TOWARD ACARE 2020: INNOVATIVE ENGINE ARCHITECTURES TO ACHIEVE THE ENVIRONMENTAL GOALS?

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Abstract

The Advisory Council for Aeronautical Research in Europe (ACARE) identified the research needs for the aeronautics industry for 2020:

- Reducing CO_2 emissions and fuel consumption by 50%

- Reducing perceived external noise by 50% with 10 EPNdB reduction per operation

- Reducing NOx by 80%

Furthermore, since these objectives have been defined the commercial and political pressure to reduce fuel consumption and CO_2 has increased considerably.

In this frame, Snecma is currently developing in parallel three engine architectures answering ACARE 2020 objectives and recent global warming concerns in different ways.

The first architecture is a high confidence Advanced TurboFan for early Entry Into Service (EIS) minimizing life cycle cost (Fuel Burn, environment and maintenance costs). It relies on the CFM56 experience and the introduction of proven innovative technologies. At 2015-2017 EIS, the LEAP-X engine is already close to ACARE 2020 requirements.

Then, two more radically innovative engine architectures have been identified to enhance environmental performances in terms of noise and CO_2 emissions:

- First one, the Counter-rotating TurboFan (CRTF) aims at providing additional noise and Fuel Burn reductions through a decreased velocity of each of the two counter rotating fans.

- Second one, the Open Rotor architecture is an even more promising concept that delivers a breakthrough on Fuel Burn and CO_2 emissions thanks to an important propulsive efficiency without any duct drag penalties.

Finally, particularly through current European Union (EU) Project VITAL and EU Project DREAM and JTI Clean Sky, Snecma has already started the detailed assessment of two main general architectures selected to go toward ACARE 2020 goals. In parallel, through the LEAP-X engine, Snecma will carry on building up technological bricks applicable on any of these three architectures in order to be ready to answer any future environmental requirements.

1 Design Strategy regarding environment

1.1 Environmental Goals

The Advisory Council for Aeronautical Research in Europe (ACARE) identified the research needs for the aeronautics industry for 2020, as described in the Strategic Research Agenda (SRA), published in October 2002. Concerning the environment, ACARE fixed, amongst others, the following objectives for 2020 for the overall air transport system, including the engine, the aircraft and operations:

- Reducing fuel consumption and CO_2 emissions by 50%
- Reducing perceived external noise by 50% with 10 EPNdB reduction per operation
- Reducing NOx by 80%

Furthermore, since these objectives have been defined the commercial and political pressure to reduce fuel consumption and CO_2 has increased considerably.

Indeed, the peaks lately reached by Fuel Burn share in usual market driven operating-cost calculations show that fuel price volatility is a major concern that must be taken into account for the design of the next generation aircraft and engines. Even on short-range aircraft where high maintenance costs usually counteract slight benefits in Fuel Burn, trend may change in the future.

On CO_2 side, the debate over climate change has led to the general acceptance that global warming is caused by the amount of carbon emitted into the atmosphere, of which the aviation industry contributes about 2-3%. As a result, at the commonly agreed traffic growth rate of 3-5% a year, the aviation industry faces a moral and economical (taxes, fuel…) challenge that could become the main requirement in the future. Technological improvements will be necessary to address this challenge. Besides, with the introduction of the aviation in the EU Emission Trading Scheme (ETS), CO_2 emissions for new aircraft are even more critical.

1.2 Engine design past trends

Since commercial aviation beginning, engines design has been the result of a fine compromise between weight, drag and Specific Fuel Consumption (SFC) resulting in Fuel Burn, speed, costs, noise, emissions and reliability while safety has always been mandatory. Improving thermal and propulsive efficiencies are the two paths to decrease SFC but have collateral negative effects on other parameters.

During the last fourty years, the common trend in turbofan design has been to improve these two parameters by raising components efficiency and temperatures for the first one and above all by increasing the By-Pass Ratio (BPR) for the last one. This trend has been amplified in the past decade by the more and more stringent requirements in terms of noise emissions.

Indeed, fan noise and jet noise are the two largest contributors to engine noise. The trend to increase BPR has had a strong impact on jet noise reduction through decreased jet velocity and has also benefited fan noise through a reduced fan tip speed. Consequently, engine manufacturers have started to propose turbofans for short range aircraft with BPR going up to values around 10.

Fig. 1 illustrates the evolution of the Fuel Consumption during the past 40 years.

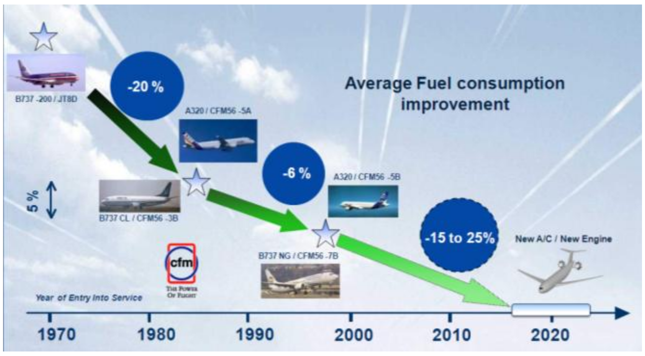

Fig. 1. Fuel Consumption Trend over years

1.3 Design Strategy for the future

With current technologies, the increase in BPR has reached its limit in terms of Fuel Burn on mission. Although a higher BPR offers a clear reduction in SFC, it also leads to a significant increase of engine weight as well as nacelle and installation drags. Above an optimum BPR value, the penalties brought about by weight and drag offset the benefits provided by higher BPR.

The challenge that is proposed today to engine manufacturers is to find technology solutions that will enable the use of higher BPR architectures without inducing Fuel Burn penalties.

In this frame, Snecma is currently developing in parallel three engine architectures answering ACARE 2020 objectives and recent global warming concerns in different ways.

The LEAP-X engine is a high confidence Advanced TurboFan for early Entry Into Service (EIS) minimizing life cycle cost (Fuel Burn, environment and maintenance costs). It relies on the CFM56 experience and the introduction of proven innovative technologies such as new metallic and composite materials, improved 3D aerodynamics…

Then, two more radically innovative engine architectures have been identified to enhance environmental performances in terms of noise and CO_2 emissions:

- A new fan concept, Low speed Counter-rotating Turbofan (CRTF) that aims at reducing noise levels and fuel burn without the need to significantly increase the nacelle diameter.

- Open rotors architectures, which are well known as the best concepts for SFC and Fuel Burn but with installation constraints and noise emission challenges.

2 LEAP-X

2.1 Concept Target and main properties

Timed for a target service entry of 2015-2017, this architecture is aiming at producing an engine with up to 16% lower Fuel Burn than current available engines, similar maintenance costs as current CFM56, up to 15 EPNdB lower cumulative margin versus ICAO chapter 4 and 50-60% NOx Margin versus CAEP6.

This concept is the most robust architecture against fuel price without compromising reliability. It relies on a strong heritage of long range engines and short/medium range CFM56 type engines. At current EIS target, the LEAP-X engine is already close to ACARE 2020 requirements.

The LEAP-X will have a bypass ratio of 10:1, which will enable the performance enhancements through its propulsive efficiency and a High Pressure Compressor (HPC) pressure ratio in the range of doubling the current 11:1 CFM56 HPC pressure ratio.

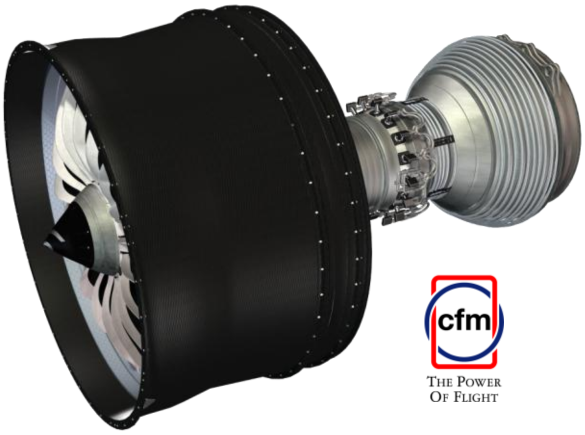

Fig. 2. LEAP-X Engine

2.2 Advanced technologies

Even though the global architecture is similar to CFM56 engines, this concept is a highly innovative Turbofan that includes a remarkable amount of advanced technologies: amongst others, a 3D woven Resin Transfer-Molded (RTM) composite fan blade set, that greatly reduces weight and allows increased BPR without any weight penalty, a 3D woven RTM composite fan case, next-generation 3D aerodynamically designed HP compressor and turbine, advanced low-pressure turbine with Titanium Aluminide blades, lean burner low emissions TAPS II combustor…

Fig. 3 hereunder shows the time scale of different advanced technologies developed by Snecma for the LEAP-X engine.

Fig. 3. Weight reduction & Aerodynamic improvement

3 CRTF

3.1 Concept Target

The main objectives are to bring, at same BPR and technological level, an additional noise and Fuel Burn benefit.

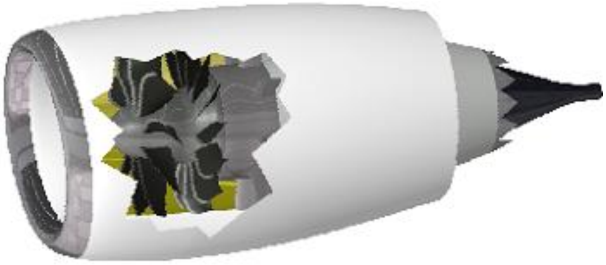

Fig. 4. CRTF Engine

3.2 Concept principles

The aim of this concept is to reduce the fan tip speed without a reduction gearbox that induces losses in efficiency and reliability. This solution consists of two counter-rotating fan stages, mounted on counter-rotating shafts linked to a low-pressure turbine with counter-rotating blade rows.

Fig. 5 describes the macro-design of the CRTF with the HP Core rotor in green, the Low Pressure (LP) front fan and turbine rotor in blue and the LP rear fan and turbine rotor in red.

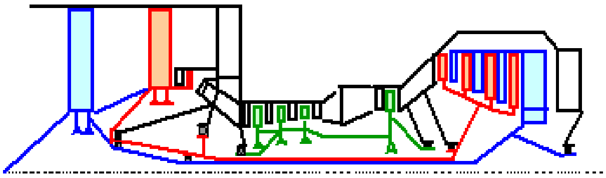

Fig. 5. CRTF Architecture scheme

Replacing the conventional fan by a dual stage counter-rotating fan is a good solution to reduce the diameter constraint: indeed, overall secondary pressure ratio can be kept at a rather high value (~ 1,4 to 1,6), which enables having a reduced fan diameter. This overall secondary pressure ratio is then split between two low pressure rotors whose performance can be achieved at reduced rotational speed, hence achieving noise reduction and efficiency optimization target.

3.3 VITAL Studies

The Counter-Rotating TurboFan (CRTF) is developed and tested by Snecma within the European Union FP6 VITAL Project.

The main components investigated in VITAL in order to prove the feasibility and level of general performance of the concept are:

- Low speed counter rotating fan that tackles low Fuel Burn through efficiency and lightweight components, and low noise through low fan tip speed
- New low speed low-pressure compressor (booster) concepts and technologies for weight and size reduction
- New lightweight structures using new materials as well as innovative structural design and manufacturing techniques
- New Metallic Matrix Composite (MMC) shaft technologies enabling the high torque needed by the new fan concepts through the development of prototypes that will be tested
- New counter rotating slow low-pressure turbine (LPT) technologies for weight and noise reduction
- Optimal installation of Very High BPR (VHBR) engines related to nozzle, nacelle, thrust reverser and positioning to optimise weight, noise and fuel burn reductions.

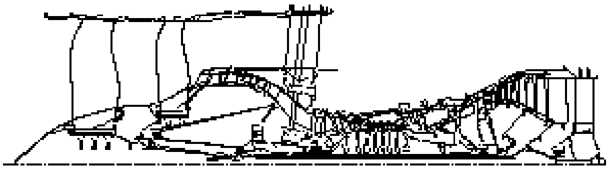

Fig. 6. CRTF X-section

This radically innovative concept intends to reduce noise levels and fuel burn without the need to significantly increase the BPR and new lightweight technologies are studied to compensate the weight penalties induced by the added components.

These technologies are currently tested and validated with aero-acoustic Wind-Tunnel Tests

(WTT) and mechanical rig tests in order to bring their Technology Readiness Level (TRL) to a level ranging between 3 (proof-of-concept) and 5 (Module and/or subsystem validation in relevant environment).

3.4 VITAL Achievements

In 2005, Snecma made a first design called CRTF1 with the support of CIAM and DLR for aerodynamic, acoustic and mechanical evaluation.

In 2006, CIAM and Comoti have manufactured the mock up hardware of the CRTF1 module and adaptation parts for the test bench.

In parallel, a large concept study project was launched between DLR, CIAM, Cenaero, with ONERA and UPMC support, in order to study CRTF1 design and potential improvement using the state of the art of the advanced aerodynamic and acoustic design tools.

In 2007, three tasks have been managed in parallel with CRTF1 mock up tests started in C3-A anechoic chamber at CIAM, Russia, SRF final detail studies and manufacturing performed by COMOTI, Romania, and design of 2 optimized Counter Fan (CRTF2a led by CIAM and CRTF2b led by DLR) that exploit the conclusions of the advanced studies performed in 2006.

In 2008, the tests on the CRTF1 configuration have been finalized in CIAM while the CRTF2a rotor was manufactured by SALIUT and the SRF rotor was manufactured by CIAM.

In 2009, the tests were performed in CIAM on the SRF configuration, giving the reference for acoustic performance. The CRTF2a was also tested in CIAM and the detailed aeromechanical conception of the CRTF2b was performed by DLR.

The first acoustic results are not as good as expected, due to the interaction noise between the two fans, but the aerodynamic performances are satisfying with a 2 points efficiency benefit.

In 2010 the CRTF2b fans will be manufactured by Aircraft Philipp and the stators will be manufactured by COMOTI. The test on this configuration is planned on October.

4 Open Rotors

4.1 Concept Target

The major aim of this architecture is to answer the recent and growing pressure on aviation industry to tackle faster and deeper the global warming issue. Therefore, the main target is to reduce fuel consumption and CO_2 emissions up to 22-28% versus 2000 engines. This step will primarily be achieved thanks to the very high propulsive efficiency reached compared to an equivalent Turbofan with a BPR around 40 and to the weight and drag benefit of duct non-existence.

However, this breakthrough requires a specific optimisation of the noise performances to tackle the absence of duct liners and the pylon interaction. To reach a better noise level, an aircraft dedicated installation becomes necessary to take benefit from shielding effects.

At the same time, the level of reliability have to be at the same level as current engines, which is a challenge as this architecture is noticeably more complex than current ones.

Aircraft manufacturers plan the introduction of such a concept between 2020 and 2025.

4.2 Concept principles

The engine global efficiency can be defined using the following quantities:

- Thermal efficiency (η_{th}) is defined as the ratio of the output power given by the engine to the airflow, to the input energy amount given by the fuel combustion.

- Propulsive efficiency (η_{pr}) is defined as the ratio of the power given to the aircraft (thrust work) to the power given by the engine to the airflow.

- Thermopropulsive efficiency (η_{thp}) is defined as the ratio of the power given to the aircraft (thrust work), to the input energy amount given by the fuel combustion:

$$\eta_{thp} = \eta_{th} \times \eta_{pr}$$

Thermal efficiency is addressed through component efficiency and temperature.
Propulsive efficiency is mainly addressed through BPR. Indeed, the following figure illustrates the links between first Fan Pressure Ratio (FPR) and BPR and then between BPR and propulsive efficiency.

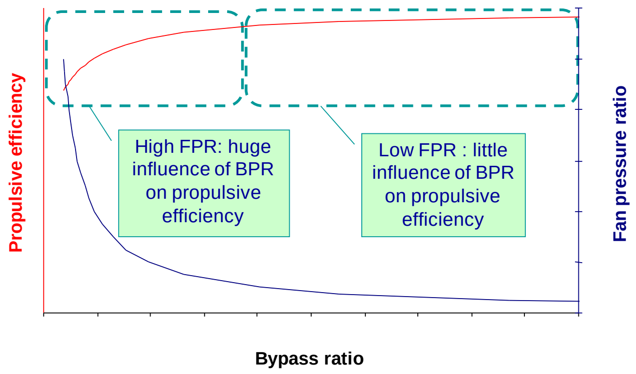

Fig. 7. Propulsive efficiency and FPR function of BPR

Therefore, reaching high propulsive efficiency requires high BPR but BPR in the range of 30-40 can't be reached with a turbofan as theoretical propulsive efficiency would be far outweighed by nacelle drag and weight. Therefore this kind of BPR is associated, even for far term future, to unducted concepts like turboprops or open rotors.

Subsequently, key gains of open rotors versus turboprops are induced by the improved propulsive efficiency and the limited fan diameter.

In fact, an important source of losses for single propeller is the rotational energy wasted in the swirl at the propeller exhaust, since only the axial component of the resulting effort on the blade is a real contributor to the thrust, as shown in the following figure.

Fig. 8. Single propeller swirl

Besides, for a single propeller, the only solution to deal with high power levels while maintaining an acceptable efficiency is to increase the propeller diameter, which turns out to be a problem for engine integration on aircraft. Sharing the global propeller load between two propellers helps improving the efficiency, while global propeller diameter remains acceptable for aircraft integration.

Fig. 9 hereafter presents a comparison between propulsive efficiency of turbofans, turboprops and open rotors. It shows how Open Rotors give the possibility to cruise at a high Mach number, through improved efficiency:

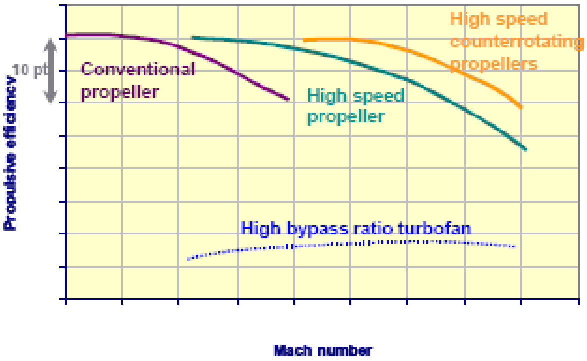

Fig. 9. Relative propulsive efficiency

4.3 Engine design challenges

Open rotor engines design raises major challenges that need to be addressed and resolved:

- Improve propeller efficiency to reach ambitious CO_2 reduction targeted. To comply with this requirement, new 3D Reynolds Averaged Navier Stokes (RANS) CFD codes were calibrated on 80's results and optimised for this kind of application and finally coupled with optimisation software. Then, WTT at low and high speed will validate predictions.

- Reduce both community and cabin noise even if the unducted configuration represents a challenge. To achieve this goal, new 3D RANS CFD unsteady codes were calibrated on 80's results and optimised for this kind of application and finally coupled with optimisation software. Then, WTT at low and high speed will validate predictions.

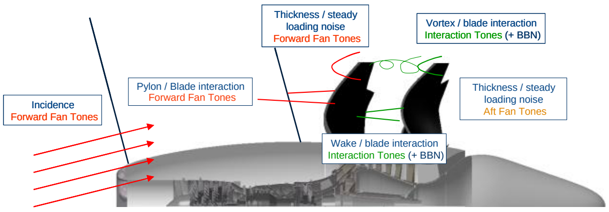

Fig. 10. Propeller Acoustic sources

- Answer certification questions over the type of engine certification to be applied, Turboprop or Turbofan. Moreover, engine burst issues are to be tackled at Aircraft level depending on the engine architecture and aircraft installation configuration.

- Make Pitch change mechanism as simple and reliable as possible to obtain an overall engine reliability at least equivalent to current engines. For this purpose, multiple brainstorming and advanced-concepts are performed and assessed. This component will then be rig tested.

- If required by the concept, design a Power Gear Box (PGB) as reliable and efficient as possible. PGB has certain advantages, which need to be less than compensated by commonly known drawbacks that are reliability, durability, safety, cost increase, efficiency losses and thermal management.

- To prove engine operability at low power with a more electric configuration. Indeed, core size resulting from open rotor concepts design is low compared to equivalent Turbofan while Aircraft power demands remain the same.

4.4 Engine design options

Then, once the general assumptions have been set up, a large number of degree of freedom is still available to reach the best configuration, with for instance concepts with or without a Power Gear Box, the propellers located in front (Puller) or at the rear (Pusher) of the Gas generator… Consequently, each relevant concept has been studied in details to compel the pros and cons in order to build a first rating of the different configurations regarding the different criteria of selection. These studies will carry on and be completed during the course of DREAM and JTI CLEAN SKY to select the best-optimised configuration.

Fig. 11 describes the macro-design of the Counter-Rotating (CR) Direct Drive Pusher design, as an example of open rotor architecture, with the HP Core rotor in green, the Intermediate Pressure (IP) core rotor in yellow, the free turbine front propeller rotor in orange and the free turbine rear propeller rotor in pink.

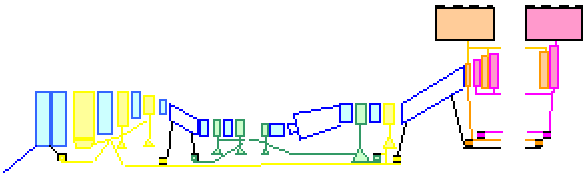

Fig. 11. CR DD Pusher Architecture Scheme

Fig. 12 hereunder shows four concepts designed and assessed by Snecma, amongst others: a CR Direct Drive Pusher, a CR Pusher with a PGB, a CR Puller with a PGB and a Single propeller Puller with a PGB.

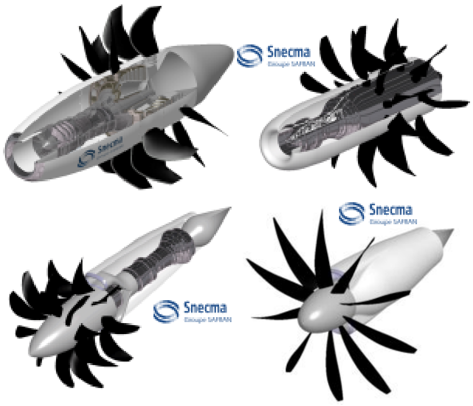

Fig. 12. Snecma Open rotor Concepts

The CR Direct Drive Pusher concept has been studied first, as characteristics of this concept are well known thanks to 80's GE engine studies called GE36 in which Snecma owned a 35% share. The noise margin used for Pushers includes pylon blowing at Take-Off to decrease the interaction between wakes of the pylon and the front propeller.

The Geared Pusher Counter Rotating Open Rotor concept has also been studied in details and is slightly lighter thanks to an important reduction in number of power turbine stages and slightly less noisy thanks to a reduction in propeller rotational speed. The utilization of a PGB on such a concept seems acceptable by the market considering the breakthrough in terms of fuel burn provided by the ultra high BPR.

The CR Puller with a PGB concept is slightly heavier and noisier with a supplementary deficit on performance because of the inlet efficiency penalty.

4.5 Aircraft integration

In addition to key Open Rotor issues and concepts relative rating, the Aircraft integration is a subject by itself as the installation of an Open Rotor engine will need a close and strong work with Airframers to develop an optimised configuration for both performance and acoustic while solving certification issues.

The challenge of installing an Open rotor on a short-range aircraft is primarily linked to the important size of the propellers and to the no-duct configuration.

Snecma has started to study different aircraft configurations and Fig. 13 shows four Aircraft installation configurations, amongst others: a CR Pusher installed on sides of rear fuselage, a CR Puller installed on sides of rear fuselage, a CR Puller under high-wing and a CR Pusher over wing for acoustic shielding.

Fig. 13. Four Aircraft integration concepts

Each configuration has pros and cons that need to be assessed regarding the following main criteria: Community noise and Cabin noise, Aircraft Certification aspects, installed engine performance and overall aircraft performance and Aircraft balance.

Preliminary main conclusions of the Aircraft installation evaluation are the following:

- Configurations with acoustic shielding are promising but include challenges on certification aspects and on installation drag
- Configurations under or over wing should bring some benefits regarding certification aspects and family extension but seem to provide more cabin noise, and therefore need solutions as cabin passive treatment (inducing weight) and/or active devices.

4.6 European projects

The Open Rotor concept is currently developed and tested by Snecma within the European Union FP7 DREAM Project and CLEANSKY project.

DREAM is a three year project started in 2008 and composed of 44 partners from 13 countries. It will deliver integrated technologies at TRL 4-6 by studying and testing these advanced technologies mainly devoted to fuel consumption / CO_2 reduction, pollution reduction, whilst retaining acceptable noise levels.

In 2009, aero-acoustic WTT campaigns have been performed at Russia’s Central Aerohydrodynamic Institute (TsAGI) at low and high speed (up to Mach 0,85) to verify both efficiency and noise levels of propellers. One configuration has been tested in 2009 and three more are planned in 2010.

The technologies developed in this project will constitute candidates ready to be used for the CLEAN SKY engine platform, which is the direct global exploitation path for DREAM. In CLEAN SKY, a seven year project started in 2008, Snecma will develop a counter-rotating open rotor engine for the Smart Fixed Wing Aircraft demonstrator.

5 Conclusions

Following ACARE 2020 objectives that tackle Fuel Burn, noise and emissions, and the recent growing sense of urgency regarding climate change and especially aviation impact, engines designed for future Short-range aircraft that will replace A320s and B737s will have to fulfil requirements presented in Fig. 14, which correspond to existing criteria with a greatly amplified influence of noise and emissions.

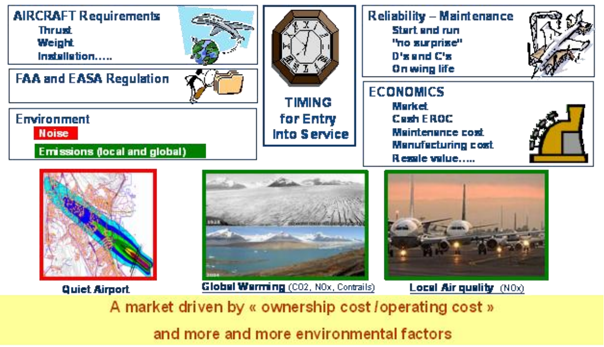

Fig. 14. Engine design criteria

To answer this challenge, Snecma has considered three different architectures that reach different targets as presented in following Fig. 15.

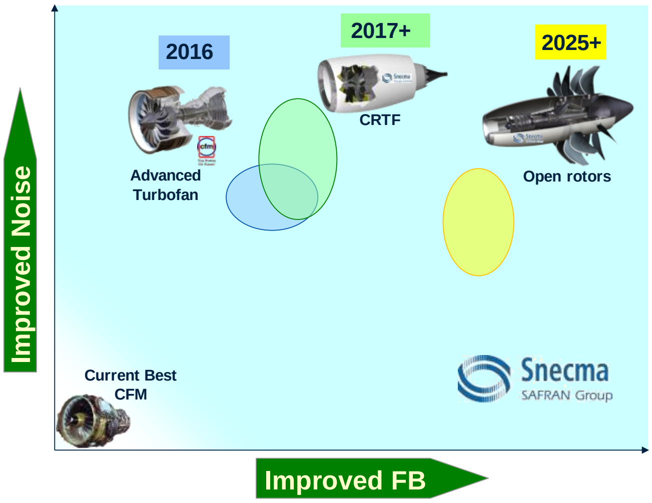

Fig. 15. Architectures Fuel burn versus Noise

The first architecture is a high confidence Advanced TurboFan for early Entry Into Service (EIS) minimizing life cycle cost (Fuel Burn, environment and maintenance costs). It relies on the CFM56 experience and the introduction of proven innovative technologies. At 2015-2017 EIS, the LEAP-X engine is already close to ACARE 2020 requirements.

Then, the CRTF is a concept that intends to improve noise and Fuel burn through decreased fan tip speed.

Finally, the Open rotor architecture is a concept that delivers a breakthrough on Fuel Burn and CO_2 emissions thanks to a great propulsive efficiency and no duct penalties. Nevertheless, some key challenges remain to be answered: Community and cabin noise, certification and reliability.

With this multiple concepts strategy, Snecma has defined a plan to develop several architectures relevant for the Short-range aircraft replacement coming in the next decade.

Indeed, particularly through current EU Project VITAL, DREAM and JTI CLEAN SKY, Snecma has already started the detailed assessment of two main general architectures selected to go toward ACARE 2020 goals. In parallel, through the LEAP-X engine, Snecma will carry on building up technological bricks applicable on any of these three architectures.

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