The huge number of aircraft now in use around the world has led to concerns about the possible effects on the environment. Nitrous oxide emissions may contribute indirectly to the so-called Greenhouse Effect. The International Civil Aviation Organisation has set emission limits. How will engine manufacturers meet them?

Knocking NOx on the head

As the number of aircraft in the skies increases, the environmental issues that concern them are becoming more important. One of the issues concerns nitrous oxide (NOx) emissions.

Aircraft account for about 3% of all the world's gaseous emissions, compared to about 60% for cars and road vehicles. Eighty percent of all gaseous pollutants are NOx, though the effect of NOx emissions on the environment is not clear-cut. NOx destroys the ozone layer in the stratosphere but produces ozone in the troposphere. The latter could be detrimental, since any ozone in the troposphere may indirectly contribute to the greenhouse effect. To be safe, it is best to reduce NOx production.

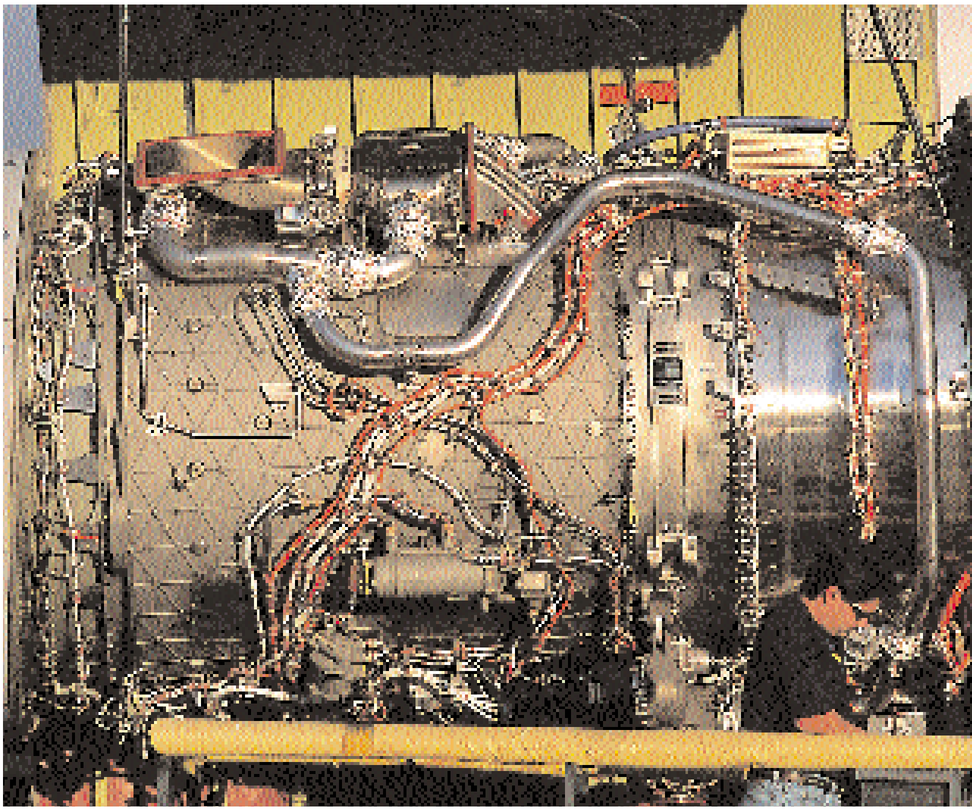
The reduction of NOx is not straightforward. This is because NOx production is a result of flame temperature. The longer the flame burns in the combustor at higher temperatures the higher the NOx production. Length of burn time at high temperatures is referred to as residence.

There is a trade in production of NOx with formation of carbon dioxide (CO_2), carbon monoxide (CO) and un-burnt hydrocarbons (UHC). That is, high residence may increase NOx, but it reduces CO, CO_2 and UHC. Short residence increases CO and UHC. These other pollutants also contribute to global warming and have to be reduced.

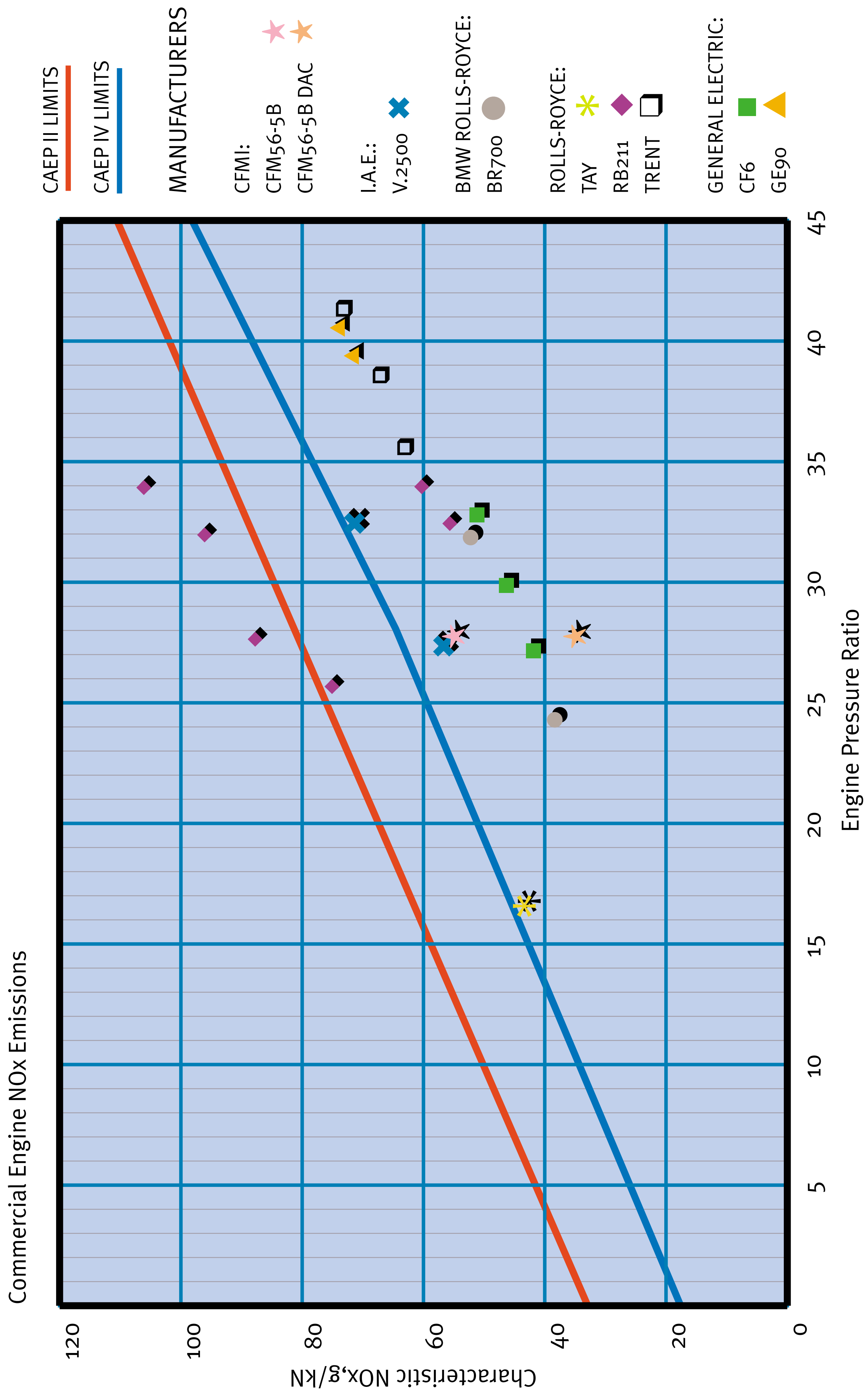
High engine thrust during take-off, climb and landing phases of flight requires high thrust and engine pressure ratio, which raises combustor temperatures. Other phases of flight with low engine thrust settings have lower temperatures and NOx emissions, but have higher CO_2 and CO emissions because of less efficient combustion. This trade between carbon and nitrous emissions means compromises have to be made when developing new combustor technology.

Another difficulty is that engine manufacturers are constantly trying to increase engine bypass ratio to improve fuel burn performance. Fuel burn reduction reduces CO emissions and thus high bypass ratios are desirable from this point. A high bypass ratio, however, also means a higher engine pressure ratio is required. This translates into higher pressure in the combustion chamber and so higher temperatures, which increases NOx. Engine pressure ratio also rises with engine thrust rating.

The consequences of this are that as engine thrust ratings increase so do NOx emissions. The largest turbofans have the highest NOx emissions. This is not only because they have the highest thrust ratings, but also because they tend to have higher bypass ratios than smaller powerplants. The large engines do, however, have lower CO emissions than the smaller powerplants.

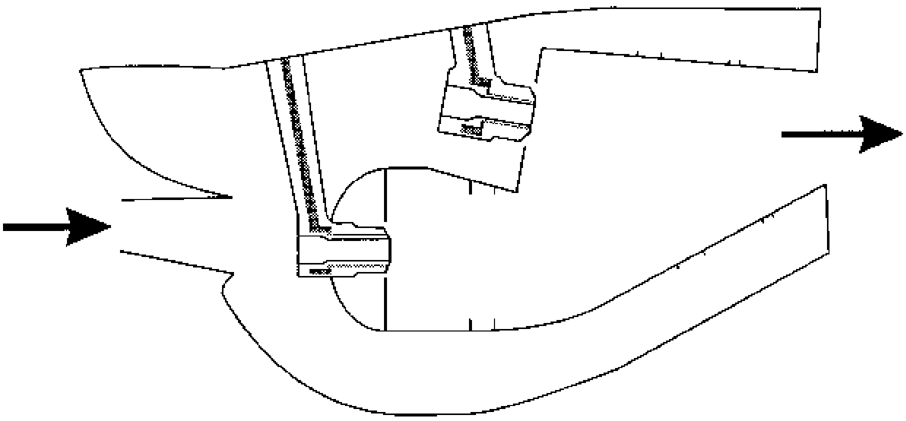


The BR700 series is able to meet CAEP IV limits with a single-stage combustor, but there is a dual-stage combustor available for the engine.



Commercial Engine NOx Emissions
CAEP II LIMITS
CAEP IV LIMITS
MANUFACTURERS
CFMI:
CFM56-5B
CFM56-5B DAC
I.A.E.:
V.2500
BMW ROLLS-ROYCE:
BR700
ROLLS-ROYCE:
TAY
RB211
TRENT
GENERAL ELECTRIC:
CF6
GE90
Characteristic NOx,g/kN
120
100
80
60
40
20
0
5
10
15
20
25
30
35
40
45
Engine Pressure Ratio

Axially staged combustion chamber



ICAO standards

The International Civil Aviation Organisation (ICAO) has set NOx and CO emission limits and also standards for newly certified engines. ICAO has agreed with engine manufacturers to allow a trade between CO and NOx emissions.

ICAO has two NOx limits that engine manufacturers have to comply with. The first, CAEP II, applies to engines certified after 1996. The CAEP II limits refer to the amount of NOx emitted, in terms of grams per kN of thrust, relative to overall engine pressure ratio *(see chart, page 40)*.

ICAO's limits allow engines certified before 1996, which have higher NOx emissions, to continue to operate indefinitely. CAEP II limits therefore do not prevent older technology engines from continuing to operate.

Moreover, CAEP II limits also allow engines certified before 1996 to be manufactured indefinitely. The Rolls-Royce RB211-535E4 and -535E4B, RB211-524G and -524H all have emissions above CAEP II standards. Their continued manufacture is permitted under CAEP II.

ICAO then introduced CAEP IV limits *(see chart, page 40)* which apply to engines manufactured from January 1, 2000. That is, although an engine may have been certified after CAEP II limits were introduced, it will still have to comply with the more stringent limits if manufactured after 1999. The Rolls-Royce engines mentioned above, therefore, cannot be continued to be manufactured with their current emission standards. Production can only continue after 1999 if the engines are modified so that their NOx emissions meet CAEP IV standards.

Most turbofans currently in production are able to meet CAEP IV limits. This has been achieved by developing new combustion chambers in some cases.

NOx reduction

The basis of NOx reduction is to reduce flame burn time at high temperature by cooling. Several engine manufacturers have taken advantage of the varying pressure ratios during different phases of flight.

The take-off and landing phases require high engine pressure and result in high flame temperatures in the combustor. In other flight phases engine thrust is lower. Combustor chambers are therefore also cooler.

Combustor design influences burning efficiency and NOx emissions. A long combustor produces a flame with high residence. CO levels are low but NOx is high. A short combustor has low residence and reduces NOx, but provides less efficient burning.

Several manufacturers have taken the route of developing combustors that provide both long and short combustion chambers. This is commonly known as a staged or double annular combustor (DAC). This system requires a control mechanism to control the correct amount of fuel burnt in each chamber during each phase of flight.

Each engine manufacturer has used technology in accordance with how close its engines with conventional combustion chambers are to meeting CAEP IV limits. Some have used staged combustor technology. Others have managed to avoid using it so far, since their engines have lower NOx emissions relative to CAEP IV limits.

BMW Rolls-Royce

The BR700 series has some of the the lowest thrust ratings compared to most other turbofans.

The BR710 is rated between 14,000lbs and 17,000lbs thrust and was certified in August 1996. It entered service in July 1997.

The BR715 is rated between 17,000lbs and 23,000lbs thrust, was certified in August 1998 and entered service in 1999.

Both BR700 engines therefore have to comply with CAEP IV limits, since their production will continue after 1999.

"The customer likes to see a margin between the set standards and actual emissions because they are concerned that ICAO may introduce further reductions at a later date," explains Norbert Brehm, head of combustion at BMW Rolls-Royce.

BMW Rolls-Royce has a conventional single annular combustor for both engines, but has also developed a stage combustor (SC), basically a DAC, for the family.

The BR710's and BR715's NOx emissions are well below CAEP IV limits, but the SC reduces these even further. "The NOx emission levels of our current engines have a very good margin compared to CAEP IV," says Brehm. "There are other considerations, however. These include user charges, in countries such as Switzerland and in Scandinavia, where they are charged according to NOx emission levels. Our SC has recently been tested on the technology demonstrator core engine.

"Combustors have to be able to operate between altitude re-light and take-off pressure. This makes the design of SC combustors difficult. The SC works by using two different combustors for low-pressure and high-pressure phases of flight. This is illustrated by the schematic *(see diagram, this page)*.

The first chamber the airflow reaches is known as the pilot chamber. The second is known as the main chamber. The pilot chamber is used for both low- and high-power phases of flight, while the main chamber is used for just the high power phases.

The quantity of airflow into both is fixed. The amount of fuel injected into both is varied. All fuel is injected into the pilot chamber during low thrust settings. Fuel in the pilot chamber burns at a high temperature for longer and so has relatively high NOx emissions. The main chamber burns at a high temperature for a short time and produces less NOx.

The distribution and amount of air

The Rolls-Royce RB211 family does not meet CAEP IV NOx standards with its original combustor. Rolls-Royce has developed a single-stage combustor for the Trent family which meets all environmental standards. This can be retrofitted to the RB211 family.

entering each chamber determines the rate at which the flame is cooled and the amount of NOx formed. The rate of cooling is also determined by the point at which the air enters the chamber.

Cooling air enters the main chamber close to the point of combustion and so allows a relatively short residence time at high temperature. NOx is reduced and CO production increased. Fuel is burnt only during high-power phases of flight, which are the most critical with respect to NOx emissions.

Cooling air enters the pilot chamber further downstream and NOx production is relatively high. However, this is only during the less critical and lower engine power phases of flight with respect to NOx production.

"The SC can be retrofitted to existing BR710 and BR715 engines," says Brehm. "Further reductions are being investigated by using lean combustion techniques. These work on a pre-mixed fuel and air mixture to achieve more efficient burning so that the flame can be cooled quickly without increasing CO and UHC."

CFMI

CFMI is another manufacturer that has developed a staged combustor for its engines. The DAC is an option for the CFM56-5B and -7B.

CFMI's DAC works on the same principles as BMW Rolls-Royce's SC. CFMI's DAC has long and short chambers. The long chamber allows longer time at high temperature and more complete burning, but increases NOx. Fuel is only burnt in this chamber during high-power phases of flight. The shorter chamber is used for low power. It burns for a shorter time at high temperature and has lower NOx production. It is used during all phases of flight.

The CFM56-5A, -5B, -5C and -7B are all compliant with CAEP IV with a single annular combustor. The DAC, however, reduces NOx emissions and gives these engines a larger margin *(see chart, page 40)*. For example, the CFM56-5B1 has an emissions level of 54.0 grams per kN of thrust with a single annular combustor. The emissions level is reduced to 35.0 grams with a DAC fitted.

It is technically feasible to retrofit existing engines with the DAC, and is offered for airlines that are sensitive to high NOx-related user charges.

Rolls-Royce

The Rolls-Royce's Trent family of engines are compliant with CAEP IV limits. The older RB211 engines currently under manufacture, some of which were certified before 1986, are not compliant with CAEP II requirements.

With all engines manufactured from January 1, 2000 needing to be CAEP IV compliant, Rolls-Royce's older engines built after this date will have to be retrofitted with the Trent's combustor technology.

The application of such technology on the RB211 has already been demonstrated by the RB211-524H-T. This engine has adopted the combustor- and high-pressure shaft technology of the Trent 700. The RB211-524G-T and -524H-T have ample margins compared to CAEP IV.

The added bonus of retrofitting this technology into the RB211-524 is a 2% reduction in specific fuel consumption.

All members of the Trent family have a similar margin against CAEP IV standards as the 524G/H-T.

Rolls-Royce has two types of combustor, known as Phase 2 and Phase 5. Phase 2 is the technology used in the RB211s and Phase 5 is used in the Trent engines and BR700 series.

Rolls-Royce has not needed to apply DAC technology to reduce NOx emissions. The Phase 5 combustor is an optimised single annular combustor which reduces NOx by basically optimising the fuel-air mixture in the different zones of the combustor.

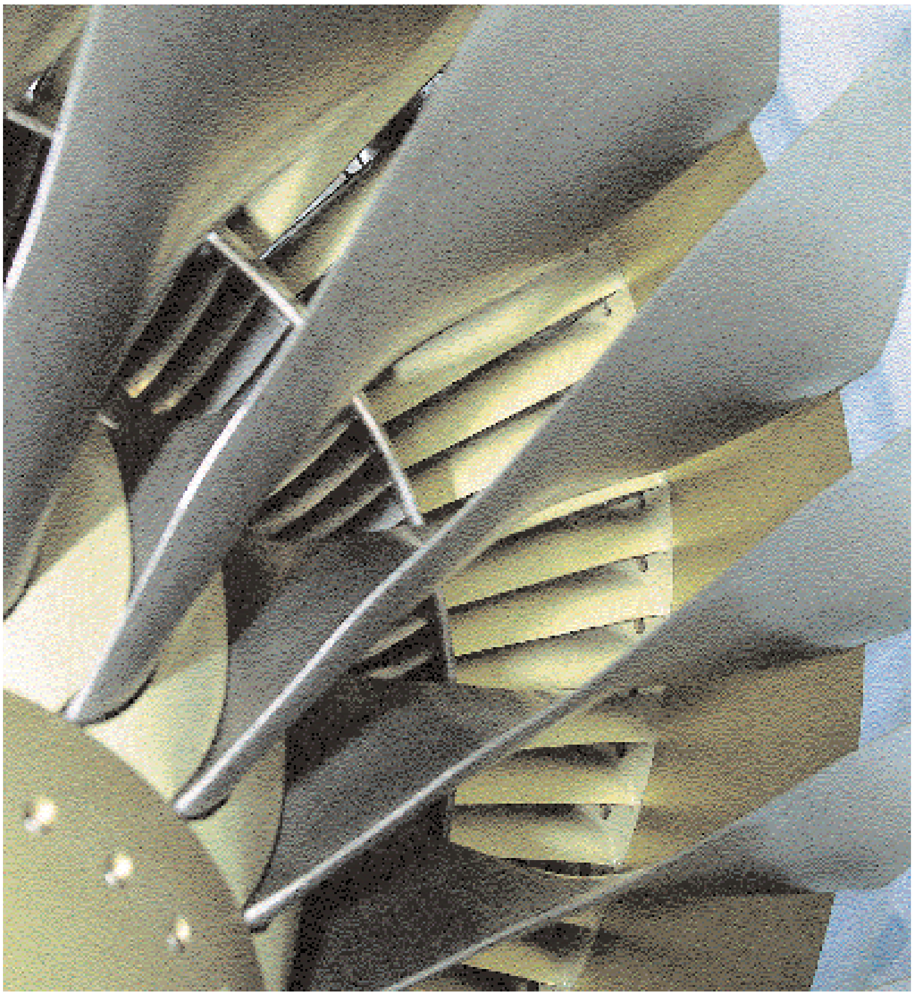
"This achieves different flame temperatures in different zones of the combustor," explains Dr Hamish Low, chief of combustion engineering at Rolls-Royce. "Combustor design is a compromise. The ability to relight the combustor at altitude and control low power emissions is enhanced by relatively long residence times of the fuel-air mixture in the combustor. This conflicts with the limitation of NOx emissions at high power conditions. This compromise will ultimately limit how far the design of a single annular combustor can be taken."

The short residence region of the combustor has lean a fuel-air mixture optimised for high power settings. It produces low levels of NOx emissions at high power.

The long residence region of the combustor has a rich fuel-air mixture appropriate for relight at altitude and low power settings. It produces low amounts of CO and UHC but high levels of NOx.

The Phase 5 combustor achieves these different fuel-air mixture ratios by fixing the amount of air entering the different zones of the combustor. "The Phase 5 combustor means there is no need for us to use DAC technology for Rolls-Royce engines yet," says Low. Rolls-Royce has demonstrated DAC technology. It has it on the shelf, but it has yet to use it. "The reduction in emissions the DAC gives us is too small compared to the Phase 5 combustor at the moment to make a sound business case," explains Low. "The DAC is expensive, heavier and inherently less reliable. Although the DAC concept is simple, it is complicated to control. Control of the DAC is one of the functions of the engine's full authority digital engine control unit. If we can we will use single annular combustor technology to avoid problems with reliability and control of the DAC."

The RB211-535 will have to use a



General Electric and CFMI have developed a DAC which is optional on the CFM56-5B and -7B series and standard on the GE90. The DAC can bring substantial savings for airlines operating in environmentally sensitive areas.

Phase 5 combustor for continued production. Like the Trent 500, Rolls-Royce is unsure where these two engines will stand relative to CAEP IV limits.

Further NOx reduction will come from controlling how fuel is put into the engine. Better mixing means and pre-vapourising of the fuel increases combustion efficiency and reduces CO and UHC production. This will then allow a lower flame temperature and faster cooling to reduce NOx, without increasing CO and UHC production.

IAE

The V.2500 series meets all CAEP IV requirements and, in addition, has a substantial margin. "Our emission levels are particularly good against competitor's engines," claims Mike Terrett, president and chief executive officer at International Aero Engines (IAE). "The V.2500-A5 is the current production engine and has been in service for more than five years. It has a significant margin against CAEP IV.

"We did look at a staged combustor, but have remained with the single annular combustor. A staged combustor is expensive and complex," says Terrett. "With regards to NOx reduction and control we have followed the same route as the higher thrust variants of the PW4000 that power the 777. The later versions of the PW4000 use Talon combustor technology to reduce NOx and we may use this later on the V.2500."

The Talon technology works by increasing atomisation of fuel in the combustor. This improves burning efficiency and reduces the time required to get adequate burning. It is basically a more advanced single annular burner.

"Staged combustors have increased UHC in the quest for lower NOx emissions. They also incur a reliability and fuel burn penalty," explains Terrett. "Our approach with the V.2500 is a simple balancing act with CO, UHC and NOx, and to have a simpler engine. The V.2500-A5 beats CAEP IV limits with a comfortable margin without the use of Talon technology. Despite possible future reductions, the V.2500 does not require a staged combustor. In fact, it is detrimental to the engine's performance. The combustor in our current engines has been designed more recently than others, which explains its low NOx emission levels."

General Electric

General Electric (GE) has also developed staged combustor technology. However, the company has only had to apply it to the GE90.

As previously described, high engine pressure ratio increases NOx production. The GE90, initially rated at 77,000lbs thrust, is the only GE engine to require staged combustors to meet CAEP IV requirements.

The only GE engines currently in production and obligated to meet CAEP IV limits are the CF6-80C2, -80E1 and GE90 series.

The CF6-80C2 and -80E1 have easily met the CAEP IV limits *(see chart, page 40)*. Both use a conventional single-stage combustor. "A DAC combustor was discussed on the CF6," says Willard Dodds, manager of combustion technology at General Electric aircraft engines. "All of the DAC design for the CFM56 was done at GE. There has not actually been the need to apply DAC technology to the CF6, despite there being economic benefits in a few European countries."

Nevertheless, work has been done to reduce NOx and other emissions from the CF6. For example, GE has developed a low-emissions combustor for the CF6-80E1. Originally, with the standard combustor the CF6-80E1's NOx levels were 30% below CAEP II limits and 18% below CAEP IV limits. The new low-emissions combustor reduced NOx to 38% below CAEP II and 28% below CAEP IV. The new combustor also achieved significant reductions in HC, CO and in smoke.

The GE90 uses the same DAC technology that had been developed for the CFM56. The first DAC combustor developed for the GE90, the DAC I, was designed at a time when it was thought the GE90 would burn with a leaner mixture than the CFM56.

Subsequently, it was decided that the GE90 would burn with a richer mixture and so the DAC II was developed. Like the low-emissions combustor developed for the CF6, the DAC II delivered improvements in emissions over the DAC I. "A richer mixture produces lower CO and UHC emissions," explains Dodds. "But this will also lead to higher NOx, hence the need to develop DAC II. The DAC II is now standard on all GE90s. It should also meet future NOx reduction requirements."

The DAC II works on the same principle as all other staged combustors. DAC II used a re-adjustment of airflow into the two combustion chambers to achieve the required reduction. AC