AERO-ENGINE TECHNOLOGY TO COPE WITH ACARE GOALS

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Abstract

To investigate, whether further developments in aero engine technology have the potential to achieve the ACARE 2020 targets, a study on the possible improvements of different technology advances has been performed. The study focuses on engine improvements, but since the ACARE targets are formulated for the air transport system as a whole, improved aircraft on realistic flight missions are also taken into account.

The results show that the isolated ACARE target of 50% fuel consumption reduction per passenger kilometre does not seem unachievable, but 1) significant research effort is still needed and 2) it seems much more challenging to achieve all of the ACARE targets at once.

Nomenclature

AFR	Air fuel ratio
BPR	Bypass ratio
c_D	Drag coefficient
FL	Flight level
FPR	Fan pressure ratio
HPC	High pressure compressor
HPT	High pressure turbine
IC/R	Intercooled and recuperated
LPC	Low pressure compressor
LPT	Low pressure turbine
$\dot{m}$	Mass flow rate
Ma	Mach number
OPR	Overall pressure ratio
p	Pressure
s	Entropy
SFC	Specific fuel consumption
SLS	Sea level static
T	Temperature
UHB	Ultra high Bypass
η	Efficiency
ψ	Turbine stage loading

Indices:

comp	compressor
therm	thermal
pol	polytropic
prop	propulsive

1. Introduction

The goals defined by the ACARE Vision 2020, to reduce aircraft fuel consumption by 50%, NO_X production by 80% and to half current perceived noise levels present a major challenge to aerospace industry. Today it becomes increasingly probable that these goals will not be achievable by further development of today's best technology, but will need the introduction of new concepts and designs for at least some components of the whole aircraft system. The extent to which new concepts are required in the different disciplines of air transport to fulfil the ACARE goals is dependent on the potential improvement, which is still achievable with standard technology, as well as on additional benefits, that might result from interdependencies of individual components in the whole aircraft system. Therefore the scope of this study is to assess the remaining potential of current aircraft engine technology and to evaluate the potential benefits of advanced concepts that are on the horizon today. Special emphasis is laid on trade-off effects and interdependencies of improved components with respect to the whole aircraft system.

2. Thermodynamic Basis and Limits of Aero Engine Heat Cycles

The prime mover of today's aero engines is a gas turbine in combination with a propulsor like a nozzle (turbojet), a ducted bypass-fan (turbofan) or a propeller (turboprop). The basis of the gas turbine as a combustion engine is the realization of a thermodynamic heat cycle combining compression, heating up, expansion and cooling down. The most efficient heat cycle between an upper T_{max} and lower T_{min} limit of temperatures is the Carnot cycle giving a thermal efficiency of

$$\eta_{therm} = 1 - \frac{T_{min}}{T_{max}} \qquad (1)$$

The realization of such a cycle is exceedingly challenging due to its extremely high pressure ratio, which will exist between the two temperature levels. For practical reasons gas turbine engines are therefore using the Joule or Brayton cycle. This cycle is characterised by its simplicity and applicability. **Figure 1** shows the Joule and the Carnot cycle in the typical temperature/entropy relation.

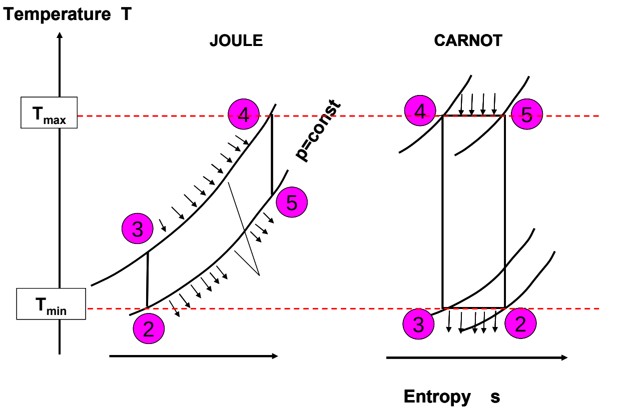

Fig. 1: The ideal Joule or Brayton cycle in comparison with the Carnot heat cycle.

The figure reveals the difficulties a practical realisation encounters by the latter, i.e. the very high overall pressure ratio and a partial isothermal compression and expansion. For example with a first pressure ratio (p_3/p_2) of two and today's feasible gas turbine temperature ratio T_{max}/T_{min} of 6 the overall pressure ratio of a Carnot heat cycle would end up in a value above 1000. So the Joule cycle remains the only thermodynamic basis from where cycle upgrades may arise. A basic principle of thermodynamic heat cycles is that their thermal efficiency will rise if the gap between the average temperature of the heat source and the average temperature of the cooling sink increases. In the following different cycle modifications will be considered.

Figure 2 shows possible gas heat cycle configurations still of an idealized type but closer to practical realization than the Carnot cycle.

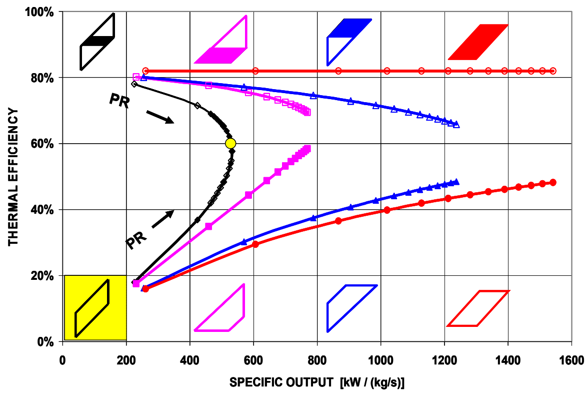

Fig. 2: Different ideal gas heat cycles and their efficiencies compared to the simple Joule cycle within the range of pressure ratios (PR) from 2 to 60 (T_{min}=288 K, T_{max}=1600 K)

The basic cycles are indicated in the lower part of the diagram, whereas the equivalent cycles, having an internal heat transfer (recuperated cycles), are pointed out in the upper part. Within the scope of the simple base cycles there is no heat cycle better than the Joule cycle with respect to thermal efficiency. Only the cycles combined with recuperation show better values.
Whereas the efficiencies of the simple cycles are increasing with higher pressure ratios the recuperated cycles show the opposite characteristic, except the one in the upper right corner (Ericsson cycle). This heat cycle yields the Carnot efficiency for any pressure ratio. All alternative heat cycles show a steadily higher specific output with increasing pressure ratio than the Joule cycle.

The following conclusion can be drawn: The higher the pressure ratio of the compared cycles the lower the difference of thermal efficiencies. For a given pressure ratio the specific power output per gas mass flow of any cycle remains the same whether there is recuperation or not. Therefore, if a gain of efficiency is the main objective for a change from the conventional Joule cycle to an inter-cooled and recuperated cycle (IC/R) than if ever possible a regime of low pressure ratios should be preferred. This shows roughly where to go in engine cycle modifications keeping in mind that high turbine inlet temperatures and low pressure ratios unfortunately are combined with very high turbine exit gas temperatures encountered by a recuperator.

In the following as an example for cruise conditions a high bypass fan engine will be coupled thermodynamically to ideal and real heat cycles on the basis of the Joule cycle and its recuperative alternative without and with a one step inter-cooling during compression. The fan pressure ratio (FPR) was selected as FPR=1.4 and to just address the heat cycle itself the specific thrust (about 90 Ns/kg) and by this the propulsive efficiency has been kept constant. The relation between SFC and efficiencies may simply be expressed by:

$$SFC = const \cdot \frac{1}{\eta_{prop} \cdot \eta_{therm}} \qquad (2)$$

For the real cycles the following assumptions have been made: core turbo components η_{pol}=90%, fan efficiency η_{pol} = 94%, heat exchange efficiency 80% and ideal gas properties with constant specific heat.

Figure 3 shows the results of this simplified analysis. The characteristics of the recuperated / inter-cooled cycles with respect to a reduction of SFC compared to the simple cycle will remain the same for ideal and real components.

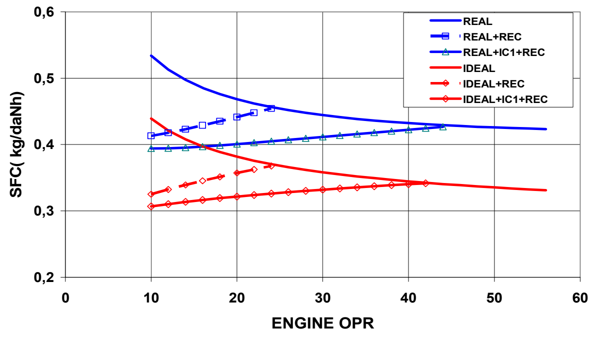

Fig. 3: Engine cycle modelling for ideal and real components. Constant specific thrust at Ma=0.82 ; FL350; FPR=1.4 ;T_4=1600K

The recuperated-only heat cycles show their advantage in efficiency only at very low pressure ratios, whereas inter-cooled and recuperated (IC/R) cycles allow for higher pressure ratios.

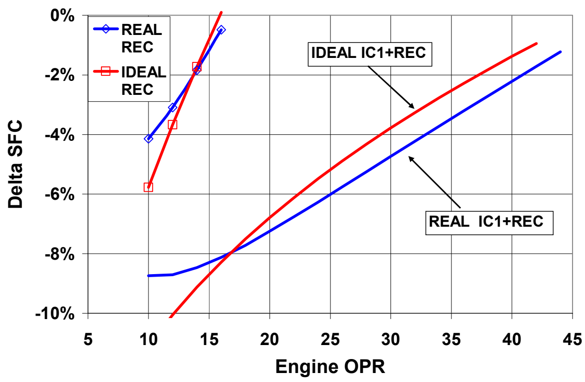

Fig. 4: Percentage of SFC reduction versus cruise design pressure ratio (T_4 =1600K) ; reference simple cycles pressure ratio of 40

Figure 4 expresses the percentage of SFC reduction of the recuperated and the IC/R-cycles over simple Joule cycle engines for ideal and real components. A comparison for the same fixed pressure ratio shows that the SFC reduction in the higher pressure ratio range will be slightly lower for the ideal cycle because of a little shift of the pinch-point (see **Figure 3**).

This analysis is promising a gain in SFC of about 5 to 8% in the range of 30 to 20 overall pressure ratio compared to the reference engine heat cycle. In consequence of addressing the thermal efficiency only there is an effect on the bypass ratio of the aero engine, which is demonstrated in **Figure 5**. This is due to the change in the specific power output of the relevant heat cycle demanding for a lower or higher core engine mass flow.

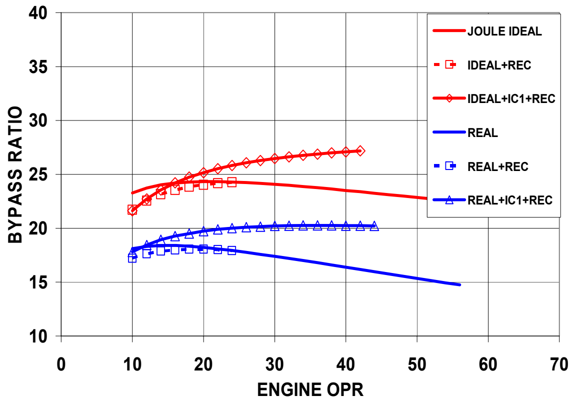

Fig. 5: Effect of engine heat cycle on the fan engine bypass ratio (constant specific thrust)

Therefore within the concepts of different heat cycles the dominating design aspects for reducing SFC are heat cycle efficiency and engine specific thrust. The latter will be dominated by the selected fan pressure ratio whereas the change of bypass ratio is a side effect.

The influence of the fan pressure ratio for a fixed heat cycle (Tmax=1600K, OPR=40) on the change of SFC and specific thrust can be seen in **Figure 6.**

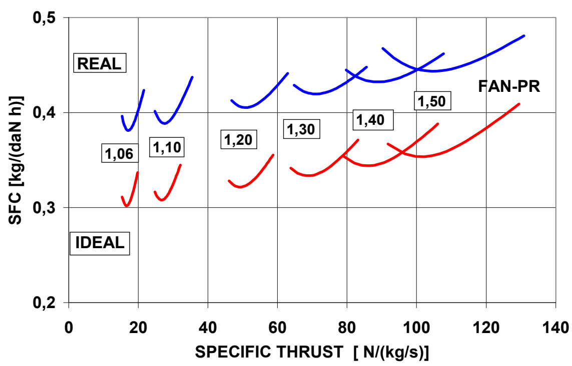

Fig. 6: SFC versus specific thrust and fan pressure ratio (engine OPR=40, T_{max} =1600K, Ma=0,82, FL350, ideal gas properties)

Two effects can be revealed. One is the variation of SFC with specific thrust related to each fan pressure ratio requiring a fine tuning by adapting the bypass ratio in case of a fixed core engine heat cycle thermodynamic. The reason for this is the varying core nozzle pressure ratio spoiling the optimum specific thrust. Typical for ultra high bypass engines with very low fan pressure ratios will be an increasing sensitivity.

Another more general effect is the steady reduction of SFC due to increasing propulsive efficiency by reducing the fan pressure ratio. The potential of SFC reduction for an engine with ideal components is nearly the same as for an engine with real behavior.

In the past civil aero engines for the subsonic flight regime have been designed to follow the aspect of optimizing the thermodynamic heat cycle by rising pressure and temperature ratios, improving component efficiencies and increasing the bypass ratio in a compromise with the fan pressure ratio. The propfan developments in the 1980s more or less were aiming at a goal of increasing propulsive efficiency. All strategies of the aero engine development succeeded in a substantial improvement of engine total efficiency and this can be shown by a steady SFC reduction over the past decades. **Figure 7** gives an overview on these facts and shows as well the limits which cannot be overcome.

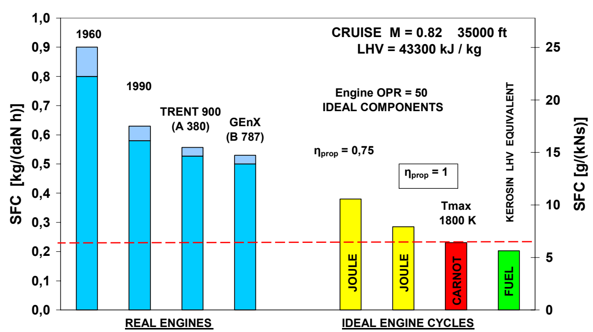

Fig. 7: Gain and theoretical limits of aero engine specific fuel consumption under cruise conditions.

3. Design trends and tradeoffs

3.1 Thermal Efficiency

The thermal efficiency of the real Joule (Brayton)-cycle depends on the pressure ratio OPR, the combustor exit temperature T4 and the component-efficiencies whereas the optimum pressure ratio is a function of T4 and the component efficiencies.

The combustor exit temperature is limited by the thermal fatigue of the turbine blades and - with rising importance - limited by environmental issues such as NO_x Emissions which rapidly increase beyond 1800K. In the next years, material research and advanced combustor designs will help rising the temperature; nevertheless these improvements will be limited.

By the year 2020 the component efficiencies will be further improved. However, today's components are already well optimized, so the benefit will be limited.

The anticipated improvements will result in an increase of the thermal efficiency (η_{therm}) and power output of the core engine which can be used to drive a fan with increased bypass mass flow. A further increase in η_{therm} will be difficult without changing the thermodynamic cycle. This may be done by choosing an intercooled and recuperated heat cycle.

3.2 Propulsive Efficiency

The propulsive efficiency can only be increased by reducing the nozzle exit speed and by simultaneously increasing the mass flow to reach the same thrust.

This can be done by increasing the fan diameter or the axial flow velocity through the fan while lowering the nozzle pressure ratio.

The axial flow velocity is limited due to choking in the fan. For example, if the axial velocity at the fan entrance is Ma 0.8, a 3% blockage in the fan disk area results in choking in the fan. Thus only very few blades are possible. With fewer blades the fan will transmit less energy; a multistage fan would become necessary. This consideration directly leads to the concept of a "Counter rotating Fan".

The engine diameter is limited by the circumferential speed of the fan blades. Today's fans already run with a tip speed of Ma 1.4. A further increase of speed would lead to flow separation and negative aero-acoustic effects. Therefore an enlargement of the fan will lead to a reduction of the fan speed. This has negative effects on the turbine, which normally runs most efficiently at high speeds. A reduction of the turbine speed leads to a higher number of turbine stages, causing an increase of weight and size. This tradeoff can be solved by the adoption of a geared fan.

Today's engines have a propulsive efficiency of approximately 0.70 to 0.80 which directly corresponds to a specific thrust of 150 to 115 N/kg/s respectively.

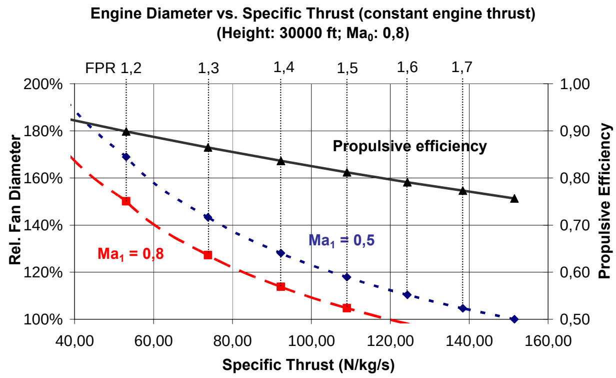

Fig. 8: Propulsive efficiency and Fan diameter vs. specific thrust. For a given specific thrust, the required FPR, the propulsive efficiency and the fan diameter can be determined.

In **Figure 8**, the influence of a change in specific thrust on the required fan diameter and the propulsive efficiency is shown. Two fan entrance Mach numbers Ma_1=0,5 and Ma_1=0,8 show the potential of reducing the fan diameter by raising the axial flow speed. Increasing the propulsive efficiency by 10% would require a specific thrust of 60-80 N/kg/s. With today's technology (Ma_1=0,5), the fan diameter would be enlarged to approx.140%. To maintain the circumferential tip speed, the shaft speed needs to be reduced to 70%. With an assumption of a constant turbine stage loading ψ (proportional to $1/u^2$) and constant mean turbine radius, the number of turbine stages is doubling.

The increase of the bypass mass flow affects the thermal efficiency; it becomes more sensitive to the fan efficiency. Higher efficiencies can be obtained by a further decrease of the fan speed, avoiding shock losses in the fan.

4. New Concepts

4.1 Geared Fan

The above considerations show that it becomes necessary to separate the rotational speed of the fan and the low pressure turbine (LPT) for ultra high bypass (UHB) engines.

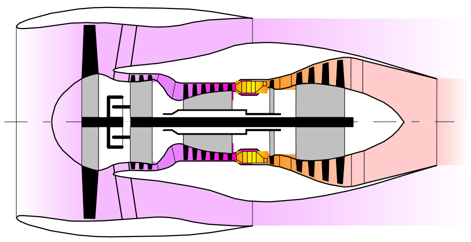

Fig. 9: Geared Fan [1]

One way is the introduction of a gearbox between the fan shaft and the low pressure compressor (LPC) shaft. A transmission ratio of around 3 allows the use of a compact high-speed turbine which is driving a low-speed fan with a large diameter.

Besides the benefits concerning a high-speed LPT that were already mentioned before, there are several other advantages. With low rotational speed, the fan will become more efficient and has - in combination with a low fan pressure ratio (FPR) - a great potential for the reduction of fan-related noise.

Due to a higher rotational speed and lower torque of the LPT, the diameter of the low-pressure shaft can be reduced, easing the integration of the LP-shaft through the HP-turbine.

The availability of extreme reliable and lightweight gearboxes will be crucial for the success of this concept. A risk of increased engine-failure probability will not be accepted by potential customers.

Integration and cooling of the gearbox pose further challenges. For large engines, a mechanical loss of 1% causes a heat output of 500kW, demanding large (and heavy) coolers.

4.2 Counter-Rotating Fan

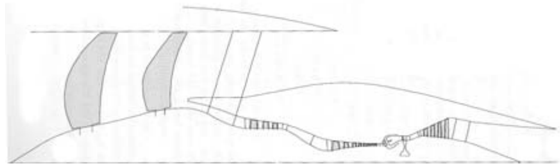

Fig. 10: Counter-Rotating Fan

A “Counter-Rotating Fan” (CR-Fan) provides the opportunity of a higher flow velocity within the fan, so that a higher bypass mass flow can be achieved without increasing the fan diameter. Splitting the fan pressure rise in two steps allows fewer blades in each stage, thus decreasing the area ratio in the fan, i.e. increasing the possible axial flow velocity.

The counter-rotating fans may be driven by a counter-rotating, statorless turbine or by a gearbox and a high-speed turbine like the geared fan. Both techniques allow compact turbines.

The use of two independent LPTs is the easiest way to drive two fans, but has no advantages in respect to the turbine size.

In addition to the challenging development of a contra-rotating, statorless turbine the CR-Fan has several disadvantages concerning engine noise. The incoming flow at the second fan will be disturbed by the wake of the first one, generating pressure fluctuations on the fan surface which propagate as a sound wave. This inherent disadvantage of the CR-Fan may be attenuated by special fan geometry; nevertheless a CR-Fan will be noisier than a geared fan.

4.3 IC/R Engine

With the limited potential to increase the component efficiencies, a change of the thermodynamic cycle itself in order to increase the thermal efficiency of aero engines gets interesting.

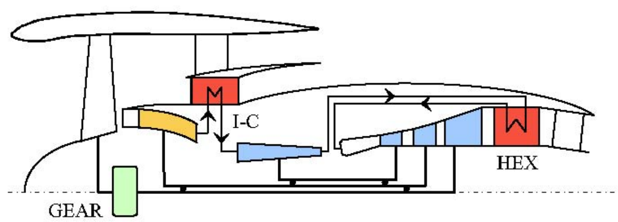

Fig. 11: IC/R engine

An intercooler, placed within the compressor, minimizes the power required for compression by removing heat from the compressed air while heating the bypass flow.

A recuperator takes heat energy from the core-nozzle mass flow and transfers it to the high pressure section in front of the combustor, over-compensating the heat loss within the intercooler.

As described in chapter 2, this process is able to reach very high efficiencies at low pressure ratios. Besides this advantage, the IC/R-process leads to an enormous increase in engine complexity and weight. To reach high recuperator effectiveness, a huge heat exchanging surface is required. Although the weight of the core engine is reduced due to the lower OPR, the additional weight of the recuperator and the intercooler will lead to heavier engines, spoiling the well known gas turbine power density with respect to weight and volume.

5. Engines 2020

In the following different engine architectures will be investigated for their potential to reach the ACARE-goals.

The thermodynamic calculations are carried out with the one-dimensional engine performance calculation program VarCycle [2]. A more general thermodynamic description of a two spool bypass engine without detailed compressor and turbine performance mapping is used. The power equations of the high and the low pressure spool have to be fulfilled taking into account the mechanical losses. Furthermore, the pressure balance and the continuity of the mass flow are used for the iteration process.

5.1 Datum Engine

As the year-2000 engine, the reference engine of the EU-Project CYPRESS **[3]** is used to represent current technology. It is derived from existing engines powering the Boeing 777. The basic thermodynamic design-values are given in **Table 1**.

OPR (T/O)	41
T4 (T/O)	1783 K
BPR (T/O)	6,1
FPR (T/O)	1,73
$\dot{m}_{core}$ **(T/O)**	180kg/s
SFC (cruise)	15,513 g/kNs

Tab. 1: Basic data of the reference engine

5.2 High Bypass Engines

Several engines with conventional cycle are chosen for further investigation. The efficiencies of the engine components are carefully selected on the basis of future trends [4]. The maximum material temperature in the turbine is set 30K above the value for the reference engine. The maximum cooling air flow is limited because higher air-flows cause lower turbine efficiencies. Hereby T4max is indirectly limited. The overall pressure ratio (OPR) was set to 45.

Engine	**UHB 1.45**	**UHB 1.30**	**UHB 1.20**
OPR	45	45	45
T4max	1880K	1880K	1880K
FPR	1,45	1,3	1,2
BPR	12	17,3	25
η_{Fan}	+0,6%	1,2%	1,2%
η_{comp}	+1%	+1%	+1%
η_{HPT}	+2%	+2%	+2%
η_{NDT}	+5%	+5%	+5%

Tab. 2: Basic design-values of the UHB engines. Efficiency gains are given in percent-points.

A higher overall pressure ratio demands either lower combustor temperatures or an increase of cooling-air flow. Both will compromise the efficiency gain. In **Figure 12** it is shown that an OPR of 50 would result in a significant loss of thrust during cruise with only small benefits in SFC.

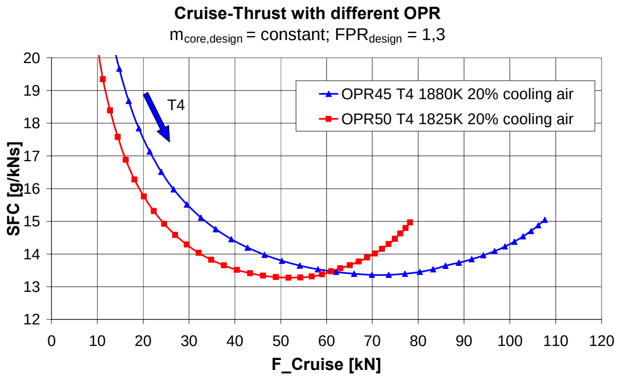

Fig. 12: Effect of higher pressure ratios with limited cooling air flow

Different FPR are selected for further analysis. For each FPR, the bypass-ratio has been optimized for best SFC during cruise.

All engines are designed to reach the same maximum thrust during top-of-climb.

By designing the engines for top-of-climb, all UHB engines achieve a large excess thrust in takeoff-condition (**Figure 13**) due to the high air density at sea level in combination with the high bypass-ratio. This gives the opportunity for a takeoff procedure with moderate turbine inlet temperatures and flexibility to execute noise-reduced climb procedures.

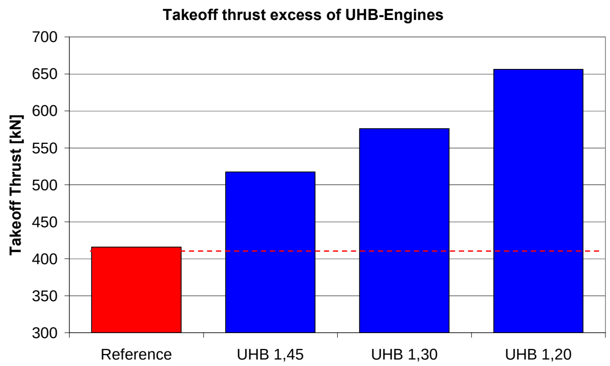

Fig. 13: Thrust excess of UHB engines

Although the temperature limits of the 2020 engines are higher, T4 at takeoff is lower than the temperature of the reference engine. This effect provides opportunities for NO_x reduction in the vicinity of the airports.

Caused by the increased thermal and propulsive efficiencies, the thrust-specific fuel consumption during cruise is significantly lower than for the reference engine (**Figure 14**).

Lowering the FPR from 1.3 to 1.2 has only a comparatively small effect on the SFC.

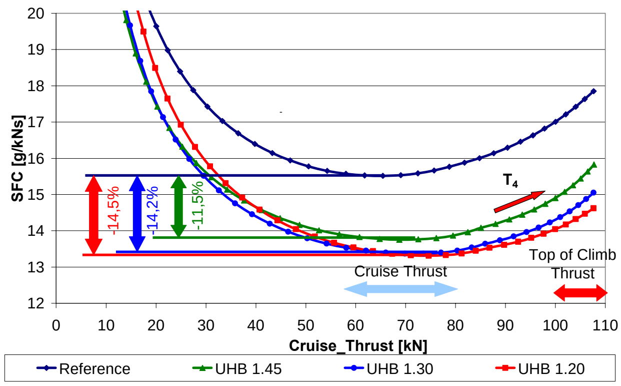

Fig. 14: Specific fuel consumption of the UHB-engines at cruise conditions (Ma 0.82, FL 350)

The relative SFC benefit of the UHB engines is highly dependant on the operating point of the engine. At takeoff, the SFC is reduced by 25-45% whereas at cruise (where the most fuel is burned) a smaller reduction of only 11-15% is achieved (**Table 3**).

	SFC (T/O)	**SFC (Cruise) Ma 0.82; FL350**
UHB 1.45	76,7%	88,5%
UHB 1.30	65%	85,8%
UHB 1.20	55,3%	85,5%

Tab. 3: SFC at takeoff and at cruise relative to reference engine

5.3 Intercooled, recuperated engines

The thermodynamic design of the IC/R engines is based on engine designs made in the EU-project CYPRESS [3]. The polytropic component efficiencies are corresponding to those of the UHB engines. The FPR was set to 1.3 while the BPR was optimised for minimal fuel consumption during cruise.

The optimal OPR was found to be 24. In contrary to the results of the theoretical cycle analysis (chapter 2), too low OPRs lead to a slightly higher SFC due to the influence of component efficiencies. Higher values had no significant change in cruise behaviour.

The selection of a maximum combustor exit temperature $T_{4,max}$ is difficult due to the low

OPR. The low compressor exit temperature enables very effective HPT cooling, allowing very high temperatures. Due to the low temperature drop in the HPT, LPT temperatures are too high for an uncooled LPT. The introduction of LPT cooling will further increase engine complexity and weight. In this study, T4max is set to 1880k, corresponding to the value selected for the UHB engines.

Several IC/R-Engines with different heat exchanger efficiencies are investigated. The heat exchanger efficiency has great influence on the weight of the recuperator-matrix. Raising the efficiency a few percent has a strong effect on the required heat exchanging area and thus on the weight of the matrix.

Engine	Reference	ICR_53	ICR_65	ICR_75
OPR	41	24	24	24
T4max	1780K	1880K	1880K	1880K
FPR	1,73	1,3	1,3	1,3
BPR	6,1	21,2	21,4	22
ε_{rec} SLS	-	53%	65%	75%

Tab. 4: Basic design data for the IC/R-Engines

By analysing the thrust specific fuel consumption during cruise (**Figure 15**) it becomes apparent, that IC/R engines with low heat exchanger efficiencies are not able to reach the fuel consumptions of conventional cycles with advanced components. To gain benefits in terms of SFC, the heat exchanger efficiency at takeoff must be well above 65%.

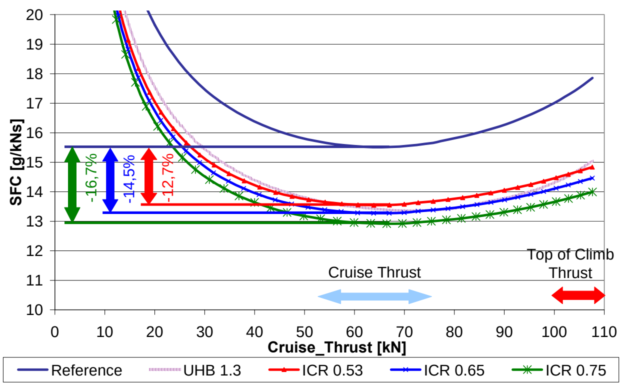

Fig. 15: Specific fuel consumption of the IC/R-engines at cruise conditions.

6. Weight Estimation

For a flight mission analysis, the weight of the engines has to be considered. Especially for the IC/R-Engines, the engine weight will be crucial for a success of this engine concept.

The weight of existing engines can be estimated by a simple correlation based on the number of shafts and the maximum takeoff-thrust. Today's engines can be calculated quite accurately (**Figure 16**).

For a geared fan the smaller LPT and the lighter shaft is supposed to compensate for the additional weight of the gearbox.

If we also assume a gearbox to drive the CR-Fan, the UHB engine weight can be derived independently of the used fan concept by extrapolating the three shaft weight correlation for the calculated takeoff-thrust.

The resulting weights are slightly above existing engine weights of the same cruise-thrust-class.

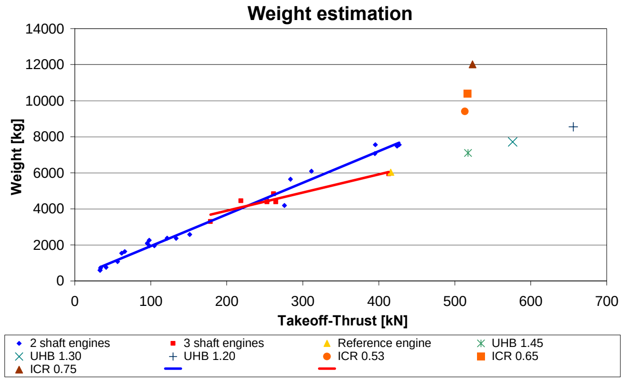

Fig. 16: Weight correlation with F0

To estimate the weight of the IC/R engine, several assumptions have to be made. The weight of the heat exchanger matrix can be calculated easily from the matrix geometry. A mean material density of 7850 kg/m^3 was selected for the matrix and for the duct pipes, as this is similar to that of steel and to that of Copper-Aluminium or Nickel-Copper alloys, which would be suitable matrix materials due to their high heat conductivity and their high heat resistance [5].

The reference engine weight is assumed to be the same as the Engine "UHB 1.3". The IC/R engine has fewer and lighter components, due to the lower pressure ratio. The weight saved by the omitted booster and the smaller compressor is assumed to be the same as the intercooler, including ducts [6].

The length of the duct pipes for the recuperator has to be twice the axial length of the combustor and the turbines, plus the recuperator length.

Therefore the weight of the IC/R engine is calculated as the weight of the reference engine plus the weight of the recuperator matrix plus duct pipes plus additional structure.

In **Figure 17**, the results of the weight estimations are shown. Besides the already mentioned slight increase in engine weight for the UHB-Engines, the enormous weight of the IC/R engines with high recuperator-efficiencies becomes apparent.

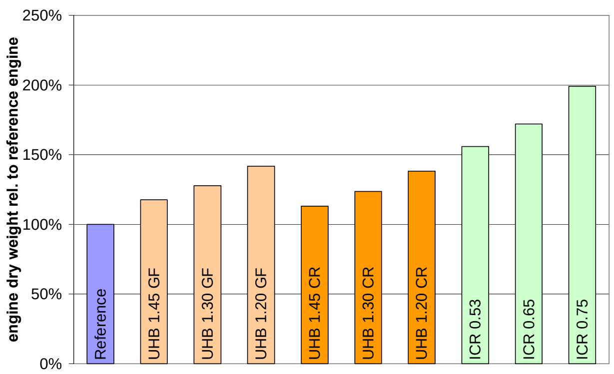

Fig. 17: Estimated weight of the investigated engines

7. Drag Estimation

For an evaluation of the potential of an aircraft engine concept, the drag estimation is vitally important. The high bypass-ratios of the investigated engines cause larger engine diameters (**Figure. 18**), although the highly efficient core engines are smaller than the reference core.

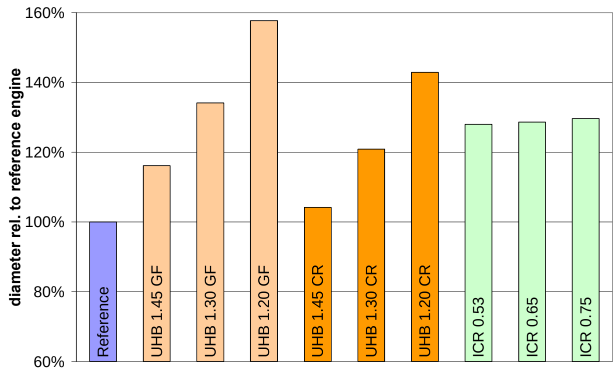

Fig. 18: Estimated diameter of the investigated engines

A constant engine drag coefficient c_D referring to the squared inlet diameter is assumed [7]. This assumption results in higher drag coefficients for the whole aircraft (**Figure 19**) and is spoiling the advantages of the advanced engines.

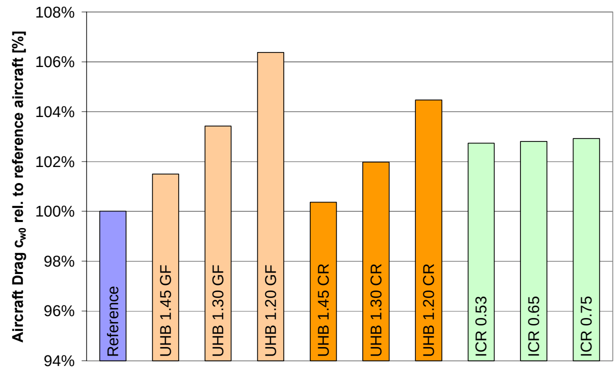

Fig. 19: Estimated aircraft drag cw,0 for the different engine concepts

Obviously an evaluation of the concepts based on cruise SFC only is not sufficient. A more detailed analysis is necessary, taking into account the results of the weight and drag analysis, to see to what extent the SFC benefits are retained on a complete flight mission.

8 Flight Mission Calculations

8.1 General Procedure

Flight mission calculations have been performed for 3000km, 6000km and 12000km range to evaluate the impact of the different engine types on the fuel consumption of a whole mission.

The aircraft model used for these calculations was the CYPRESS large 2-engined aircraft. On each flight mission this aircraft model carries 375 passengers with an average weight of 100kg per passenger including luggage. According to a short parameter study, the optimum flight altitude for all three ranges would be 39000ft (11887m). Minimum fuel consumption is achieved without a step climb. All aircraft-engine combinations are able to climb immediately to their cruise altitude, because the take-off weight even for the longest range mission is below the MTOW, so take-off thrust required will be significantly below nominal thrust.

The mission calculation starts with the take-off run, which is performed with the engine thrust adapted to the aircraft weight to make full use of the available runway. After take-off, the aircraft climbs and accelerates with constant fan speed to 6000m followed by a climb phase with constant indicated air speed (IAS) until cruise altitude is reached. After the cruise phase the aircraft starts to descent with engines at flight idle until a sink rate of 3° is reached, afterwards the 3° sink rate is maintained until touch-down.

The landing weight - which contains the aircraft empty weight, the passenger load, the engines' weight and the fuel reserve - is the same for all missions, except for the engines' weight. This is only a small proportion of the aircraft landing weight; therefore the descent profiles are nearly identical for all missions.

8.2 Impact of Improved Engines

8.2.1 Improved Conventional Engines

Figure 20 shows the reduction in fuel consumption achieved by the introduction of the improved conventional engine types. Obviously the greatest fuel consumption reduction is achieved by the UHB1.30 engine for all mission ranges, although the highest propulsion efficiency is achieved by the UHB1.20, and subsequently its cruise SFC is lowest of all conventional technology engines when comparing for the same cruise thrust level.

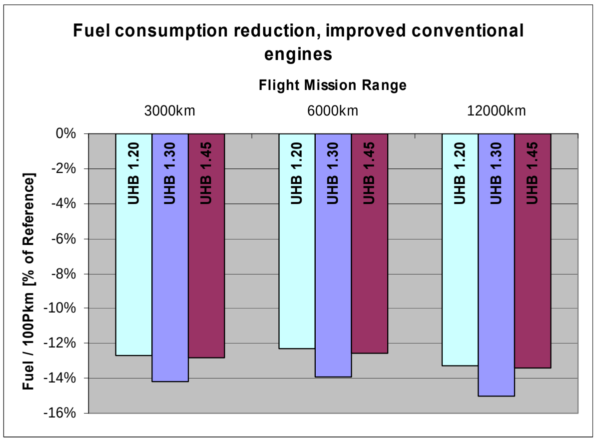

Fig. 20: Fuel consumption reduction achieved by introduction of improved conventional engines, relative to the reference engine

But the better propulsive efficiency of the UHB1.20 is counteracted by the higher weight and drag of this engine. Therefore on the flight mission, the UHB1.20 runs at a higher thrust level than the smaller and lighter UHB1.30 and UHB1.45 engines, which results in increased fuel consumption. The lowest additional weight and drag is added to the aircraft by the UHB1.45, but this engine's SFC is too high (because its propulsive efficiency is lower) to achieve a greater reduction in fuel consumption than the UHB1.30. Thus the greatest fuel consumption reduction of the conventional engine types is achieved by the UHB1.30 engine.

In addition the figure shows that the improved engines have the maximum effect on the longest range mission. With increasing range the impact of lower fuel consumption is amplified by the subsequent reduction of the initial fuel load, which has to be carried by the aircraft.

8.2.2 Intercooled Recuperative (IC/R) Engines

The IC/R engines achieve similar low reductions in fuel consumption than the conventional ones, although they nearly double the contribution of the engines to the aircraft weight (**Figure 21**).

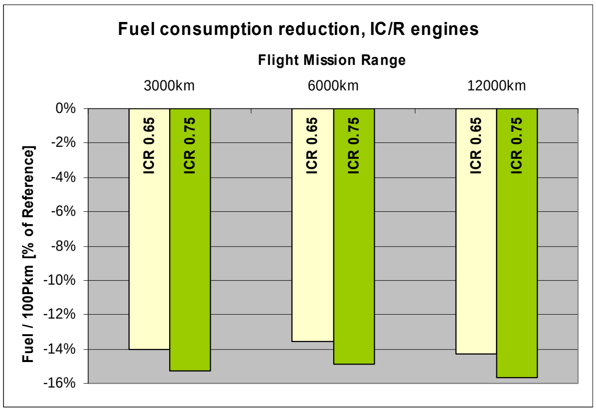

Fig. 21: Fuel consumption reduction achieved by introduction of IC/R engines, relative to the reference engine

The lower SFC values of these engines equalise their higher weight. The best fuel consumption reduction is achieved by the engine with 75% heat exchanger efficiency, although this engine is much heavier than the one with 65%, due to its higher overall efficiency. This engine achieves even a slightly greater reduction than the improved conventional engines, while the 65% efficiency IC/R engine does not meet the reduction of the best conventional engine type (UHB1.30).

8.2.3 Fuel Consumption per 100 Passenger-km

Figure 22 shows the amount of fuel needed to carry one passenger over 100km on each of the flight missions.

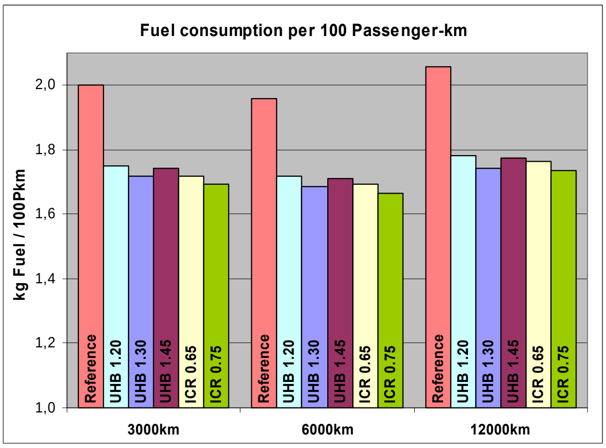

Fig. 22: Fuel consumption per 100 passenger-kilometres (Pkm), all flight missions

The lowest fuel consumptions are achieved by the UHB1.30 conventional engine and the 75% heat exchanger efficiency ICR0.75 engine. Although the greatest fuel consumption reduction, relative to the reference engine, was achieved on the longest range mission, the 6000km mission still is the most fuel-efficient, because this is close to the optimum range of the aircraft. Furthermore, with the improved engines the differences in fuel consumption for different flight mission ranges have been slightly reduced, compared with those of the reference engine.

As a first conclusion, none of the improved engines reaches the engine related ACARE target of 20% reduction of whole mission fuel consumption. The best engines achieve close to 16% reduction, which results in a mission fuel consumption of only 2.1litres per 100 passenger-km. Further reduction is possible by improving the aircraft itself:

8.3 Impact of improved aircraft

To evaluate the impact of aircraft technology on mission fuel consumption an improved aircraft model has been created. This model features a 12% lower structural weight, resulting in landing weight decreased by about 9%, and 12% less drag than the reference aircraft. Flight mission calculations of 3000km, 6000km and 12000km range have been performed with the conventional engine with the lowest fuel consumption on all missions, the UHB1.30. Compared to the reference aircraft equipped with UHB1.30 engines, the improved aircraft reduces mission fuel consumption by about 23.5%, with hardly any influence of the mission range looked at.

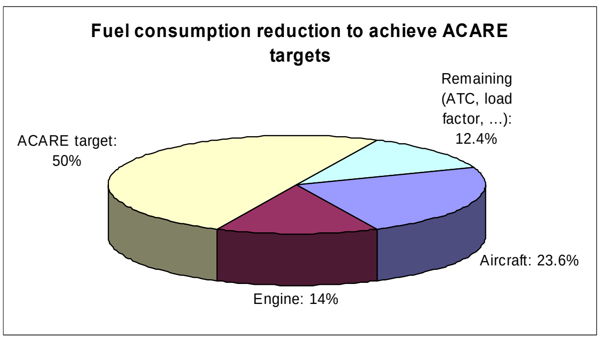

Fig. 23: Possible aircraft and engine contributions to ACARE targets (based on 6000km mission)

Figure 23 shows the contributions of engine and aircraft improvements to the ACARE 50% fuel consumption reduction.

A further 12.4% reduction remains to be generated by ATC improvements, like more direct routing, avoiding holding patterns, use of optimum flight altitudes, etc. Improving the load factor is another measure to reduce fuel consumption per passenger-km:

8.4 Impact of increased load factor

The impact of a 10% increased load factor has been investigated for the 6000km range mission of the reference aircraft with UHB1.30 engines, carrying now 37 passengers more. This results in a landing weight increase by 3.7t. Subsequently the amount of fuel required for this flight mission is slightly higher (+1.2%) than that of the reference mission, but fuel consumption per passenger km is reduced by 7.9%, which would reduce the remaining gap to only 4.5%.

9. NO_x Emissions

NO_x emissions of aircraft engines are strongly dependant on combustor technology. A detailed analysis on potential future NO_x reduction technology was not possible in the scope of this study, but regarding the parameters that are driving NO_x production allows at least some statement about the NO_x emissions behaviour of the advanced engines.

NO_x production is mainly driven by combustor pressure and temperature as well as residence time of the reacting gas in the zone of high temperature. Assuming conventional combustor technology, the residence time of the advanced engines' combustors will be similar to the reference engine. The influence of the combustion temperature can be approximated by the combustor inlet temperature and the air-fuel ratio (AFR).

Comparing the change of p_3, T_3 and AFR values during the flight mission reveals that until an altitude of 5000m is reached, all of these values are lower for the advanced engines than for the reference engine, due to their high by-pass ratio, that creates high excess thrust at low altitudes and velocities, allowing the engine to be run at a lower (relative) thrust setting than the reference engine. Therefore, with the same combustor technology, the emission index of NO_x (EI NO_x = g NO_x / kg Fuel) during take-off and climb to 5000m will be lower for the advanced engines than for the reference engine. The emitted NO_x mass flow will be additionally reduced by the lower fuel flows of the advanced engines.

During cruise, T_3 values are close to those of the reference engine, p_3 is slightly higher and the AFR is lower. In CYPRESS exponents of 0.55 and 0.37 have been used to characterise the impact of AFR and p_3 (respectively) on $EINO_x$. Applying these exponents allows for an estimation of the cruise $EINO_x$ of the advanced engines, based on the $EINO_x$ data of the reference engine from [3]. **Table 5** shows that, while $EINO_x$ is increased by the higher AFR of the advanced engines, their lower fuel consumption results in a small net decrease of NO_x emissions in cruise, even with conventional combustor technology.

	UHB 1.20	UHB 1.30	UHB 1.45
EI NOx Change	10,9%	8,4%	6,6%
NOx Change	-1,7%	-5,9%	-6,1%

Tab. 5: Change of cruise EINOx [g/kg] and NOx rate [g/s] with advanced engine types, relative to reference engine

To summarise, even with conventional combustor technology the UHB engines will result in a reduction of NO_x emissions in the vicinity of airports at least of the same magnitude as that the reduction of the fuel consumption. Even during cruise a NO_x emission reduction due to the better efficiency of the engines can be anticipated, although smaller than that of the fuel consumption. Since initial climb and cruise are the flight regimes that dominate the whole flight mission emissions, the UHB engines will be able to reduce whole mission NO_x by about the same amount as the cruise NO_x rate is reduced, even with conventional combustor technology.

A NO_x reduction of the size required by the ACARE targets is only achievable by introducing advanced low NO_x combustor technology. Lean combustion concepts seem most suitable to achieve substantial NO_x reductions, but these concepts are still in the development stage.

10. Summary and Conclusions

To figure out, whether improvements in aero engine technology that will be available in the near future have the potential to achieve the ACARE 2020 targets, a study on the impact of different technology advances has been performed. Starting with a thermodynamic analysis of the potential to improve the thermal efficiency of the core engine heat cycle the theoretical and practical limits of the basic Joule cycle and alternative cycles – in particular intercooled and recuperated – have been shown.

A means to achieve a further reduction in fuel consumption is to increase propulsive efficiency by decreasing the fan pressure ratio while raising the by-pass ratio. Two concepts that facilitate a significant by-pass ratio increase have been investigated, the counter-rotating and the geared fan concept. Both concepts allow for a considerable fuel consumption reduction, but to the cost of increased engine weight and size.

The effect of increased thermal efficiency of the core engine cycle has been studied by introducing intercooled and recuperative heat cycles. The results show that realising the great potential of these cycles to reduce fuel consumption will result in aircraft engines with far more weight and complexity than the conventional cycles.

To investigate the effects of reduced fuel consumption and increased engine weight and size on the whole aircraft efficiency, flight mission calculations have been performed.

The results of these calculations show that simply minimising engine SFC does not necessarily lead to minimum aircraft fuel consumption. In particular with increasing by-pass ratio it is essential to optimise the aircraft-engine system as a whole, taking into account the effect of the engines weight and drag on airplane performance.

Moreover, the results reveal that neither the assumed component efficiency improvements nor the improved engine cycles are sufficient to achieve the ACARE engine target of 20% reduction in fuel consumption. Particularly the superior efficiency of IC/R engines is for the most part spoiled by their enormous weight. Nevertheless, combined with an improved airframe and increased loading factor, the ACARE target of 50% fuel consumption reduction for the whole aircraft does not seem completely unachievable.

A sound prediction of future NO_x emission levels is impossible on the basis of publicly available information. But the results show that even with conventional combustor technology a NO_x emission reduction by several percent is achieved simply as a side effect of the reduced fuel consumption. Nevertheless to achieve the ACARE target of 80% NO_x reduction, further intense research on combustor technology is essential. In particular lean combustion technology, combined with the advanced engine concepts investigated here, seems promising to achieve a substantial step towards meeting the ACARE engine targets [8].

Noise prediction as well is virtually impossible without detailed geometry data. However, the measures to improve propulsive efficiency will also facilitate engine noise reduction, particularly the lower jet velocities. New concepts like a geared fan have further potential for noise reduction by lowering the fan rotational speed.

Although there are several measures that allow meeting single ACARE targets, it seems much more challenging to achieve all of them at once. Considerable research effort is still needed until the technological maturity of these concepts, but their introduction into service will significantly improve the environmental compatibility of air transport.

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