The General Electric GEnx family and Rolls-Royce Trent 1000 have been through a series of high profile upgrades and modifications. The technical details of each programme and the outcome is examined.

Major modifications & upgrades for the GEnx & Trent 1000

The General Electric (GE) GEnx-1B and -2B, the Rolls-Royce (RR) Trent 1000 power the 787 family and 747-8. Both engine families have been through a series of upgrade and modification programmes. These have been to improve fuel burn performance and operational reliability. These are described in detail.

GEnx

GE developed the GEnx to provide a replacement for the CF6 family of turbofans. The GEnx family has several main variants rated at 54,000-76,100lbs of thrust.

The two main series of the GEnx are the GEnx -1B, which is an engine option on the 787; and the GEnx -2B, which exclusively powers the 747-8. They have incorporated the same technologies and have been designed with the same main performance levels and goals, but some of their parts and airfoils are not interchangeable. The fan, low pressure compressor (LPC) and low pressure turbine (LPT) are different. The core modules, the high pressure compressor (HPC) and high pressure turbine (HPT) can share the airfoils, depending on engine configuration, and have the same life limited parts (LLPs). The -1B and -2B also have 80% line replaceable unit (LRU) and 90% line tool commonality.

The GEnx incorporated various new technologies to achieve the required performance levels, including 15-20% lower fuel burn over previous generation engines, and longer on-wing removal intervals and lower maintenance costs.

The GEnx's fan module incorporates 18 swept, wide-chord composite fan blades; and also uses a composite fan case. Other features include titanium aluminide LPT blades, contra-rotating shafts to reduce loading on turbine inlet guide vanes, and a high pressure ratio of 23:1 to achieve high fuel burn efficiency. The architecture of the -1B and -2B are different, however. For example, the -1B does not have bleed air systems, since it powers the 787, which maximises the use of electrical power.

The -1B has a fan diameter of 111.1 inches, 18 composite fan blades and nine thrust ratings ranging from 54,000lbs to 76,000lbs, with corresponding bypass ratios from 9.0:1 to 8.8:1, compared to 5.0-5.2:1 for the CF6-80C2, which powers the 767-300ER and 747-400.

The -1B's core engine architecture includes a four-stage LPC, a 10-stage HPC, a dual-stage HPT with unshrouded blades, and a seven-stage LPT.

The -1B has been selected for 830 787s, compared to the Trent 1000 which has been selected for 455 aircraft. There are another 142 aircraft for which the engine type has not yet been decided.

There are three main groups of -1B engines, and then several variants within each group. The nomenclature of the -1B family is a suffix of two digits, which indicate the number of thousands of pounds of the engine's thrust rating.

The -2B has a bleed air system, and has a smaller fan diameter of 104.7 inches and a thrust rating of 66,500lbs. The engine has a bypass ratio of 8.0:1, which again compares to 5.2:1 for the CF6-80C2B1 powering the 747-400.

The -2B's core has a three-stage LPC, 10-stage HPC, dual-stage HPT, and six-stage LPT. This makes the -2B about 15 inches shorter in length than the -1B. The -2B powers 153 747-8Is and -8Fs.

The -2B later incorporated a booster anti-ice system, denoted by a 'B' suffix in the engine variant's name. Most of the initial configuration engines were modified to B configuration before entering service. This was before the -2B's PIP configuration.

Configuration upgrades

There are two sets of configuration upgrades and modifications, for -1B and -2B engines.

There were two main performance improvement programmes (PIPs) for the GEnx-1B.

The first group of -1B engines are the base or original engines, known as Block 4 engines. There is only one variant in this group, the -1B70, which is rated at 69,800lbs. This powers 25 aircraft, which are exclusively operated by Japan Airlines (JAL). These were manufactured from 2011, when the 787 entered service. The -1B70 is the engine for three 787s that JAL has on order.

The Block 4 engines' fuel burn was 4-5% poorer than the original specification. The Block 4 standard featured an under-performing LPT that required a re-design.

A small number of modifications for Block 4 engines were incorporated to increase durability. They included an enhanced eTAPS combustor, and revised cooling flow of the first HPT stage. Only a small number of Block 4 engines was built, and then configuration was switched to the first major upgrade and modification package.

GENX-1B 787 FLEET SUMMARY

Engine series	Aircraft type	Build years	No. Active	No. Stored	No. Order	Total fleet
Base engine						
-1B 70	787-8	2011-2020	22		3	25
Sub-Total			**22**	**0**	**3**	**25**
PIP 1 Engines						
-1B 64 PIP 1	787-8	2013-2016	21		2	23
-1B 67 PIP 1	787-8	2011-2013	11	2		13
-1B 70 PIP 1	787-8	2012-2013	14			14
1B 70/75 PIP 1	787-8	2013-2014	9			9
Sub-Total			**55**	**2**	**2**	**59**
PIP 2 Engines						
-1B 64 PIP 2	787-8	2013-2019	36	1	4	41
-1B 70 PIP 2	787-8/-9	2012-2022	54	1	3	89
-1B 70/75 PIP 2	787-8/-9	2012-2018	38		1	39
-1B 74/75 PIP 2	787-8/-9	2013-2019	234	1	192	427
-1B 76 PIP 2	787-10	2018 ONWARDS	9		97	106
1B 76A PIP 2	787-9	2016-2018	9	1		10
Sub-Total			**410**	**7**	**329**	**746**
Overall Total			**487**	**9**	**334**	**830**

This included an increase in fan blade length, which effectively increases the fan diameter by half an inch. This has been achieved by changes to the blade root contours. Drag has been reduced by using optimised outlet guide vanes (OGVs), which guide the air into the LPC. The fan frame has been refined to increase airflow through the LPC.

The second main module to be upgraded is the LPC to increase airflow. There has also been an upgrade to the fourth stage of the HPC to increase airflow and improve its aerodynamics and optimise its blade clearances.

The fourth main feature is an upgrade to the HPT by improving durability. This is also included in the combustor.

The fifth item is the upgraded and revised seven-stage LPT.

There are several other upgrades to the core modules and the engine that include the use of the same combustor used in the -2B engine's PIP.

Overall, the -1B 74/75 PIP 1 is the most numerous, having been selected for 427 aircraft. The -1B 76 PIP 2 has been selected for 106 787-10s.

Genx-2B PIP

The GEnx-2B has had a single PIP. In February 2011 initial flight tests indicated that the -2B's fuel burn performance fell short of targets. This shortfall was up to 2-3%, and was similar to the initial -1B's fuel burn performance shortfall. The -2B's shortfall was clarified as being 2.7%.

The PIP for the -2B entered service in 2013 with the aim of bringing the engine within 1.1% of its original fuel burn target, thereby tackling most of the 2.7% shortfall. The PIP for the -2B restores the 747-8's original range of 8,000nm.

The PIP featured a major re-design of the -2B engine, including aerodynamic improvements to the LPT, which was actually an all-new design that came from the -1B's PIP 1. There were also aerodynamic improvements to the HPC, based on improvements that were included on the PIP 2 for the -1B engine.

Changes include: the use of 3D aerodynamics in the HPC airfoils, modifications to the fan and LPC modules, upgrades to the HPT which are improvements taken from the -1B's PIP 2, upgrades to the LPT, which use new materials and an all-new design, and improvements to the combustor.

The -2B engines that have all of these improvements are designated -2B XX/P; the XX denoting the thrust rating.

In addition to the PIP, GE launched a durability upgrade, which included improvements in the coating and cooling patterns in the fuel nozzles and combustor liner, and to the stage 1 HPT blades and nozzles. These are included to improve time on-wing.

GEnx-1B PIP 1

The second main group of engines are those which have the first PIP, PIP 1, incorporated into the -1B's hardware. Within this group there are four variants: the -1B64 PIP 1; -1B67 PIP 1; -1B70 PIP 1; and -1B70/75 PIP 1. These power just 59 aircraft, and were manufactured from 2011 to 2016.

The PIP 1 for the GEnx-1B was developed mainly because the 787 had 2-3% higher fuel burn than the original specification indicated by Boeing.

The main features of the PIP 1 programme were the use of three dimensional (3D) aerodynamic blades in the LPT, which also featured an upgraded design. This included additional blades, vanes and nozzles in each of the stages. These additional airfoils in each stage led to the use of lighter titanium aluminide material in the sixth and seventh stages to offset the increase in weight.

The PIP 1 also included improvements to the HPC and the HPT.

The aim of the PIP 1 for the -1B was to bring the 787-8/-9 To within 1.4-1.6% of fuel burn performance target. It is widely accepted that the programme has achieved more than this.

GEnx-1B PIP 2

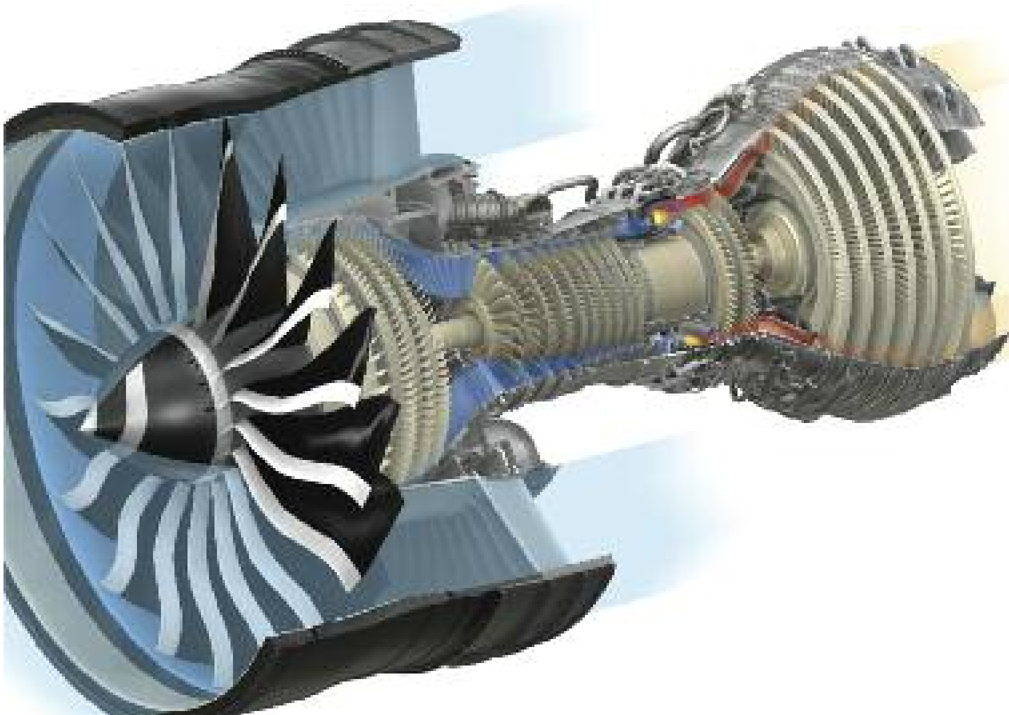
The second main upgrade programme for the GEnx-1B was the PIP 2. There were several reasons for this. First, the Block 4 and PIP 1 engines had thrust ratings up to 75,000lbs. The PIP 2 was first required to bring the -1B's fuel burn performance to within 1% of the specification required for the higher thrust of 78,000lbs. Second, the PIP 2 engine could be used as the standard engine for the 787-10.

Engines with the PIP 2 configuration are the third main group of production engines. There are seven variants in all: the -1B64 PIP 2; -1B67 PIP 2; -1B70 PIP 2; -1B70/75 PIP 2; -1B74/75 PIP 2; -1B76 PIP 2; and -1B76A PIP 2.

The -1B 76 PIP 2 engine powers the 787-10. All other -1B variants either power the 787-8 or -9.

The PIP 2 is overall a re-design of about one-third of the engine's hardware. The main features of the PIP 2 for the -1B are first an upgrade of the intake fan.

The GEnx-1B has taken about 55% of market share of 787 engine selections. The two PIP programmes have brought the engine's fuel burn performance within the original specification, and taken it up to the highest thrust rating of 78,000lbs.



Trent 1000

The RR Trent 1000 was one of two engine options for the three variants of the 787 family: the 787-8, -9 and -10. The Trent 1000 was the fifth member of Trent family to be developed, preceded by the 700, 800, 900 and 500.

The Trent 1000 has nine different take-off thrust ratings ranging from 58,200lbs to 76,400lbs. "A Trent 1000 variant's thrust rating and operating profile affects the lives of its LLPs," says Ben Davis, technical representative engines, at SGI Aviation. "These different thrust ratings and operating profiles are denoted for each variant by a letter suffix *(see table, page 44)* that denotes the life limit of a particular LLP part number."

The first four are the Trent 1000-H rated at 58,200lbs, the -AE (originally A) rated at 64,100bs, the -G rated at 67,300lbs, and the -CE (originally C) rated at 70,100lbs. These four variants all power the 787-8.

The -D is rated at 70,200lbs and used for specialised hot and high operating conditions on the 787-8 and -9 *(see table, page 44)*.

The -J is rated at 74,400lbs for the 787-9. The -K is also rated at 74,400lbs, and the -N is rated at 76,400lbs in hot and high conditions, and both are used for the 787-9 and -10.

The -M is rated at 76,400lbs in normal operating conditions, and is used for the 787-10 *(see table, page 44)*.

As with other modern engine types, the Trent 1000 was configured to achieve a high pressure ratio to improve fuel burn performance. The Trent 1000 has a 110-inch diameter fan, which uses swept-back fan blades. The fan section also has a relatively small diameter fan hub, and overall this helps to maximise airflow through the engine. Like all Trent family engines, the 1000 has a three-shaft design configuration that uses a high pressure (HP), intermediate pressure (IP) and low pressure (LP) spool. The use of contra-rotating IP and HP spools contributes to efficiency.

The Trent 1000 has a bypass ratio of more than 10:1, compared to a bypass ratio of 8.0:1 for the GEnx -1B. The Trent 1000's core engine configuration is based on an eight-stage intermediate pressure compressor (IPC), six-stage high HPC, single-stage HPT, single stage intermediate pressure turbine (IPT), and a six-stage LPT *(see table, page 44)*.

The Trent 1000 has four main configuration sub-variants, referred to as 'A package', 'B package', 'C package', and 'TEN package' engines. The letters denoting these modification packages bear no relevance to thrust ratings.

The latter three were developed with some upgrades, modifications and hardware improvements following some publicised performance shortfalls and technical and reliability problems.

Package A engines

The initial Trent 1000 A package engines were introduced on some of the first 787s in service in 2011, but had at least a 1% worse specific fuel consumption than the initial specification required by Boeing. The fuel burn shortfall may have been up to 4-5%.

"The A configuration engines were used for entry into service, but are now obsolete," says Davis. "They were followed by B configuration engines, but the hardware changes between the two were so big that A engines could not be converted to B engines. All Nippon Airways (ANA) started its 787 operation with A package engines, but swapped them to B engines."

Package B upgrades

The B package was a PIP issued to rectify this fuel burn shortfall. To date 71 787-8s and -9s have been equipped with B package engines, built from 2010 to 2014. This accounts for the smallest number of Trent 1000 engines.

The B package PIP was issued in 2012, and 166 engines now have this configuration. "This was mainly to rectify the fuel burn performance shortfall and reliability issues," says Davis.

The package included several revised engine configuration changes: a tweaked root-to-tip twist of the fan blade to match the changes in the pressure ratio caused by the reduction in the fan nozzle area, improved cooling flow for the IPT, enhanced aerodynamics in the six-stage LPT, and changes to the secondary air system to remove cooling air at the lower pressure stages of the LPT.

There were additional improvements to the package B modifications that were targeted at further cutting fuel burn by 2%. These included better air sealing, optimised HPT cooling flow and aerodynamics, and advanced case cooling for the HPT and LPT.

The B package engines, however, started to experience technical and reliability problems.

The first two main technical problems encountered were atmospheric corrosion on the IPT blades and oil leak findings. Corrosion-related fatigue cracking of IPT blades was discovered at ANA in early 2016 when an IPT blade separated.

This issue related to sulphidation of the IPT blades, which were corroded by pollutants in the atmosphere when

TRENT 1000 787 FLEET SUMMARY

Engine series	Aircraft type	Build years	No. Active	No. Stored	No. Order	Total fleet
Base engine						
-58 B	787-8	2009/10	1	3		4
-64 B	787-8	2012-2014	6			6
-67 B	787-8	2012-2014	54	6		60
-74 B	787-9	2014	1			1
Sub Total B Engines			**62**	**9**	**0**	**71**
-67C	787-8	2014-2017	14	5		19
-70C	787-8	2014-2017	19	1		20
-70/74C	787-8/-9	2016-2018	17	1		18
-74C	787-9	2013-2017	94	3		97
-74/76C	787-9	2014-2017	15	3		18
Sub-Total C engines			**159**	**13**	**0**	**172**
-67 TEN	787-8	2018-2022	5		13	18
-70 TEN	787-8	2017/2018	2			2
-70/74 TEN	787-9	2018	2			2
-74 TEN	787-9	2017-2020	47		76	123
-74/76 TEN	787-9	2018-2020	2		3	5
-76 TEN	787-10	2017-2021	8		54	62
Sub-Total TEN Engines			**66**	**0**	**146**	**212**
Overall Total			**287**	**22**	**146**	**455**

exposed to high core engine temperatures of about 2,300 degrees centigrade. These temperatures are experienced in the take-off and climb phases when the engine is operating at a higher thrust rating. Engines operating shorter and therefore a higher number of cycles will therefore encounter these problems earlier than engines operating longer missions. Atmospheric pollutants are also generally higher than a few decades ago, and higher at certain airports.

Corrosion-related fatigue cracking of IPT blades was discovered at ANA in early 2016. There have been eight IPT blade releases since October 2015, resulting in seven in-flight shutdowns. Six release events were recorded when engines had accumulated 1,295-1,984 engine flight cycles (EFC). Most of these were in long-haul operations with long average FC times. Two others were at 2,768EFC and 4,855EFC, and were medium- and short-haul operations. The cracks caused by the corrosion progressed over several hundred FCs.

All engines in the fleet showing excessive corrosion, detected via a borescope inspection, which would result in blade fracturing, were pulled from service and repaired in a shop visit.

The European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) ordered hat all engines showing more than a particular level of corrosion be removed from the aircraft and have blades replaced in a shop visit. Up to 500 engines, operated by a range of airlines, were affected by the IPT blade issue after ANA grounded half of its 787-9 fleet in 2016.

The possibility of IPT blade failure and separation in flight can clearly lead to an in-flight shutdown. This issue first resulted in more frequent borescope inspections to aid early detection of the problem. It was overcome by rolling out more corrosion-resistant blades with an improved platinum-chromium protective coating in January 2017 via a service bulletin (SB) for installation during an engine shop visit (SV). Installations started in March 2017, and the SB had been installed on more than 62% of the fleet by September 2018.

The second main technical issue that arose was a higher-than-expected rate of deterioration in the HPT blades. The original cooling holes were inadequate to prevent relatively quick blade oxidation and deterioration. The problem caused leading edge erosion, with the result of earlier than planned engine removals for SV maintenance. A new blade was issued in mid-2017 with an improved network of cooling holes to improve cooling and durability.

A related issue with the original HPT blade and its problems of premature deterioration, is the fracturing of the blade, which releases material into the gas path and leads to an in-flight shutdown.

Another problem with the HPT blade was creep, which is a lengthening of the blade due to the high temperatures it experiences and the centrifugal force.

The HPT blade problem followed shortly after the IPT blade fracture became apparent. Again, the solution was to develop a new blade, which became available in October 2018. Clearly an engine SV would be needed to carry this out. It also led to a requirement for more frequent borescope inspections to monitor the condition of HPT blades, and follow their rate of deterioration.

Package C upgrades

The C PIP was introduced and certified in the fourth quarter of 2013, and delivery of aircraft with engines in this configuration started in 2014. This first improved the engine's fuel burn performance by 1%, although the original plan was to improve the fuel burn by as much as 2%. To date, 172 787s and -9s have been equipped with C variant engines. These were mainly built from 2014 to 2017.

The C package included several revisions to the engine's configuration and hardware, such as advanced tip clearance control systems in the HPT, IPT and LPT which was achieved by semi-active case cooling, modified blades in the IPC, changes to the secondary air system, aerodynamic optimisation in the compressor and turbine case cooling technology, and an overall increase in air mass flow that results in a higher exhaust gas temperature (EGT) margin.

The C engines also included the new P/Ns for the IPT and HPT blades that replaced the original parts in the B package engines that resulted in the first reliability problems.

"While the hardware changes between the B and C engines were large, it was possible to rebuild B engines to C configuration," says Davis.

The Trent 1000 C package engines then suffered from a third reliability problem: excessive vibration of the IPC blades.

Under certain altitudes and air speeds, the rotation of blades in the first stages of the IPC could create a wake in the airflow that causes blades in latter stages to vibrate. This could cause the blades to separate, leading to an in-flight shutdown and compromising the aircraft's safety.

This again required the development of a new blade, which was made

The TEN package for the Trent 1000 was introduced to reduce fuel burn by 3% compared to the C package engines. The TEN package became the standard configuration for all Trent 1000 engines, and is used for all 787 variants.

available in January 2019. The blade is being installed in engines in early 2019. "The problem of original blades in the engine is being managed by repetitive borescope inspections and following engine health monitoring (EHM) data," says Davis. The first C engines have been fitted with the new IPC blade and have been returned to service.

A fourth technical issue has now emerged with the discovery of cracks in the IPC's seal. This has only affected a small number of Trent 1000 engines.

The four technical problems the Trent 1000 has suffered have occurred in relatively quick succession: in early 2016 for the IPT blade corrosion and 2018 for the IPC blade vibration problem. These issues affected more than 230 B and C configuration engines.

First, because of all the issues, the borescope inspection interval for C configuration engines was reduced from 200 flight cycles (FC) to just 80FC.

Second, all three problems can only be rectified by installing replacement blades in the IPT, HPT and IPC, which clearly requires engine removal, disassembly and an SV. This naturally led to a series of premature engine removals and SVs, which not only incurred an additional cost for engine-related maintenance but also caused a substantial disruption for Trent 1000-powered 787 operators. The IPC blade issue on C configuration engines alone affected about 170 aircraft, and 340 installed engines. A large number of engines requiring extensive shop maintenance in a concentrated period led to the grounding of aircraft for a period due to a lack of spare engines, a waiting period for new blades to be manufactured in sufficient quantities, and a limited number of appropriately equipped engine shops. Thai International grounded two-thirds of its 787-8 fleet because the replacement of ITP blades.

These technical problems were subsequently compounded by the fact that the Trent 1000 C's 330-minute extended-range twin-engine operational performance (ETOPs) certification was reduced to 140 minutes by the EASA and FAA in April 2018. This certification allowed aircraft with C configuration engines to operate on a single engine in the event of an in-flight engine shutdown, for up to 330 minutes over water, and to operate the same route as three- and four-engined aircraft on virtually all long-haul routes.

The revised 140-minute ETOPs certification meant that many airlines were unable to operate the long-haul routes for which they acquired the 787. Examples include Air New Zealand, which selected the 787 to operate on transpacific routes, Avianca, British Airways, Ethiopian Airlines, LOT Polish, Norwegian, Thai International and Virgin Atlantic. Some of these airlines had to acquire other aircraft as substitutes, and sought financial compensation from Rolls-Royce.

The 330-minute ETOPs status is reinstated when the new IPC blades have been fitted.

Package TEN upgrades

Rolls-Royce developed a third configuration improvement and upgrade package for the Trent 1000 referred to as Thrust Efficiency and New Technology (TEN). Its main objective was to achieve a further 3% reduction in fuel burn over C configuration or 'Package' engines. It was also configured for the 787-10, but is intermixable with all 787 variants. The TEN package was first run in 2014.

The TEN configuration engine was the standard production engine from 2017 onwards, with the last C configuration engines being built in 2018. The TEN engines are available for all nine thrust ratings.

The TEN package engines have been selected for 212 aircraft, most of which are on order. Of the 212 aircraft, 62 are the 787-10, 130 are the 787-9 series, and 20 are the 787-8 series.

The TEN configuration includes many design improvements, including all the fixes to the previous hardware and reliability issues. There is also a re-bladed eight-stage IPC, that allows a higher airflow rate; a new six-stage HPC, with the use of blisks for the first three stages; and the IPC and HPC that have been scaled down from the Trent XWB-84 engine, which was being developed for the A350 at the time. The XWB-style IPC included inter-case stiffness to achieve better blade tip clearance. The TEN's new compressor system has contributed most to improving fuel burn reduction.

The TEN configuration also features a new HPT with improved cooling. The HPT architecture is shared with the Trent XWB-97, and is expected to provide a better component life for the module.

The Trent 1000 also has a modulated HP air system, referred to as MAS, which is unique to the TEN.

There are also modifications to the LPT for improved drum life. Overall, the configuration changes are extensive and 70-75% of the parts are new compared with the earlier C configuration.

The TEN configuration has been an option for Trent 1000 customers, since it entered service in November 2017. The TEN package engine is subject to ETOPs restrictions as regulatory authorities seek to harmonise regulations on all Trent 1000 variants. AC