The steady evolution of CAEP standards with respect to NOx emissions has resulted in an improvement in engine combustor technology. All major engine manufacturers have developed lower-polluting combustors for their engines to comply with CAEP VI.

CAEP IV & VI NOx emissions standards

Aviation has long had a reputation for not being environmentally friendly but, in reality, aviation is responsible for just 2-3% of global carbon dioxide (CO_2) emissions, which is a fifth of that produced by road transport.

Air transport continues to grow, but it is also constantly finding ways to shrink its carbon footprint by reducing fuel consumption and by exploring the future use of alternative fuels. Having said that, the other big greenhouse gases that are a cause for concern for aviation are nitrous oxides (NOx). Although NOx is known to do some harm, its exact effect on the environment is still not completely known and, because the aircraft industry releases this gas at a much higher level in the atmosphere than other industries, this means that NOx could be doing more damage than CO_2.

For this reason the aviation industry, and particularly the International Civil Aviation Organisation (ICAO), has been looking at ways in which the industry can reduce the NOx emissions produced by aircraft engines.

NOx regulations

ICAO set up a committee to look at aircraft engine emissions, as well as aircraft noise. The Committee on Aviation Environmental Protection (CAEP) was established in 1983 and assists ICAO in deciding the policies and standards that its member states follow.

The CAEP group meets about once a year and puts forward new recommendations for ICAO to form into international standards. Emission standards were introduced in 1981, but it was soon realised that more needed to be done. CAEP's second meeting, in 1991, resulted in a regulation called CAEP/2. This regulation applied to engines certified after 1996, and limits the amount of NOx emitted by the engine during landing and take-off (LTO). This is measured in terms of grams per kN of thrust, relative to the overall engine pressure ratio. Originally, the regulations applied only to new engine certifications, and did not prevent those engines certified prior to 1996, which did not meet CAEP/2 standards, from flying.

In 1998 ICAO introduced CAEP/4, a second level of regulation that reduced the permitted NOx levels by 20% for newly certified engines, and also applied to any engine that was still in production. The CAEP IV limits were a variation of NOx limits, expressed in grams of NOx per kN of engine thrust in relation to engine pressure ratio. Engine pressure ratio is an indication of engine power or thrust rating, and NOx emissions levels are permitted to increase in proportion with engine pressure ratio *(see red line in chart, page 50)*.

The compliance date for CAEP/4 was 1st January 2000, so all engines manufactured from this date had to meet the new reduced NOx levels. Any engine type that could not comply could therefore no longer be manufactured.

This meant that many of the engines that had escaped the strict CAEP/2 regulations now had to cease production, even if they were certified before 1996. Many manufacturers used this point in time to develop modifications to reduce NOx emissions for their engines, in order to allow an older engine type to continue being manufactured.

Further regulations called for a reduction in NOx emissions by another 16% for engines certified after 2004. A meeting in 2004 produced regulations known as CAEP/6. These tighter regulations apply to all engines manufactured after December 2007.

Again, NOx emissions are permitted to increase in proportion with engine thrust *(see blue line in chart, page 50)*.

The limits to be set in CAEP/8 are already being considered, and could involve the emissions produced during climb and cruise in addition to the amount produced during LTO or below an altitude of 3,000 feet. This is likely to come into effect at some point after 2010, when the relevant meeting will be held.

ICAO, through CAEP, has collected data on the exhaust emissions of all engines in recent years, particularly those currently in production. The ICAO Aircraft Engine Emissions Databank lists the NOx, CO_2 and noise emissions for engine models, as well as their margins from various regulations, such as CAEP/2/, CAEP/ 4 and CAEP/6.

Causes of NOx

NOx is produced when a flame is burned at high temperatures, in the combustion chamber of an engine. The longer the flame burns at these high temperatures, the higher the amount NOx produced. The length of burn time at high temperatures is referred to as resistance, with high resistance producing higher levels of NOx. The advantage of high resistance in engine designs is that it reduces undesirable emissions such as carbon monoxide (CO), CO_2 and unburned hydrocarbons (UHC).

The opposite, short resistance, increases CO and UHC, but reduces NOx. Engine manufacturers are therefore forced to make compromises. The high engine thrust required for take-off, climb and landing, means raised temperatures in an engine's combustor and therefore higher NOx emissions. The cruise phase of flight can be the opposite, with low NOx emissions.

In an ideal world, all these emissions would simultaneously be reduced to a minimal level. One solution is the use of alternative fuels, while another is the redesign of many engines, in particular the combustion section, to gain the best of both worlds.

The difficulty faced by engine

Rolls-Royce developed its Phase 5 combustor for the Trent family of engines, and subsequently utilised the technology on the RB211-535E4 & R211-524G/H so they could comply with CAEP VI standards.

manufacturers is that they are pressured by airlines to improve the fuel burn performance of engines, as well as to increase their engines' thrust ratings. These both lead to manufacturers increasing engine bypass ratios, which necessitates higher engine-pressure ratios, which in turn lead to higher temperatures in the combustion chamber. CO2 is reduced by higher bypass ratios and reduced fuel consumption, while NOx emissions are raised by higher combustion temperatures and higher bypass ratios. Generally, the larger the engine, the higher the NOx emissions.

NOx reduction

The basic concept for reducing NOx emissions is for an engine to have shorter flame burn times at high pressure. As an engine's pressure ratio varies according to the phase of flight it is in, some engine manufacturers are therefore taking advantage of this in their newer designs.

Take-off and landing need the engine pressure and flame temperature to be high because of a high thrust requirement, whereas other phases do not require the same levels. The research and development into lower NOx emissions has therefore been focusing on flame burn times.

A long combustion chamber produces a flame with high resistance, low CO and high NOx. Conversely, a short combustion chamber produces low resistance and lower NOx, but a less efficient burning of fuel.

Many designs have therefore involved an engine that combined long and short combustion chambers. These were called staged or double or dual annular combustors (DAC). These engines vary the fuel burned in each combustion chamber, dependent on the phase of flight that the aircraft is in at the time. The DAC could be turned on either at the start or during the cruise phase of flight, depending on the design and technology involved. The disadvantages of the DAC, according to Bill Brown, marketing director for the GEnx engine at General Electric (GE), was that it could "cause temperature spikes as well as maintenance drawbacks". This was due to the more intricate nature of the combustion chamber and the fluctuation of temperatures involved. But Brown continues that, despite the drawbacks, "the emission levels were good and the DAC evolved into TAPS technology, that GE first used on the GE90".

TAPS is an acronym for twin annular pre-mixing swirl, and involves the mixing of air and fuel in the combustor before the fuel is lit. This means that the mix of fuel and air can be varied according to the phase of flight. TAPS is about ensuring that the fuel mix is at its optimum, with it burning a leaner mix of fuel and air than traditional older engines.

CFMI

GE is not the only engine manufacturer to have invested in developing versions of the DAC technology. The DAC has been used on the CFM56-5B and -7B and uses the idea, as mentioned above, of a long chamber and a short chamber. The shorter chamber is used for low power and burns for a shorter time at high temperature. This produces lower NOx emissions and is used during all phases of flight.

The older, and no-longer manufactured, CFM56-2, CFM56-3 and CFM56-5A engines all have good CAEP/4 margins.

The CFM56-5B, -5C and -7B are still being manufactured, and have to be CAEP/6 compliant. The higher thrust-rated variants of the earlier-built -5B engines are not CAEP/6 compliant. These are the -5B1, -5B2, -5B3 and -5B4.

CFMI later introduced an improved performance modification, denoted by a /P suffix on the engine's name, and the majority of original engines were upgraded to /P standard. The -5B1/P, -5B2/P and -5B3/P variants still do not comply with CAEP/6.

CFMI then introduced DAC versions of the -5B series, and these are denoted by a /2 suffix. All /2 engines with DAC technology are CAEP/6 compliant. Margins are actually 25-42%.

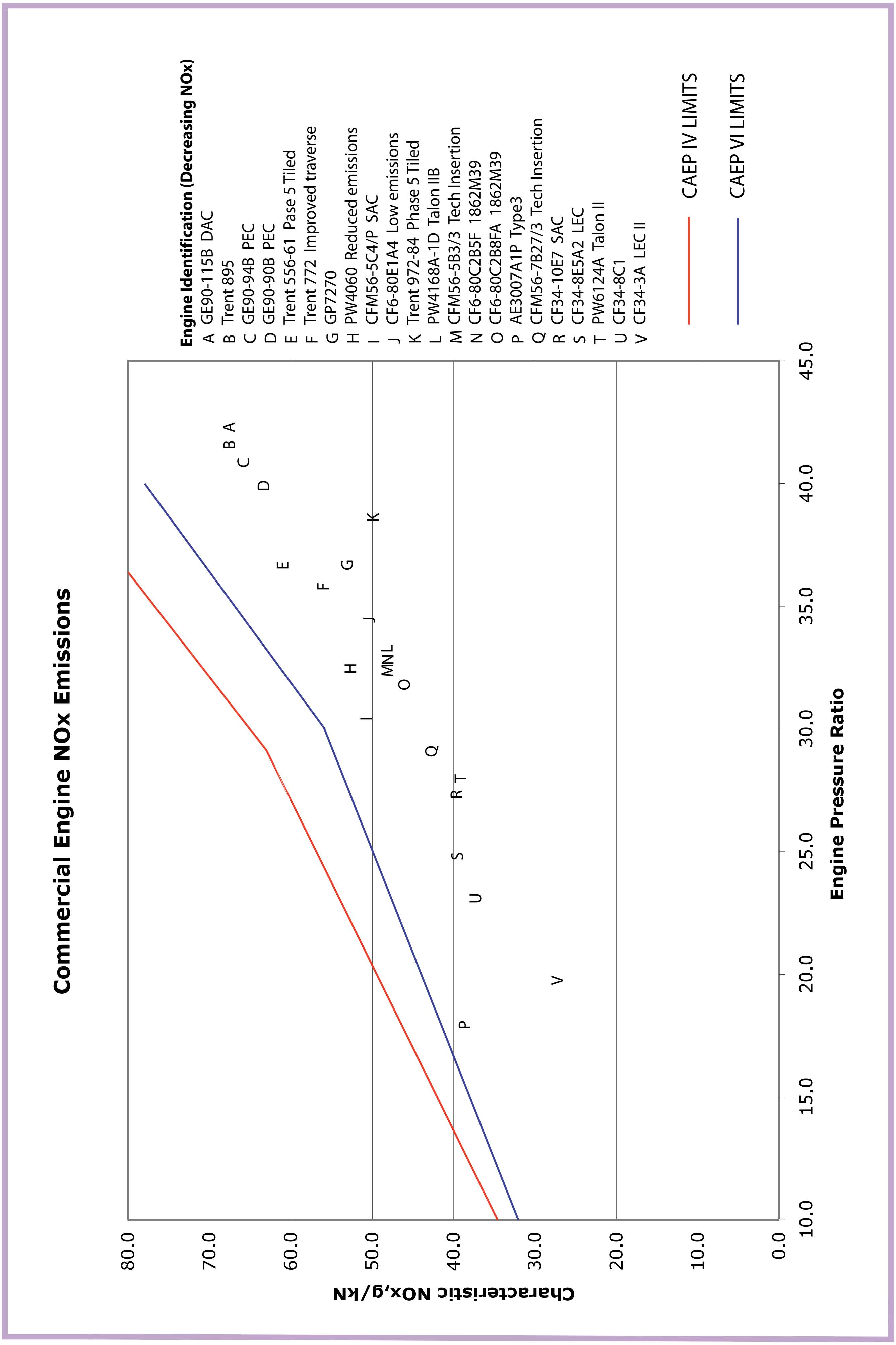
With the DAC II technology, the margins are further increased, with some examples being up to 45% within CAEP/6 requirements.

CFMI introduced another modification to further reduce NOx emissions. This is the Tech Insertion programme, and was introduced as standard build from late 2007 to make all -5B series engines CAEP/6 compliant. The highest-rated variant is the -5B3/3,and has a CAEP/6 compliance margin of 20.2% *(see table, page 51)*. All lower-rated variants have higher margins.

The original CFM56-5C engines are CAEP/4 compliant, but not CAEP/6 compliant. A performance improvement programme was introduced, and one effect was to reduce NOx emissions. The /P versions of the -5C series have CAEP/6 compliance margins of 1.6-6.8%.

The latest CFM56 model is the -7B series. There are six thrust ratings in this series, and the four highest-rated engines of the original series are not CAEP/6 compliant. CFMI first improved the -7B with a DAC combustor, the effect of which is to reduce NOx emissions and make all variants CAEP/6 compliant. All engines have a /2 suffix. The model was not popular, however, and only one aircraft is listed with these engines.

CFMI then introduced the Tech56 modification as a standard-build specification. The improvements include a single-annular combustor, and all engines have a /3 suffix. All are CAEP/6 compliant, and have margins of 20-30%. The highest-rated variant is the -7B27/3, and has a compliance margin of 20.8%


Commercial Engine NOx Emissions
Characteristic NOx,g/kN
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Engine Pressure Ratio
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
Engine Identification (Decreasing NOx)
A GE90-115B DAC
B Trent 895
C GE90-94B PEC
D GE90-90B PEC
E Trent 556-61 Pase 5 Tiled
F Trent 772 Improved traverse
G GP7270
H PW4060 Reduced emissions
I CFM56-5C4/P SAC
J CF6-80E1A4 Low emissions
K Trent 972-84 Phase 5 Tiled
L PW4168A-1D Talon IIB
M CFM56-5B3/3 Tech Insertion
N CF6-80C2B5F 1862M39
O CF6-80C2B8FA 1862M39
P AE3007A1P Type3
Q CFM56-7B27/3 Tech Insertion
R CF34-10E7 SAC
S CF34-8E5A2 LEC
T PW6124A Talon II
U CF34-8C1
V CF34-3A LEC II
CAEP IV LIMITS
CAEP VI LIMITS

(see table, this page).

CFMI anticipated further reductions in allowed NOx emissions, and began working on new technology in 1999. Ron Klapproth, LEAP 56 Program Director at CFMI, comments that, "with anticipated CAEP/8 standards and potential changes in the regulated flight phases, the effects of TAPS are truly unprecedented, with NOx emissions being 50-60% below today's NOx regulations".

CFMI has been able to take advantage of the GE research on the subject for the GE90, meaning that CFMI has now developed a second-generation TAPS for the LEAP 56 programme.

The LEAP-X is a further development, and further reduces NOx emissions. With an advanced turbofan and rotor fan, this engine is about more than just the combustor. The engine promises a 16% improvement on fuel burn over CFM56 Tech Insertion engines. With the use of TAPS, it also promises major NOx reductions. This engine aims for a first run in 2012 and will be certified in 2016, with margins well within potential CAEP/8 regulations.

General Electric

Of the three GE in-production engines listed on the emissions databank, the oldest is the CF6.

The original -6 series is not CAEP/4 compliant. The later -45 and -50 series powering the DC-10-30 and 747-200 are CAEP/4 compliant. These were last built in the 1980s.

The -80A series was introduced in the early 1980s, and is also CAEP/4 compliant. The versions of the -80C2 series powering the A300-600, A310 and MD-11 are also CAEP/4 and CAEP/6 compliant, but these are no longer being manufactured.

The other -80C2 variants powering the 767 and 747-400 are also compliant with CAEP/4 and CAEP/6. There are still a few orders for CF8-80C2-powered 767s and 747-400s outstanding, and their manufacture date means that these engines naturally have to be CAEP/6 compliant. The highest-rated -80C2B5F and -80C2B8FA, powering the 747-400 and 767-300ER have compliance margins of 18% *(see table, this page).*

All variants of the CF6-80E1 series powering the A330-200/-300 are CAEP/6 compliant. The highest-rated -80E1 variant has a compliance margin of 21.3% *(see table, this page).*

The GE90, as mentioned previously, was developed with new combustor technology in mind. This means that virtually all variants of the GE90 comply with CAEP/4 and CAEP/6 regulations.

The GE90 started off with the same DAC technology that was used on the CFM56. Then it was decided that the GE90 would burn a much richer mixture of fuel and air, so the DAC II combustor was developed, to ensure that NOx emissions did not rise with the richer mix. This resulted in larger CAEP/6 margins, although engines with the DAC I combustor were already compliant. Moreover, the highest rated -94B with the DAC II combustor is not CAEP/6 compliant.

GE then later introduced the performance enhanced combustor (PEC). This is used on the most recently built variants of the 123-inch fan engines, and lowers NOx compared to engines with earlier combustors. The GE90-94B, for example, has a CAEP/6 compliance margin of 4.7%. The GE90-115B, which uses the DAC combustor, has a CAEP/6 compliance margin of 5.7%.

Another GE in-production engine is the CF34, whose results demonstrate that it has taken advantage of all the previous research. Also, because it is a much smaller engine, used on smaller aircraft compared to the GE90, this means that the CF34's NOx emissions are naturally lower. CAEP/6 regulations mean, however, that engines with lower pressure ratios also have lower CAEP/6 limits *(see chart, page 50).*

All CF34 series are well within CAEP/6 regulations, with margins of about 45% for the -3 series, 25-30% for the -8 series, and 20-25% for the -10 series *(see table, this page).* This means that it is likely that the CF34 series will have no problem meeting potential CAEP/8 standards.

The latest engine to come out of the GE fold is the GEnx. According to Brown, the advanced TAPS technology in the GEnx uses an optimum mix of fuel and air depending on the stage of flight. This in itself would reduce NOx levels. Brown explains that a pilot source is used in a conventional combustor system with a rich mixture to start with to stop flame-out. A lean mixture, with more air, is then used, without passing through high temperatures. This then produces lower NOx emissions. "NOx emissions for the GEnx will be 60% below CAEP/6 regulations," comments Brown. This should ensure that this engine also exceeds CAEP/8 regulations. The engine will also include electronic engine controls, to ensure that the TAPS and fuel mix is managed efficiently.

IAE

The sole International Aero Engines example is the V2500. The engine is a joint venture between PW, RR, MTU Aero Engines and Japanese Aero Engines Corporation. This has meant that different companies have been

CURRENT-PRODUCTION ENGINES NOX EMISSIONS & CAEP/6 COMPLIANCE MARGINS

Engine type	Combustor type	NOx g/kN	Pressure ratio	CAEP/6 margin
AE3007A1/P	Type 3	38.4	17.9	5.6%
CF34-3A	LEC II	27.7	19.7	45.5%
CF34-8C1		37.6	23.0	27.5%
CF34-8E5A2	LEC	39.7	24.8	22.6%
CF34-10E7	SAC	39.9	27.3	18.7%
CFM56-5B3/3	Tech Insertion	48.3	32.6	20.2%
CFM56-5C4/P	SAC	51.0	30.5	1.6%
CFM56-7B27/3	Tech Insertion	43.1	29.0	20.8%
PW6124A	Talon II	39.4	28.0	18.6%
Trent 556-61	Phase 5 Tiled	61.3	36.6	10.1%
Trent 772	Improved traverse	56.2	35.8	7.5%
Trent 895		67.9	41.5	4.1%
Trent 972-84	Phase 5 Tiled	50.1	38.6	23.8%
CF6-80C2B5F	1862M39	48.2	32.8	18.0%
CF6-80C2B8FA	1862M39	46.4	31.7	18.1%
CF6-80E1A4	Low emissions	50.5	34.5	21.3%
GE90-90B	PEC	63.5	39.9	6.4%
GE90-94B	PEC	66.2	40.8	4.7%
GE90-115B	DAC	67.9	42.2	5.7%
PW4060	Reduced emissions	52.8	32.4	4.2%
PW4168A-1D	Talon IIB	48.6	33.1	13.7%
G7270		53.3	36.6	24.0%

The original combustor technology used in the CFM56-7B engines meant that the higher-rated variants were not compliant with CAEP VI. The Tech56 modification has made all -7B variants compliant, and Tech56 is consequently standard specification on the CFM56-7B.

responsible for different areas of the engine, with PW incorporating its PW4000 'floatwall' combustor.

The original engine complies with the CAEP/4 standards, but all variants just fail to comply with CAEP/6 limits by 2-3%. It was therefore necessary for the V2500 to be adapted and developed in order for it to comply with CAEP/6 standards, as well as potential CAEP/8 regulations. A staged combustor would be detrimental to the engine's performance, so IAE has instead looked at talon technology.

In the meantime, the V2500 SelectOne upgrade programme improves time on-wing by up to 20% and makes all variants compliant with CAEP/6 NOx standards. It entered service in 2008.

Pratt & Whitney

There are a number of PW engines in the databank, the oldest of which is the JT3D. The JT3D, JT8D and JT9D are not CAEP/4 compliant, although this is not an issue, since they have not been manufactured for several years.

The PW2000's emissions have a large compliance margin with CAEP/4 standards, but only the PW2037 is within those set down by CAEP/6. Again, this is not a problem because the engine is no longer produced.

The PW4000 also has mixed results. The PW4000 should be considered in three sub-families. The first is the 94-inch-diameter fan series, which powers 1980s-generation widebodies. The PW4152/56 engines powering the A300-600 and A310 have wide CAEP/4 compliance margins. The same is true for the PW4056/60 models powering the 767 and 747-400. The PW4460/62 powering the MD-11 are also CAEP/4 compliant.

There are a small number of outstanding orders for the 767-300ER with PW4000-94 engines. This means that they have to be CAEP/6 compliant. The PW4056/60, with reduced emissions standards, are compliant with CAEP/6, but by just 3.8-4.2%. The PW4060 has a compliance margin of 4.2% *(see table, page 51)*.

The second series is the PW4164/68, with a 112-inch-diameter fan, which power the A330. The earlier-specification models with the floatwall combustor are compliant with neither CAEP/4 or CAEP/6 standards.

The best results are seen from the models that have Talon II and IIB technology. Both of these have made the PW4164/68 CAEP/4 and CAEP6 compliant. The highest-rated PW4168A-1D has a CAEP/6 margin of 13.7% *(see table, page 51)*.

The third series is the 112-inch-diameter fan engine that powers several 777 variants. Only a few of these are just CAEP/6 compliant.

Talon II technology is also used on both PW6000 models, to an even better effect. These engines, powering the A318, have CAEP/6 margins of 18-28%.

Pratt and Whitney has now developed the PW1000G, a geared turbofan. Through a lighter and shorter engine, with fewer stages, the new engine design promises to produce 55% less NOx than other similar engines. This has meant that the PW1000G has many of the advantages of the smaller engines, environmentally, but with the thrust ratings of medium-sized engines, such as the CFM56 family.

Rolls-Royce

Most earlier variants of the RR RB211 series powering the L-1011 and 747-200/-300 fail to comply with CAEP/4 regulations, although this was not necessary since their manufacture ceased after 1999.

The smaller -535 engines powering the 757 were also not compliant with CAEP/4 regulations. The continued production of the 757 meant that an engine modification was required, and the Phase 5 combustor technology gave the RB211-535E4 a compliance margin of 15-20%.

The Phase 5 combustor is just a single annular combustor that reduces NOx by optimising the fuel-air mixture in the different zones of the combustor. This was technology developed for the Trent family of engines.

The original RB211-524G/H models powering the 747-400 and 767-300ER also failed to comply with CAEP/4 and CAEP/6 regulations. The production of the 747-400 after 1999 meant that compliance was required, and Rolls-Royce introduced combustor and high-pressure shaft technology from the Trent 700 into the -524G/H. This resulted in the -524G-T and -524H-T, which are both CAEP/4 and CAEP/6 compliant. The compliance margin with CAEP/6 regulations is 8-9%.

The Trent series of engines, being a much younger design and having the Phase 5 combustor, have compliance margins well within CAEP/6 standards. The Trent 900 performs particularly well, with at least a 20% margin to CAEP/6. This is due to the use of Phase 5 Tiled technology, which also enables the older Trent 500 to perform well within the CAEP/6 regulations. Margins for the four highest-rated variants of each Trent type are 7.5-23.8% *(see table, page 51)*.

Engine Alliance

The GP7270, the second engine powering the A380, has a CAEP/6 margin of 24.% *(see table, page 51)*. The GP7270, despite its power rating, has a generous margin. This illustrates that NOx emissions regulations have produced environmental benefits. AC