FUTURE OF AIRCRAFT PROPULSION

ISABE 2017
Manchester, UK

Dr Jerome BONINI
VP Research & Technologies
Safran – An international high-tech group

**AEROSPACE**

Safran Nacelles
Safran Ceramics
Safran Aero Boosters
Safran Electrical & Power
Safran Transmission Systems

**Safran Aircraft Engines**

Safran Landing Systems
Safran Helicopter Engines

**DEFENSE**

Safran Electronics & Defense

* ArianeGroup is a 50/50 joint company between Safran and Airbus Group

**€15.8 bn**
Sales in 2016

**Near 58,000**
Employees

**30 countries**
Global presence
# Safran Aircraft Engines – Military and commercial aircraft propulsion

<table>
<thead>
<tr>
<th>Aircraft</th>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpha Jet Larzac®</td>
<td>Atar 14kN</td>
<td>14kN</td>
<td>31,020 lb</td>
</tr>
<tr>
<td>Mirage F1</td>
<td>M88 75kN</td>
<td>75kN</td>
<td>16,538 lb</td>
</tr>
<tr>
<td>Rafale</td>
<td>M53 95kN</td>
<td>95kN</td>
<td>21,068 lb</td>
</tr>
<tr>
<td>Mirage 2000</td>
<td>M53 95kN</td>
<td>95kN</td>
<td>21,068 lb</td>
</tr>
<tr>
<td>A400M</td>
<td>TP400 (3) 11k00 shp</td>
<td>11k00 shp</td>
<td>12,480 lb</td>
</tr>
</tbody>
</table>

**PowerJet** (50/50 Safran Aircraft Engines-NPO Saturn)

**CFM International** (50/50 Safran Aircraft Engines – GE )

**EPI** (ITP, MTU, Rolls-Royce, Snecma)

**In cooperation with GE**

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**Falcon 5X**

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SaM146(1)</td>
<td>9500 to 12500</td>
<td>20,946 to 27,556</td>
</tr>
<tr>
<td>SaM146(1)</td>
<td>15400 to 17800</td>
<td>33,988 to 39,683</td>
</tr>
</tbody>
</table>

**SSJ100**

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-7B(2)</td>
<td>19500 to 21600</td>
<td>43,095 to 47,682</td>
</tr>
<tr>
<td>CFM56-5B(2)</td>
<td>21500 to 23300</td>
<td>47,962 to 51,562</td>
</tr>
</tbody>
</table>

**A320**

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEAP-1A(2)</td>
<td>21500 to 23300</td>
<td>47,962 to 51,562</td>
</tr>
<tr>
<td>LEAP-1B(2)</td>
<td>21500 to 23300</td>
<td>47,962 to 51,562</td>
</tr>
<tr>
<td>LEAP-1C(2)</td>
<td>21500 to 23300</td>
<td>47,962 to 51,562</td>
</tr>
</tbody>
</table>

**A320neo**

<table>
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<tr>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5C(2)</td>
<td>31200 to 34000</td>
<td>69,600 to 75,460</td>
</tr>
<tr>
<td>CFM56-5C(2)</td>
<td>52500 to 57800</td>
<td>116,320 to 128,200</td>
</tr>
<tr>
<td>GP7200(4)</td>
<td>85000 to 103000</td>
<td>188,500 to 230,320</td>
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</tbody>
</table>

**A380**

<table>
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<tr>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
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</thead>
<tbody>
<tr>
<td>GP7200(4)</td>
<td>70000 to 85000</td>
<td>154,000 to 188,500</td>
</tr>
<tr>
<td>GP7200(4)</td>
<td>93700 to 115300</td>
<td>206,860 to 255,800</td>
</tr>
</tbody>
</table>

**777**

<table>
<thead>
<tr>
<th>Engine</th>
<th>Thrust (kN)</th>
<th>Thrust (lb)</th>
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</thead>
<tbody>
<tr>
<td>GE90(4)</td>
<td>93700 to 115300</td>
<td>206,860 to 255,800</td>
</tr>
<tr>
<td>GE90(4)</td>
<td>~100000</td>
<td>220,460</td>
</tr>
</tbody>
</table>

**777X**

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<th>Engine</th>
<th>Thrust (kN)</th>
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<tr>
<td>GE9X(4)</td>
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(2) CFM International (50/50 Safran Aircraft Engines – GE )

(3) EPI (ITP, MTU, Rolls-Royce, Snecma)

(4) In cooperation with GE
CFM56® – The world's best selling commercial engine

CFM56-5B
CFM56-7B

A320ceo
737 NG

More than 31,000 CFM56 engines delivered worldwide

Every 2 sec. a CFM56-powered aircraft takes off somewhere in the world

3 million travelers use CFM56-powered aircraft daily
LEAP® – Combining the best technologies from Safran Aircraft Engines and GE

**LEAP-1A**
Entry into service: August 2016

**LEAP-1B**
Entry into service: May 2017

**LEAP-1C**
Entry into service: 2018

More than 14,000 engines ordered to date

-15% lower fuel consumption*

-15% reduction in CO₂ emissions*

* Compared with previous-generation engines
LEAP® – Combining the best technologies from Safran Aircraft Engines and GE

Direct-drive
High bypass ratio

Composites
Fan blades & case

Debris rejection system
Airfoils protection against erosion

High-pressure compressor
10 stages
22:1 compression ratio

Low-pressure turbine
4th gen 3-D aero

Titanium-Alumin TIAI lightweight LPT Blades

Combustor
Lean-burn and low emissions

3D Woven Resin Transfer Molding (RTM) technology
→ 500 kg of mass reduction
→ Improved reliability to shocks
30 years of experience

Accessory gearbox (AGB) on fan module

TAPS 2
Twin Annular Premixing Swirler
→ Reduce particles and NOx emission with 50% margin to OACI CAEO/6 regulation

4th gen 3-D aero
Advanced cooling
CMC materials
Active clearance control
The factory of the future is transforming the way manufacturing is done

Additive manufacturing

2008 : Rapid Prototyping Tool
2013 : Components for Development and Production Engines
2025 : 20% Reduction in Engine Parts Count

Set up of a specific organization relying on:

○ Close to business Integrated Design and Production Unit
○ Generic skills and materials

Advanced assembly lines
Robotized inspection methods
Augmented and Virtual Reality Tools
Say hello to the future

The LEAP engine has 19% less fuel. While they may look deceptively simple from the outside, this revolutionary design, growing using additive manufacturing, is keeping human NOx emissions in line. We're re-shaping the future from the inside out.

Another first. CFM gives you more to believe in.
Go to cfmaeroengines.com

Can we go further?

NOx the socks off emissions

Not only does our LEAP engine reduce NOx emissions by 50%*, but it also delivers a 25% gain in CAFM*II regulations. Innovation with an eye to the future.

Another first: CFM gives you more to believe in.
Go to cfmaeroengines.com

Can we extract more?

No one extracts more

The LEAP engine is naturally innovative. Punctuated with advanced materials and leading-edge aerodynamics to quench your thirst for superior performance and a very healthy bottom line. Pure CFM, it's a great way to start your day.
Go to cfmaeroengines.com
Ensure sustainable growth of air traffic

End 2034 Fleet Evolution by Aircraft Type (36+ pax)

End 2034 Fleet Size 40 390

End 2034 Fleet Growth x 1,9

Turboprop 1672
Regional Jet 3037
Short Medium Range 3556
Long Range 3675

World fleet to double by 2034
more than 40 000 new aircraft
54% in SMR category
Environmental impact

Condensation trails

Global Surface Temperature: 1880–1920 Base Period

Total CO₂ Emission per km² in 09/2010
Environmental engagement

ACARE

75% ↓ CO2
90% ↓ Nox
65% ↓ Noise
0 emissions taxi

2050 vs. 2000

Aeronautic is the 1st industry engaged to reduce impact on environment

- 75% ↓ CO₂
- 90% ↓ Nox
- 65% ↓ Noise
- 0 emissions taxi

2005 2010 2020 2030 2040 2050

Million tonnes of CO₂

No action
Technology
Operations
Infrastructure
Additional technologies and biofuels
Carbon-neutral growth
-50% by 2050

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Fuel forecast

An inevitable decline in fuel world reserves ... but still an acceptable cost

Biofuel successfully tested on CFM56 engine in 2007 and in operation on Air France A321 in 2015 ... but need for industrialization of production and overall CO2 impact estimation
Full Electrical propulsion: a distant option for large aircraft

Even @1000 Wh/kg, an All-Electric Airbus A320 would require 170 t of batteries
Our way to future propulsion: working on the three layers of efficiency

1. Improve powerplant efficiency (thermopropulsive efficiency)
2. Improve powerplant system integration into airframe
3. Improve energy management (propulsive and non-propulsive) on the whole mission
Improving powerplant efficiency

Thermopropulsive efficiency

\[ \eta_{thp} = \frac{PW_{aircraft}}{PW_{fuel}} \]

Thermal efficiency

\[ \eta_t = 1 - \frac{1}{OPR \left(1 + \frac{1}{2} M_e^2 \right)} \]

Propulsive efficiency

\[ \eta_p = \frac{2}{1 + \frac{V_{out}}{V_{in}}} \]

Core efficiency

Transfer efficiency

HP parts

LP parts

Overall (thermopropulsive) efficiency

(Carnot efficiency ~ 0.87)

Core efficiency (-)

Propulsive x Transfer efficiency (-)

Challenges on core technology

Improving propulsive efficiency

Challenge on integration

Overall (thermopropulsive) efficiency

Turboprop
Regional turbofan
Business jets
Short medium range turbofan/open rotor
Long range turbofan

0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

0.3 0.4 0.5 0.6 0.7 0.8 0.9

0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9

Improving powerplant efficiency

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Improving powerplant efficiency

Increase OPR

- OPR 45 → 50
  Thermal efficiency ~ + 1 pt

Overall thrust level required

- HPC exit temperature (T3)
- HPT Entry Temperature (T41)

Core size

Reduce core size → impact on component efficiencies:
- HPC feasibility, HPT cooling system integration, HP materials...

Overall Pressure Ratio

Overall Pressure Ratio

Thermal efficiency (ideal engine)

Overall Pressure Ratio

- 0.5
- 0.55
- 0.6
- 0.65
- 0.7
- 0.75

Thermal efficiency, at constant technology

Theoretical evolution, at constant technology

Increase engine temperatures
→ Need for higher cooling amount
→ Partially offsets / annihilates SFC improvement

SFC

Cooling

Resulting SFC

SFC without cooling

SFC

Operation

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Improving powerplant efficiency

Ceramic Matrix Composites ... beyond metals

20%
Higher thermal capability

1/3
the weight

New, higher-performance metallic alloys, such as titanium aluminide (TiAl), which are lighter and resist very high temperatures

New-generation single-crystal materials and advanced cooling techniques to improve engine core performance

Blades and Nozzle
Decrease FPR → Increase BPR

Contributors to losses (excluding core)

\[ FN = W \times \Delta V \]

- Constant
- Decrease to improve propulsive efficiency
- Increase massflow!
Improving powerplant efficiency

Decrease FPR → Increase BPR

Contributors to losses (*excluding core*)

- Propulsive efficiency losses
- Bypass duct losses (pressure loss, scrubbing drag...)
- LPT losses (isentropic efficiency)
- Fan losses (isentropic efficiency)

SFC decrease is very slow beyond BPR 20

BPR 16 → BPR 30 : -4% SFC

Fan bypass duct losses show a major and increasing contribution
Improving powerplant efficiency

Decrease FPR → Increase BPR

Installation effects linked to drag and weight are key contributors to losses for ultra high bypass ratio configurations.
Improving powerplant efficiency

UHPE : UHBR concept demonstrator

- Advanced high-load high speed booster
- Next gen aero high speed CMC LPT
- Low weight – low drag nacelle
- BPR > 15
- Reduction gearbox
- Next gen composite fan blades
- 3D RTM woven fan blade

2025
Improving powerplant efficiency

Improving powerplant system integration into airframe

2025

Installation challenge

- Pylon & nacelle geometry and wing shape optimization

- Additional challenge on integration constraints
- Drag, weight for ducted configurations

- Impact on landing systems length and weight
- Snowball effect on aircraft structures
Let's go further…

Contributors to losses (excluding core)

- Fuel burn optimum
- UHBR configuration
- Weight
- External drag
- FPR / Propulsive efficiency
- Bypass duct losses (pressure loss, scrubbing drag …)
- LPT losses (isentropic efficiency)
- Fan or Propeller losses (isentropic efficiency)

Improving powerplant efficiency

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Improving powerplant efficiency

Let’s go further…

Contributors to losses (excluding core)

- Fuel burn optimum
- UHBR configuration
- Weight (made equivalent to thermopropulsive efficiency)
- External drag
- SEC optimum (ducted configuration)
- FPR / propulsive efficiency
- Bypass duct losses (pressure loss, scrubbing drag ...)
- LPT losses (isentropic efficiency)
- Fan or Propeller losses (isentropic efficiency)

BPR

% useful propulsive power lost

- SFC optimum
-ducted configuration

Improving powerplant efficiency

Let’s go further…

Contributors to losses (excluding core)
Improving powerplant efficiency

Let's go further…

Contributors to losses (*excluding core*)

- Fuel burn optimum (ducted configuration)
- Weight (made equivalent to thermopropulsive efficiency)
- External drag
- FPR / propulsive efficiency
- Bypass duct losses (pressure loss, scrubbing drag …)
- LPT losses (isentropic efficiency)
- Fan or Propeller losses (isentropic efficiency)

Remove casings and Switch from ducted turbofan to unducted open rotor

- Weight reduction equivalent to BPR 20 ducted engine
- Mechanical transmission similar to geared turbofan
- Lower nacelle drag
- No bypass duct loss
- Propeller with lower efficiency than ducted fan
Improving powerplant efficiency

**OpenRotor concept**: only engine architecture allowing a **30% reduction of fuel consumption** and **CO2 emissions** compared to the CFM56 engine

- Counter rotating propeller
- 3D RTM composite blades
- Propeller pitch control system
- Lightweight front and rear rotating frame
- Power Turbine
- Power Gear Box
- Gas generator
- Optimized nacelle
Improving powerplant efficiency

OpenRotor concept: Safran demonstration plan

**Mechanics tests**

Preliminary tests of the specific control system with a pitch and its efficiency, in terms of mechanical integration, has been demonstrated on a full scale mock-up.

**Aero-acoustics tests**

Wind-tunnel tests done

Same emitted noise as the LEAP engine (compliance with Chapter 14 requirements, including a margin).

**Ground test demo**

Full-Scale Open Rotor to test Propulsion System Integration

Test plan in progress

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Improving powerplant efficiency

Improving powerplant system integration into airframe

Aircraft Integration challenge

Open Rotor
~170”

GE90-115B
128”

CFM56-7B
61”

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Improving powerplant system integration into airframe

A way to decrease fan inlet speed: Boundary Layer Ingestion

**Additional advantages:**
- Reduced external drag (part of the nacelle is not a wetted surface)
- Reduced pylon weight

**Challenges:**
- Strong fan distortion
- Water ingestion dripping from fuselage to engine
- New boundaries between airframer and propulsion manufacturer

2030

Lower inlet speed: improved thermopropulsive efficiency

Lower absolute exhaust speed $\rightarrow$ lower jet noise

Fuselage wake compensated by engine thrust

(courtesy: Bauhaus Luftfahrt)

**Fuselage boundary layer**
- Propulsion system jet flow field
- Jet momentum equivalent for ideal fuselage wake compensation
- Jet momentum equivalent for aircraft residual thrust requirement
Improving powerplant efficiency

Improving powerplant system integration into airframe

Improving energy management (propulsive and non propulsive)

Various energy sources management and coupling, as well as distribution of functions over the whole airframe, can bring significant energy savings.

Use of electricity → Hybridization

A single powerplant makes it all ...

<table>
<thead>
<tr>
<th></th>
<th>Propulsive power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off &lt; 5 %</td>
<td></td>
</tr>
<tr>
<td>Climb</td>
<td></td>
</tr>
<tr>
<td>Cruise &gt; 50 %</td>
<td></td>
</tr>
</tbody>
</table>

Use of electricity → Hybridization
A stepped approach to electrical propulsion

Improving powerplant efficiency

Improving powerplant system integration into airframe

Improving energy management (propulsive and non-propulsive)

High power energy transmission feasibility

Distributed propulsion, electric drive

2030
Hybrid propulsion

2035
Hybrid distributed propulsion

2035

10% electrical propulsion, coupled with BLI

100% electrical propulsion
100% thermal energy

100% electrical propulsion
0% CO2 emissions

2040+

Energy storage density

10% electrical Propulsion for T/O climb and Idle

20-50% electrical propulsion, coupled with BLI

2030

Hybrid propulsion

Energy storage density
Improving powerplant efficiency

Improving powerplant system integration into airframe

Improving energy management (propulsive and non-propulsive)

Aircraft Engines
Nacelles
Power Units
Electrical & Power
Landing Systems
Transmission Systems

Auxiliary Power Unit (APU)

Electric engine and nacelle architecture

Electrical power distribution and management

Landing extraction and generation

Green taxiing® - electric drive for aircraft on the ground

2 to 4% Fuel burn reduction
One configuration studied…

Improving powerplant efficiency
Improving powerplant system integration into airframe
Improving energy management (propulsive and non propulsive)

- Electronic Distributed Propulsion
- Fuel cell
- Green taxi
- BLI Gas generator
- TURBO-GENERATOR POWER PACK
- SMART E-MOTOR
- E-PROULSOR
- POWER MODULE PACKAGING SiC COMPONENTS
- HIGH-DENSITY POWER ELECTRONICS
- INTEGRATION TECHNOLOGY SMART ACTUATOR
- HIGH POWER DENSITY ELECTRICAL MACHINE

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… On numerous others configurations explored
Conclusion

Higher inter-dependence between airframe and propulsive system

Clever combination of inter-dependent improvements:
- engine efficiency
- aircraft integration
- aircraft energy management
WE BRING THE FUTURE TO YOUR DOORSTEP.