a time of 5-10 minutes.

The APU cycle times will therefore average about 15 minutes of 0.25APUH.

In the case of long turnaround times, and when the aircraft is left for an extended period or between long-haul sectors, the APU can be switched off, since the aircraft does not require power. The APU will then be used twice during the turnaround.

The APU will first be used during taxi-in, be started after landing and kept on when arriving at the gate. It can be turned off when ground power sources are connected, but kept running for up to 25 minutes to maintain air conditioning when arriving at a hot airport while passengers disembark from large, long-haul aircraft. The APUC for the taxi-in period can therefore be 10-45 minutes, depending on the airport and the size of the aircraft.

The second cycle will be during the pushback and engine start phase. The APU will be started after pushback clearance has been received, and turned off once all engines are started and running. This can take 10-20 minutes.

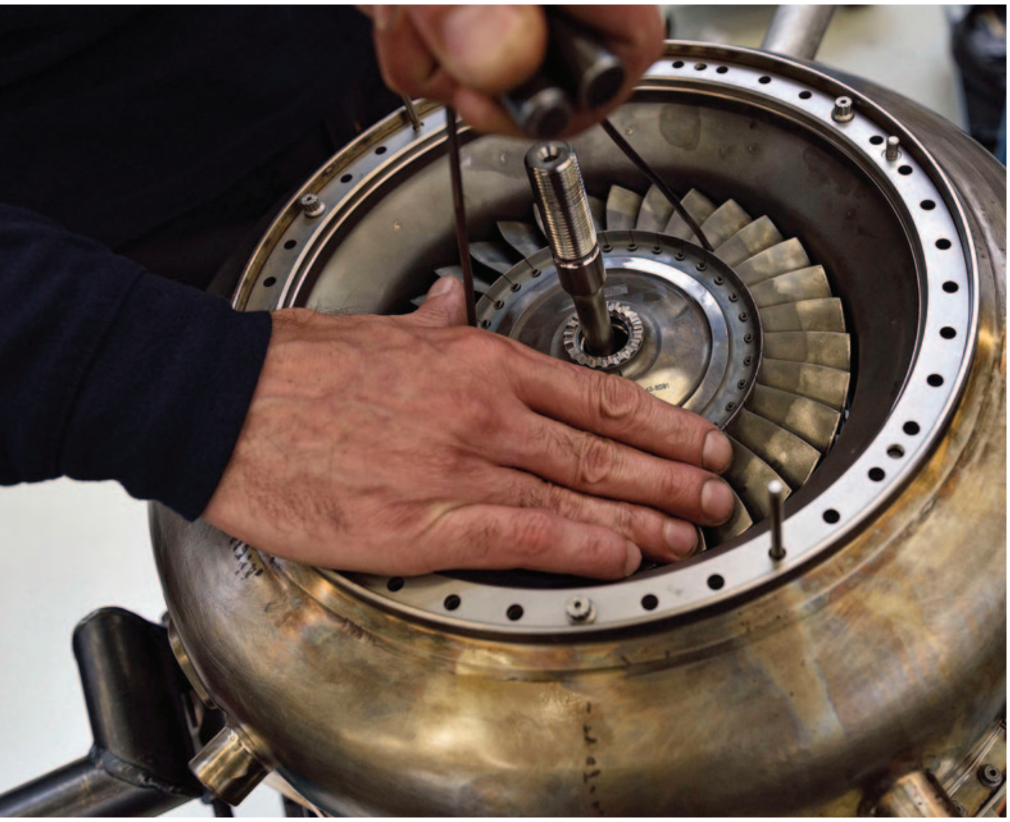
Maintenance management

This range of APUC times therefore affects the maintenance management of the unit. In the case of most APU cycles, times are short and rarely exceed 30 minutes. While APU LLP life limits are 30,000APUC in most cases, this life can quickly be used up during operations. Regional jets (RJs) operate at about 1,500APUH and 3,000APUC per year, so the average APUC time is 30 minutes.

Most short-haul aircraft achieve utilisations close to 2,000FC per year, and two APUC per FC will mean that close to 4,000APUC per year can be used. LLP life limits can therefore be reached in seven years.

In the case of long-haul aircraft completing 600-800FC per year, the APUC utilisation will be lower at 1,200-1,600APUC. The LLPs would therefore only expire after18-20 years' operation.

LLP lives in relation to annual rates of utilisation are one factor that influences the maintenance management of engines. Another will be the removal intervals for SVs. These are shorter than the LLP lives,



APu maintenance is based on soft removal intervals for shop visits. These are mainly related to known rates of deterioration, which are related to the wear of airfoils in the turbine stages, combustor and engine compressor sections.

so LLP replacement needs to be factored into planned removal intervals and the timing of a full disassembly and a heavier workscope that will allow LLP replacement. The factors that cause deterioration of APU hardware and cause removals therefore determine the time between removals and SVs.

Standard Aero comments that SVs are mainly for unscheduled repairs and performance deterioration. Examples of unscheduled events are problems with the oil system and clogged combustors. SVs are also used for scheduled maintenance events and replacement of LLPs.

The main components that deteriorate and cause a loss of performance are the airfoils, particularly those in the engine compressor, turbine sections and combustion chambers. Their deterioration will increase EGT, and so reduce and erode EGT margin. This can be monitored through the electrical output and shp.

Foreign object damage (FOD), although less likely than with jet engines, can lead to unscheduled removals. Items ingested can include stones and grit, as well as pieces of ice in some environments. Sand is a major cause of FOD and a fast rate of hardware deterioration for aircraft operating in a desert environment. Standard Aero explains that the wear of bearings is another issue, and this will lead to vibration and hot-section distress.

The main causes of scheduled removals are therefore hardware and EGT margin deterioration and LLP replacement, while the main causes of unscheduled removals are FOD damage and bearing failure or unexpected hardware distress.

Even so, and despite the ability to monitor performance by mainly using data relating to electrical and shp output, many airlines do not have specific soft times or planned intervals for removals and SV.

"A typical range of SV removal intervals is 4,000-8,000APUH, depending on the APU type," says Nick Filce, director of asset sales and MRO at Aerfin. "The removal interval of most APU types is 5,000-7,000APUH. The intervals are partly affected by average APUH:APUC ratio, which in turn is determined by the number of APUC per turnaround period. Shorter APUC times will increase the rate of deterioration. Modern generation APUs will be more reliable than older types.

"Many APUs are managed under an alternating SV pattern of performance restoration and overhaul," continues Filce. "The intervals of 5,000-7,000APUH are about equal to 10,000-14,000APUC in the case of APUs used for short-haul aircraft, because the average APUC time is about 30 minutes. The APUs used for long-haul aircraft may have slightly longer average APUC times because of the length of the after-landing cycle due to the time required for passenger disembarkation."

In most cases the interval between removals for SVs will be between one-third and half the 30,000APUC LLP life limit. Several APU types have LLPs with shorter limits of 20,000APUC. It therefore makes sense to have an average removal interval closer to an average of 10,000APUC.

The life limits are 30,000APUC for the four parts in the GTCP 131-9A that equips the A320 family aircraft, and the -9B that equips the 737NG.

The APS 3200, which is the alternative choice for the A320 family, has four LLPs with lives of 32,000APUC and 50,000APUC.

The GTCP 85-129, which equips the 737-300/-400/-500, has no parts with life limits.

The GTCP 331-200, which equips the 757-200/-300, has three LLPs, and two in the HPT with life limits of 20,000APUC and one with a 25,000APUC limit. The same applies to the GTCP 331-200ER, which equips the 767 family.

The smaller APS 2300, which equips the Embraer E-Jet family has three LLPs with lives of 35,000APUC, 50,000APUC and 60,000APUC.

The GTCP 331-500B, which equips the 777 family, has six LLPs with lives of 27,000APUC.

The APS 5000, which has no load compressor and equips the 787 family, has three LLPs with life limits of 24,000APUC, 41,000APUC, and 44,000APUC.

The GTCP 331-350, which equips the A330 and A340-200/-300, has no parts with life limits.

Removal intervals

Standard Aero notes that unscheduled removals are often the main cost drivers for APU maintenance programmes. The reliability of APUs generally results in one or two unplanned removals before a full SV that involves complete disassembly of the engine for LLP replacement. The actual timing of the unscheduled events will affect how much of the LLP life is actually used.

As described, the removal intervals of most narrowbody APUs are 5,000-7,000APUH, depending on the style of operation and turnaround times used.

The first scenario of a single APU cycle for a short turnaround during short-haul operations will be an average of 0.50-0.67APUH. With typical SV intervals of 5,000-7,000APUH, this will be equal to 7,500-14,000APUC.

The second scenario of two APU cycles used during a longer turnaround will produce average APU cycles of 15-20 minutes. These will result in intervals of 15,000APUC and more.

The third scenario involves turnaround times of several hours, especially for medium- and long-haul flights, assuming that ground power is available. Where the APU is kept running during passenger disembarkation, the cycle time will be 45 minutes. The second cycle during engine start and initial taxi-out will be 10-15 minutes, and average APUC time 30.

Removal intervals of 5,000-6,000APUH for the main APU types, such as the GTCP 331-350 for the A330, and GTCP 331-500 for the 777 family. The PW901A, used on the 747-400, achieved similar intervals. When used with two APUC per turnaround averaging 30 minutes, the intervals will be 15,000-16,000APUC.

For modern generation widebodies, average APU removal intervals are 5,500APUH and a similar number of APUC for the GTCP 331-500 (77 family), and 6,000APUH or 4,600APUC for the HGT 1700 (A350).

Shop visits

The main narrowbody types are the most common. The GTCP 131-9A/-9B has two main levels of SV workscopes, a repair to get the unit serviceable, and a heavy workscope involving full disassembly.

Gerd Ockerman, programme manager at Jet Engine Management, says the total cost of repair workscopes can range from $50,000 to $300,000, at 7,000APUH in the case of the -9A and -9B. One variable will be the removal interval, but the condition at removal also varies. An average cost of $200,000 can be expected.

The refurbishment workscope can cost $300,000 to $550,000, excluding LLPs. An average of $450,000 could be used. This workscope involves a full disassembly for all the gas turbine stages to be inspected and repaired. The gearbox, LRUs and accessories also have to be repaired. The LLPs will also be replaced at this stage in most cases, after reaching a total time of close to 30,000APUC.

The actual total time across the SV cycle to the heavy SV and LLP replacement will be 22,000-27,000APUC in most cases. The total cost of the two, or possibly three SVs if a small repair were required, together with the replacement of a shipset of LLPs at a list price of $314,000, would be $860,000-1,000,000. The equivalent reserve would be $40 per APUC, but how this translates to a cost per aircraft FH or FC depends on style of operation.

Ockerman explains that SV costs for the APS 3200, the alternative APU choice for the A320ceo family, are higher for refurbishments or overhauls at $350,000 to $600,000. The repair SV costs are similar to the GTCP 131-9A, while the four LLPs have a lower list price of $243,000.

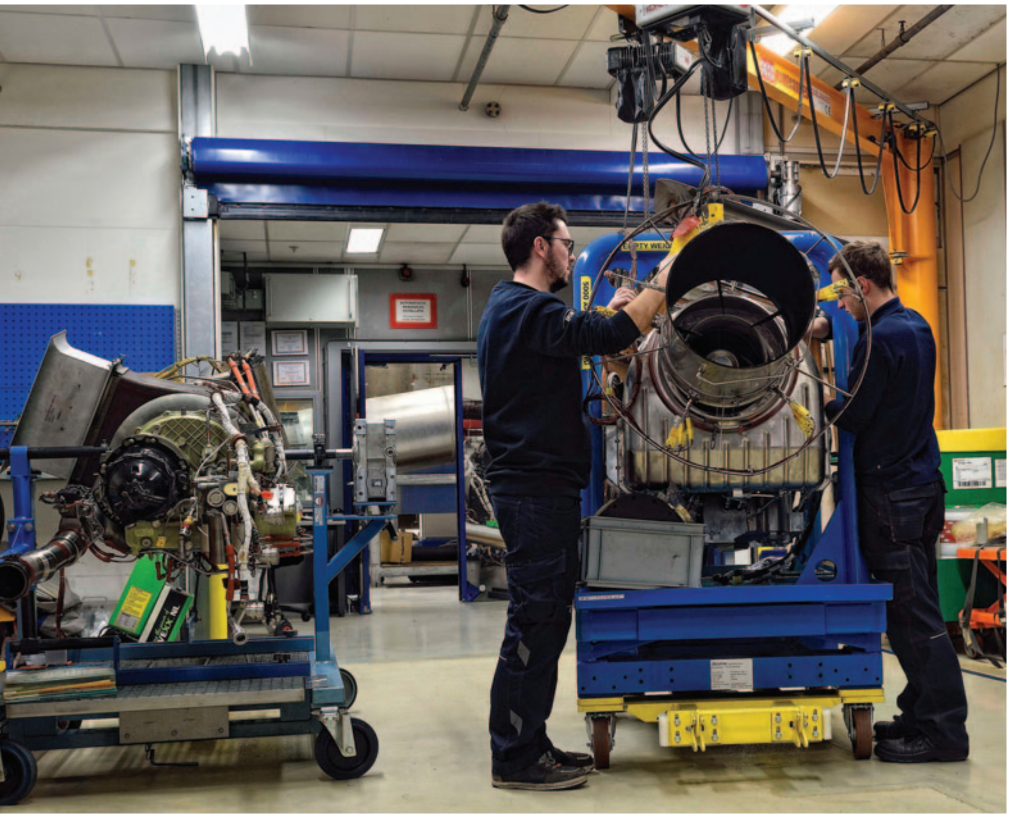
APU aftermarket

In the case of an ageing fleet, and an aircraft type that has had large numbers parked and in storage during the Covid-19 pandemic, it is possible for airlines to acquire APUs with remaining maintenance life relatively cheaply. Units that are 'time-continued' or have 'green time' remaining may be cheaper than putting an APU through an SV, especially where this would involve LLP replacement. This option is more difficult or impossible for airlines whose APUs are on maintenance cost per hour (MCPH) contracts with large maintenance, repair and overhaul (MRO) providers or original equipment manufacturers (OEMs).

"It is possible to get a time-continued APU, which may have been salvaged from a parked or stored aircraft, into a serviceable state very quickly if its maintenance condition was reasonable when it was acquired," says Brian Postel, senior vice president at Unical Aviation. "A lot of airlines acquire green-time APUs in the hot summer months on short-term leases because this is the season when there are more reliability problems. Many APUs are taken on short-term leases to provide cover when an airline's own APU is going through an SV."

SVs are 30-45 days, with another 15 days for logistics and transport in both directions. Minimum lease terms are therefore 60 days, and up to 90 days to cover possible SV delays.

There are also risks with time-continued units, however, including a lack



Airlines can manage the maintenance of APUs on a time and material basis mainly for older models, while younger types are often managed on a maintenance cost per hour basis. The surplus of aircraft during the pandemic has led to an oversupply of green time APUs, making their acquisition or lease attractive compared to regular shop visits.

of warranties that can protect from failures and reliability problems. The number of warranties that can be claimed against reduce as time on-wing since the overhaul progresses.

There can also be unscheduled or early unit failures, causing inconvenient delays.

The large number of aircraft that have been parked and stored has increased the supply of rotable components and APUs that are available on the market, thereby reducing market values and enhancing the case for avoiding SVs. "Depending on the aircraft type, APU used market values have dropped by 15-25%," says Postel.

The cost of acquiring a time-continued unit and its likely maintenance life has to be considered against the likely SV cost of a unit that has been, or is due to be, removed. "The soft time between removals is 5,000-7,000APUH for most units," says Conrad Vandersluis, senior vice president strategic material and asset management at AJW Group. "If a unit can provide up to 1,500APUH on-wing, then buying it is probably a good choice. This can save $100,000-200,000 compared to putting the used unit through an SV."

Another scenario to be considered is the lease return conditions stipulated by lessors. "This includes a minimum number of APUC for time since new (TSN) and cycles since new (CSN) on the unit's LLPs, and the date of manufacturer of the whole unit," says Vandersluis. "So the APU can be 10-15% older than the aircraft. This allowance is used because lessors know that components get swapped between aircraft. The TSN and CSN are also restricted by return conditions; for example, the APUH total time cannot be more than twice the airframe life. There is usually a minimum time since the last SV. This means there is an active market for APUs when returning aircraft off lease."

APU supply

There are several sources of used and time-continued APUs, from stored and dismantled aircraft, and via specialists. There are also independent APU workshops that often lease out APUs.

"These are used on a short-term basis to cover during SVs," says Vandersluis. "The market is dynamic, and lease rates can change relatively quickly. The GTCP 131-9A/-9B for the A320ceo family and 737NG can attract a lease rate of $25,000 per month, including maintenance reserves for the time used. This is equal to $750-800 per day. Including maintenance reserves ensures the shop gets repair work when it comes due, so competitive rates are achievable."

Most of the 757 fleet has been retired, so the supply of used APUs should always be relatively high. "With older aircraft types, market values fluctuate," says Vandersluis. "An increase in supply brings down market values, so airlines opt for acquiring these units over putting APUs through SVs. The supply of green-time units dries up, which increases their market values, so more units get put through the shop. More aircraft get retired, which increases the supply of green-time units, so market values go up and down."

Examples of lease rates for larger types are $900-1,300 per day for the GTCP 331-500 on the 777 family; equal to $27,000-40,000 per month. This will also include maintenance reserves. "This is a specialist unit, since few shops other than the OEM Honeywell can provide maintenance capability. Lease rates are very depressed for the GTCP 331-350 used on the A330, because many aircraft are grounded," says Vandersluis.

Buying time-continued units is also a consideration. Light repairs and SVs can keep an APU airworthy, and only heavier SVs are required when LLPs have to be replaced, if applicable, or an airfoil unit has failed.

The narrowbodies that dominate the fleet are the A320 family and 737NG. Large numbers of these are in storage, so supply of green-time APUs has increased. "Market values of GTCP 131-9A/-9Bs and APS 3200s are $150,000-350,000, but they are affected by many variables," says Vandersluis.

The main widebody type is the A330, which shares the same GTCP 331-350 as the A340-200/-300, virtually all of which have been retired. Many A330s remain parked and stored following the pandemic, and the oldest A330-300s are now 29 years old. The large number of aircraft that have been retired or stored, and are unlikely to return to service, has increased the availability of APUs. "Market values of GTCP 331-350 are highly variable. This type has no LLPs, so values range from $90,000 to 400,000 based on condition and accumulated time," adds Vandersluis.

The second main widebody type with large numbers in storage until the pandemic was the 777 family. Many of the -200, -200ER and -300 series aircraft are unlikely to return to operation, increasing supply of units for the remaining aircraft; many of which will be -200ERs and -300ERs. "The GTCP 331-500 does have LLPs, which is affecting market value," says Vandersluis. "This ranges from $350,000 to $950,000."

The A350 and 787 families are the other main widebody types, but as they are young there are few or no spare APU units.

Widebodies that have seen a large reduction in active numbers, and so increased the supply of APUs, are the 767 family, 747-400 and A380. AC