Abstract
In view of ever more stringent environmental regulations and increasingly scarce resources aviation is facing tremendous challenges. Therefore, the European aviation industry and research community have defined ambitious targets to reduce the environmental impact of future air traffic early on, and the European Commission has launched a number of large-scale technology programs. The major part of the necessary improvements will have to come from the engines. This paper provides an overview of the large technology programs launched in Europe over the last 15 years, presenting the objectives, approaches taken and major innovative technologies developed. Finally, the improvements achieved are assessed at aircraft level based on complete engine platforms. According to the results of this assessment, the CO2 emissions of engines will be cut by approximately 25%, thus exceeding the reduction targets stipulated in the ACARE’s Vision 2020 roadmap. NOx emissions will be reduced by around 60%, which is in line with the set goal, and the noise reduction of 9 EPNdB will miss the target value by a small margin only.

Introduction
The history of aviation is an impressive success story. Revolutionary technological developments have made aircraft a means of mass transportation over the last decades. In 2013, 3.1 billion passengers were carried on scheduled air services across the globe. However, this success also brings major challenges for the future of air transport, considering that commercial air traffic – if it continues to grow at the current average rate of around 5% per year – will double every 15 years. Society expects the aviation industry to satisfy its continuously growing mobility needs, while at the same time preserving resources, mitigating the impact on climate and environment and reducing noise emissions.

As early as in the year 2001, European aviation companies and research establishments defined ambitious targets for the future of air traffic (Vision 2020 [1]) and established the Advisory Council for Aviation Research and Innovation in Europe (ACARE) to support the implementation of the agreed goals. The need to enhance the environmental compatibility of aircraft, and in particular the challenging targets in terms of reducing CO2 and NOx emissions as well as noise, have been key to driving technological innovation in the last decade. In 2011, the Flightpath 2050 vision was released. It builds on the ACARE Vision 2020 and defines the goals to be achieved by the year 2050. A year later, ACARE published its new Strategic Research and Innovation Agenda (SRIA [2]), which updates the 2020 targets and introduces medium-term targets for 2035. Moreover, the CO2 reduction goals are split into the major component areas, covering airframe, propulsion system, air traffic management and airline operations (Table 1).

<table>
<thead>
<tr>
<th>CO2 Emissions</th>
<th>Vision 2020</th>
<th>SRIA 2020</th>
<th>SRIA 2035</th>
<th>SRIA 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air traffic per passenger kilometer</td>
<td>-50 %</td>
<td>-43 %</td>
<td>-60 %</td>
<td>-75 %</td>
</tr>
<tr>
<td>Airframe</td>
<td>-25 %</td>
<td>-20 %</td>
<td>-30 %</td>
<td>-45 %</td>
</tr>
<tr>
<td>Engine</td>
<td>-20 %</td>
<td>-20 %</td>
<td>-30 %</td>
<td>-40 %</td>
</tr>
<tr>
<td>Air traffic management</td>
<td>-12 %</td>
<td>-7 %</td>
<td>-12 %</td>
<td>-12 %</td>
</tr>
<tr>
<td>Operation</td>
<td>-4 %</td>
<td>-4 %</td>
<td>-7 %</td>
<td>-12 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>NOx Emissions</th>
<th>Vision 2020</th>
<th>SRIA 2020</th>
<th>SRIA 2035</th>
<th>SRIA 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air traffic per passenger kilometer</td>
<td>-80 %</td>
<td>-84 %</td>
<td>-90 %</td>
<td></td>
</tr>
<tr>
<td>Margin rel. ICAO LTO CAEP6</td>
<td>-60 %</td>
<td>-65 %</td>
<td>-75 %</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Noise Emissions</th>
<th>Vision 2020</th>
<th>SRIA 2020</th>
<th>SRIA 2035</th>
<th>SRIA 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aircraft</td>
<td>-15 EPNdB</td>
<td>-11 EPNdB</td>
<td>-15 EPNdB</td>
<td>-19 EPNdB</td>
</tr>
</tbody>
</table>

Table 1: Environmental targets for aviation in Europe (relative to the year 2000)

Through the International Air Transport Association (IATA), the airline industry, too, has committed itself to far-reaching collective goals [3]:
- an average improvement in fuel efficiency of 1.5 % per year from 2009 to 2020
- CO2-neutral growth as from 2020
- a reduction in CO2 emissions of 50 % by 2050 as compared with 2005 levels

The climate protection targets to be met by the airline industry apply at a global level, the expected growth in air traffic volumes included. To address these challenges IATA has adopted a four-pillar strategy [4] which comprises technological efforts in conjunction with the above goals, including the introduction of sustainable low-CO2 fuels, improvements of operations and infrastructure as well as suitable economic measures to fill the remaining emissions gap, e.g. a global carbon offsetting scheme or global emission trading system.

Potential for improvement
Basically, the total efficiency of aircraft engines can be broken down into two elements: propulsive efficiency and thermal efficiency (Fig. 1).
Technologies developed in the past allowed the thermal efficiency to be raised from approx. 40% to 50% and the propulsive efficiency from 50% to 75%. These increases were made possible by higher overall pressure ratios (thermal efficiency) on the one hand and higher bypass ratios (propulsive efficiency) on the other. But there is still room for improvement, considering that the theoretical and practical overall efficiency limits are substantially higher. The Geared Turbofan will achieve up to 90% propulsive efficiency whereas propellers or the Open Rotor are capable of delivering propulsive efficiencies of more than 90%. The Carnot cycle – the ideal thermodynamic cycle – would permit a thermal efficiency of almost 90% to be achieved (Fig. 1). Aircraft engines based on gas turbines, therefore, are still far from having reached their physical limits, but still offer considerable potential for improvement.

Core Technologies

For the conventional simple gas turbine cycle (Joule/Brayton), the thermal efficiency of a turbomachine essentially depends on the combustor outlet temperature and on the overall pressure ratio (Fig. 2). In future, engine operating temperatures can be increased to a limited extent only, since much higher values would exceed the maximum temperatures the materials are capable of withstanding or result in an excessively high cooling air demand. Moreover, higher temperatures cause higher NOx emissions. This is where the heat exchanger comes in, which would allow the thermal efficiency to be further improved while the maximum temperatures remain at the same level. In a first step, the introduction of an intercooler between the low-pressure and high-pressure compressors results in enhanced thermal efficiency, since the compressor work is reduced at higher overall pressure ratios (Fig. 2). Further substantial improvements are possible through the installation of a heat exchanger in the exhaust gas that uses the thermal energy of the exhaust jet to heat the compressed air before it enters the combustor; see Fig. 2.

Low pressure spool technologies

In turbofan engines, the necessary thrust is generated most efficiently with a high mass flow at a relatively low velocity. This can be achieved by high bypass ratios. But the improved propulsive efficiency comes at a price: Higher bypass ratios require larger fan diameters, which increase the aerodynamic drag of the nacelle as well as the weight of the nacelle, fan and low-pressure turbine. Therefore, the bypass ratio needs to be optimized for minimum mission fuel burn (Fig. 3).

Further improvements of the propulsive efficiency can be achieved with an open rotor design that eliminates the need for a nacelle. The advantages afforded by the Open Rotor are lower weight and reduced aerodynamic drag. But this is a concept that comes with some major drawbacks, among them high noise emissions, reduced flight velocity, significant aircraft installation problems and tight
certification requirements. Before open rotor engines can actually be used to power airliners, therefore, a number of technological challenges will have to be overcome. As a result, the next-generation aircraft engines, which are slated to enter service as from the year 2025, will again be ducted turbofans with further enhanced bypass ratios, such engines being the subject of the following chapters.

**Technology needs**

For turbofan engines with a simple gas turbine cycle the key parameters for engine efficiency improvement are overall pressure ratio, combustor outlet temperature and bypass ratio. In the past, therefore, every effort was made to continuously increase these parameters (Fig. 4).

The most recent technology programs are aimed at developing technologies that permit overall pressure ratios of up to 70 and bypass ratios of up to 20 to be achieved. In many areas, therefore, engineers will have to find solutions outside the well-known design space and venture into new technological territory. The most important technology fields for the development of future turbofans are shown in Fig. 5.

The desired high bypass ratios can best be achieved by turbofans featuring a gearbox between the fan and the low-pressure turbine. Consequently, low-loss gearboxes – especially also for large engines – as well as high-speed low-pressure compressors and low-pressure turbines are needed. As a result of the high bypass ratio and the high pressures the size of the core engine and thus also the airfoil height are reduced. So, technologies that help minimize gap losses, particularly in the rear high-pressure compressor stages, are indispensable. The high pressures and temperatures prevailing during the combustion process lead to an increased production of oxides of nitrogen. Thus, major improvements to the combustion chamber are necessary to make sure the desired reduction of pollutant emissions can be achieved. Also of great importance are new high-temperature materials for high-pressure turbine and combustor components, since temperatures cannot be further increased without such materials.

**European technology programs**

Over the last few years, numerous large-scale research and technology projects have been conducted as part of the European Union’s 5th, 6th and 7th Framework Programs (FP5, FP6, FP7) and the Clean Sky Joint Technology Initiative. These programs were co-funded by the European Commission and coordinated by the Engine Industry Management Group (EIMG). The projects were planned in a manner to make sure the entire range of necessary technologies is covered (Fig. 6):

- technologies for core engines with improved thermal efficiency and reduced pollutant and greenhouse gas emissions,
- technologies for low-pressure systems with improved propulsive efficiency and reduced noise,
- noise reduction technologies,
- enabling technologies, and
- demonstrator programs for validation of the technologies.
overall pressure ratio of approximately 30 and a bypass ratio of around 5 (e.g. CFM56-5B or Trent 772B). To improve the thermal efficiencies technologies have been and are being developed in several steps that will permit overall pressure ratios of up to 70 to be achieved. In addition, projects were conducted at a lower technology readiness level to investigate new thermodynamic cycles, for example concepts using an intercooler and/or an exhaust gas heat exchanger. In the field of technologies to improve the propulsive efficiency a two-pronged approach was pursued: Development efforts focused on ducted turbofans on the one hand, the aim being to continuously increase the bypass ratio to values of up to 20, and on open rotors with ultra-high bypass ratios on the other. This paper deals with the ducted turbofan, which represent the most promising propulsion system for the next generation of commercial aircraft due to enter service as from 2025.

Typically, the technologies of the level 2 programs are developed up to a technology readiness level (TRL) of 5 (component validation in relevant environment) and then validated in a series of rig tests for compressor, combustor, turbine and other modules. Under the level 3 demonstrator programs launched as part of the Clean Sky Joint Technology Initiative the technologies are further matured to TRL 6 (system/subsystem prototype demonstration in a relevant environment). Since the year 2000 the following two level 2 projects have been launched: EEEAF [5] [6], SILENCER [7], VITAL [8], NEWAC [9] [10], DREAM [11], OPENAIR [12], LEMCOTEC [13], E-BREAK [14] and ENOVAL [15]. Some of them have already been completed, others are still underway (Table 2).

<table>
<thead>
<tr>
<th>Project</th>
<th>Technology</th>
<th>Application</th>
<th>Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEEAF</td>
<td>Efficiently Engineered Engines</td>
<td>Core engine</td>
<td>101 M€</td>
</tr>
<tr>
<td>SILENCER</td>
<td>Significantly Lower Community</td>
<td>Low pressure system</td>
<td>124 M€</td>
</tr>
<tr>
<td>VITAL</td>
<td>Exposed to Aircraft Noise</td>
<td>Low pressure system</td>
<td>30 M€</td>
</tr>
<tr>
<td>NEWAC</td>
<td>Engineering Friendly Aero Engines</td>
<td>Low pressure system</td>
<td>75 M€</td>
</tr>
<tr>
<td>DREAM</td>
<td>Validated on Radial Engine</td>
<td>Open Rotor</td>
<td>40 M€</td>
</tr>
<tr>
<td>OPENAIR</td>
<td>Architecture for Low Environmental</td>
<td>Optimization for Low Environmental</td>
<td>30 M€</td>
</tr>
<tr>
<td>LEMCOTEC</td>
<td>NOX Impacts Impact Aircraft</td>
<td>Core engine</td>
<td>60 M€</td>
</tr>
<tr>
<td>E-BREAK</td>
<td>Engine to Engine Components</td>
<td>Enabling technologies</td>
<td>30 M€</td>
</tr>
<tr>
<td>ENOVAL</td>
<td>Efficient Neck Design</td>
<td>Low pressure system</td>
<td>45 M€</td>
</tr>
</tbody>
</table>

Table 2: Recent large scale European aero engine programs

Because of the exacting technical requirements to be met and the high technology readiness level (TRL 5), which must be validated in large-scale rig and engine tests, these level 2 technology programs are rather costly, their budgets amounting to as much as 30 to 110 million euros. The programs typically bring together between 20 and 50 partners, among them major players from the European engine (aerospace) industry, small and medium-sized enterprises as well as research establishments and universities. Thanks to an optimum breakdown of the work into suitable subtasks even competitor companies work together in one and the same program. The technology programs normally comprise a sub-project aimed at providing the necessary specifications and evaluating the results, several technical sub-projects to develop the technologies and validate them, as well as a management sub-project. To ensure effective program management, an Executive Board is put in place that is made up of all sub-project managers as well as representatives of the major industrial participants. As a rule, risk management is also an integral part of the technology program, and external consultants and specialists are involved as when required.

In line with the ACARE and SRIA goals, the main objectives of the technology programs are reductions of CO₂ emissions or mission fuel burn, NOₓ and noise emissions. Details of the objectives of the level 2 programs can be taken from Table 3, which also shows the total improvements relative to the year 2000 engine or aircraft achieved under the programs, including predecessor projects.

<table>
<thead>
<tr>
<th>Project</th>
<th>CO₂ Reduction %</th>
<th>NOₓ Reduction %</th>
<th>Noise Reduction dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 2000</td>
<td>SILENCER</td>
<td>E-BREAK</td>
<td>ENOVAL</td>
</tr>
<tr>
<td>Engine</td>
<td>alone</td>
<td>alone</td>
<td>alone</td>
</tr>
<tr>
<td>NOX Reduction</td>
<td>rel. year 2000</td>
<td>5</td>
<td>24%</td>
</tr>
<tr>
<td>Core engine</td>
<td>5</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>Low pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEMCOTEC</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-BREAK</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENOVAL</td>
<td>1%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Main objectives of recent Level 2 European technology programs

Technologies developed in recent European programs

Some of the most important technologies for the new engine concepts that have been and are being developed under the European technology programs are presented under this heading. A major focus of the activities performed was on technologies for fan and nacelle, the aim being to increase bypass ratio, reduce noise emission and lower weight (Fig. 7). Such technologies were and are being developed mainly in the VITAL, SILENCER, OPENAIR and ENOVAL programs. Examples include conventional and contra-rotating fans for low pressure ratios, variable fan area nozzles to ensure fan stability and new designs and materials for a light-weight intermediate case. The use of a contra-rotating fan reduces the pressure ratio per stage and hence the circumferential speed, the result being lower noise emissions. As an additional benefit, a contra-rotating fan can be directly driven by a contra-rotating turbine without the need for a gearbox. Regarding noise reduction for example the aero-
acoustic optimization of the fan, improved acoustic liners, an active stator and new nacelle geometries have been investigated.

Compressor technologies were a major focus particularly under the EEFAE, NEWAC and LEMCOTEC programs for the high pressure compressor and under the VITAL and ENOVAL programs for the low pressure compressor. Measures aimed at improving compressor stability ranged from advanced casing treatments, stall active control by bleed valves all the way to active and passive surge control by means of tip injection. An increase in aerodynamic loads and efficiency could be achieved by boundary layer aspiration and 3D-contoured casing walls, and the negative effects of the small cores on efficiency and stability could be minimized by active or passive clearance control mainly in the rear compressor stages. In addition, high-speed low-pressure compressors for the geared turbofan, new materials and manufacturing processes for lower weight and higher temperatures and improved blade/casing rub management for lower in-service deterioration were developed (Fig. 8).

Turbine technologies were developed mainly in the EEFAE, VITAL, DREAM, LEMCOTEC and ENOVAL programs (Fig. 9), with special emphasis being placed on the high-speed low-pressure turbine. High stage loading and high blade loading help reduce the stage and blade count. Advanced cooling and new coatings permit higher turbine temperatures. New materials, such as TiAl for blades and new designs of the turbine center frame reduce the module’s weight. The demand for reduced noise emissions and high efficiencies calls for low noise design and active clearance control. As lean burn injectors produce swirl and temperature distributions new cooled turbine designs are necessary. In addition to optimizing the individual components, the development work is increasingly focusing on the integration and optimization of the entire expansion system taking the interactions between turbines and ducts into account.

Given the higher pressures and temperatures in the combustor low NOx combustion concepts are of particular importance. As part of the NEWAC and LEMCOTEC programs, various lean burn concepts are being developed (Fig. 10) that feature an excess of air to reduce the combustion temperature and hence limit the formation of oxides of nitrogen. Up to 70% of the air flow in the combustion chamber must be mixed with the fuel before the combustion zone proper is reached. An adequate operating range is ensured by means of fuel staging using internally staged injectors, which create a pilot zone and a main combustion zone in one single annular combustor. Different lean combustion concepts are being developed to suit different overall pressure ratios (OPRs): Lean Premixed Pre-vaporized (LPP) for OPRs up to 25, Partial Evaporation & Rapid Mixing (PERM) for OPRs up to 50, Multiple-Stage Fuel Injection (MSFI) for OPRs up to 60 and Lean Direct Injection (LDI) for OPRs up to 70.

Figure 7: Key technologies for fan and nacelle

Figure 8: Key technologies for compressors

Figure 9: Key technologies for turbines

Figure 10: Key technologies for combustor and system
In addition, technologies to reduce losses in the gearbox for the geared turbofan and new high torque shaft designs are being investigated (VITAL; LEMCOTEC). Furthermore sub-systems like oil system, secondary air system, variable mechanical systems and health monitoring have to be improved (E-BREAK). Another highly promising approach is the use of cooled cooling air, which permits the cooling air mass flow as well as losses in the high-pressure turbine to be reduced (NEWAC).

Basic technologies for an intercooled recuperated core had already been developed under the EEFAE/CLEAN programs. These were further improved and refined in the successor program NEWAC. Decisive factors for the viability of the intercooled or intercooled recuperated core concept are low pressure losses in the air ducting system and in the heat exchanger, the effectiveness of the heat exchanger and engine integration. Weight, reliability and costs also play major roles. Essential technologies developed under the CLEAN and NEWAC programs are shown in Fig. 11. Estimates of the thermal efficiency made in NEWAC suggest an improvement of approximately 2% for the intercooled core and of around 5% for the intercooled recuperated core over the simple gas turbine cycle at the same technology level. From today’s perspective, these efficiency increases do not appear to justify the higher complexity, weight and the associated costs. However, further improvements of the concept are conceivable, in particular in the areas of air ducting and heat exchanger.

![Figure 11: Key technologies for the intercooled and intercooled recuperated core](image)

Before new technologies can be introduced in engines their maturity must be demonstrated. This is why rig tests or tests using engine demonstrators were performed as part of the level 2 technology programs. Some examples are shown in Fig. 12.

![Figure 12: Technology validation – examples of rig and engine tests](image)

A very special test was the simulation of an intercooled recuperated engine at the University of Stuttgart’s altitude test facility. The test item was built up using an original core engine, low-pressure turbine and exhaust gas heat exchanger. The missing components fan, intercooler and low-pressure compressor were simulated by a water brake and the altitude test facility (Fig. 13).

![Figure 13: Test set up for an intercooled recuperated engine](image)

**Technology assessment and achievements**

The assessment of new technologies within the complex overall system consisting of airframe and engine is very difficult because of the interactions between the individual components. As part of the EU’s VITAL and NEWAC programs, therefore, a new assessment method was developed which is based on complete engine platforms for different engine concepts and applications. These engine platforms are generated using preliminary design tools. The new technologies are then integrated in the concept and finally the improvements at engine and aircraft level are determined. The engine platforms used under the most recent technology programs are shown in Fig. 14.

![Figure 14: Recent engine platforms](image)

For these engine platforms the improvements at aircraft level were calculated on the basis of the rig test results and compared with the target values. Figure 15 shows estimates of the reductions of CO₂, NOₓ and noise emissions. The CO₂ emission estimate applies to ducted turbofans for long-haul applications. All European technology programs combined are expected to reduce CO₂ emissions by more than 25% as compared with the year-2000 engine. This result markedly exceeds the ACARE Vision 2020 target and represents a major step towards achieving the SRIA 2035 goal. The anticipated reduction in NOₓ emissions likewise is within the target range. New results obtained under the
LEMCOTEC program will be available soon. With around -9 EPNdB noise reduction, by contrast, fell slightly short of the ACARE Vision 2020 target of -10 EPNdB. Therefore, the 2035 target defined in the new Strategic Research and Innovation Agenda was reduced to -11 EPNdB. A comparison of the objectives of the EU programs regarding CO₂, NOₓ and noise emissions, ACARE/SRIA goals and historical engine data is shown in Fig. 16 ([16], [17]).

Overall, the efforts undertaken under the European technology programs have proved successful in advancing the development of sustainable engine concepts. The results obtained suggest that the targets in terms of fuel burn and NOₓ emission reductions defined for 2020 and 2035 will in all probability be achieved and that the 2020 noise reduction target will be missed by a small margin only (Fig. 16).

**Conclusion**

In the last 15 years, many important and promising technologies have been developed and matured under the European level 2 programs. Taken together, these technologies and the outcome of the programs that are still underway will make a substantial contribution towards achieving the targets defined for the engine in ACARE Vision 2020 and SRIA 2035. The ducted turbofan with simple gas turbine cycle and gearbox still offers great potential for improvement and will remain the propulsion system of choice for the next 20 years.
Figure 17 shows that overall pressure ratio and bypass ratio have increased steadily over the last decades and that this trend will continue also with the engine platforms developed under the most recent program ENOVAL.

The intercooled and intercooled recuperated engines are interesting options, but the heat exchanger and the air ducting system still require significant improvement. Open Rotor propulsion systems will be accepted by society only if their noise emissions can be reduced to the levels generated by advanced ducted turbofans. Moreover, installation problems must not outweigh the higher propulsive efficiency.

For the participating companies the level 2 programs not only represent a major step forward technology-wise but will pay dividends down the road also in terms of economic success. Examples of the introduction of the innovative developments in new engines include compressor technologies from the EEFAE (ANTLE) and NEWAC programs, which have found homes on the Trent XWB, Trent 1000-TEN and BR725. Noise reduction technologies developed under the SILENCER and VITAL programs are used on the LEAP engine and NEWAC compressor technologies on the SaM146 and Silvercrest. And the high-speed low-pressure turbine, which builds on technologies developed under the EEFAE (CLEAN), VITAL and DREAM programs, is a key component of the PW1000G family of geared turbofan engines.

Acknowledgement

The author would like to thank the European Commission for supporting the development of engine technologies in the past 15 years. A large part of this study has been carried out in the framework of the ENOVAL program (Engine Module Validator), which receives funding from the European Commission’s Seventh Framework Program under the Grant Agreement No. 604999.

References


[16] Jane’s Aero Engines, Issue 26

[17] ICAO Aircraft Engine Emissions Databank 01/2015