Aircraft and Engine Innovations & Designs to Decarbonize Commercial Aviation

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INTRODUCTION

Aviation contributes to approximately 2.1% of global CO_2 emissions[1]. By comparison, this is around the same as the servers and transmission cables of the internet (not including the computers and tablets accessing the internet). But if nothing is done, this share will grow as traffic continues to increase substantially in coming years and other industries decarbonize. Aviation have therefore decided to embark on a path leading to Net Zero emissions by 2050 and all its stakeholders (airlines, manufacturers, airports) have committed to it.

In this context, ENAC Alumni together with the French Ministry of Transport sent a call toward the community of ENAC graduates for a commitment to a more sustainable aviation. This manifesto, signed by some 500 ENAC graduates, stated:

- The acknowledgement of scientific studies about the global warming resulting from greenhouse gas (GHG) emissions.
- The need for aerospace as a vanguard industry to actively contribute to a complete decarbonization, even if its contribution is very small.

Total human CO_2*
2019
43.1Gt

Total human GHG*
2018
53Gt

Total aviation CO_2
2019
0,915Gt

This led to the creation of several workgroups aiming at documenting the various levers for decarbonization. The current document synthesizes the levers resulting from the workgroup called "**Innovation in Aircraft Design and Propulsion Systems**".

Based on scientific and industrial publications, this document identifies the various levers that should enable decarbonization of commercial aviation from the aircraft and engine side. It does not cover topics related to operating the aircraft or improving the infrastructure. It stays on the design and manufacturing side, where every percentage of efficiency gain requires a massive amount of research and testing.

It is organized around two main chapters:

- Efficiency Improvement Technologies;
- New Technologies Based on Alternative Fuels;

and each section summarizes the current state of development of a specific technology, based on publicly available sources. These technologies are not mutually exclusive and to the contrary, could often be combined to ultimately achieve a fast and complete decarbonization.

This document should help provide a view on the most promising technologies and prioritize them. Some will be used as necessary transitions until new radical technologies can be implemented. Others, very promising but long term, must continue to be researched now as it will take years before they can reach the required levels of safety and efficiency.

The next step for our work at ENAC Alumni is probably to determine and prioritize which of these technologies our industry needs to focus on and when, and from that, define a realistic technological roadmap for aviation to reach Net Zero in 2050.

Every step in the right direction counts, and there is no way back for aviation but to ultimately design and manufacture non-GHG-emitting aircraft and engines.

[1] Source: ATAG Waypoint 2050.
* CO_2 emissions includes CO_2 from forestry. GHG: including CO2-eq from other GHG emissions covered by UNFCCC. Global Carbon Project December Global Carbon Budget 2019

EXECUTIVE SUMMARY

Decarbonizing aviation is certainly not a small feat, as it is probably one of the most difficult industries to decarbonize.

In this review of technical and scientific articles, the Workgroup identified a vast range of technical levers aiming at reducing or replacing kerosene in future aircraft. However, there will be no immediate miracle, as none of these levers can alone replace soon the use of kerosene. In addition, many will come with penalties on the payload or the available range.

Some of these technologies can apply tomorrow, some will take time to develop, others will be dead ends. The beauty with physics is that it is independent from opinions, so research must continue!

What is almost certain considering the various axes of development is that the future aviation will require, for the first time, a mix of energies. The choice of energy will apply differently for short-range or long-range, small aircraft or large aircraft. This choice of energy will be adapted to the targeted aircraft mission.

It is also clear that smaller aircraft will benefit first from radical changes such as the use of alternative fuels. Simply because it will be easier to implement than on larger aircraft and because their missions are often less constraining.

It will take time to totally decarbonize aviation, so some hybrid solutions will certainly be key as intermediate steps to reach some more long-term goals. But in every case, a total life-cycle approach will need to be conducted. It would be counter-productive to totally decarbonize aviation at the expense of some other industry. And at the same time, the move by other industries toward new fuels will certainly play a major role in facilitating the introduction and use of those new fuels in aviation. Aviation is global so global economies of such new fuels must exist before aviation can benefit from them. This implies that finding technological solutions at aircraft or engine level will not be sufficient, and the infrastructure behind must follow, be it for fuel production or airport infrastructure.

It is also evident that aircraft ad engine manufacturers cannot achieve this on their own. The rest of the industry must back those developments through workgroups and governmental support. Funding the research will be critical, and the good news for investors is that aviation thrives. Traffic will continue to grow as the global role of aviation expands. Any investment in key R&D technologies will certainly convert into major intellectual property assets, providing great returns.

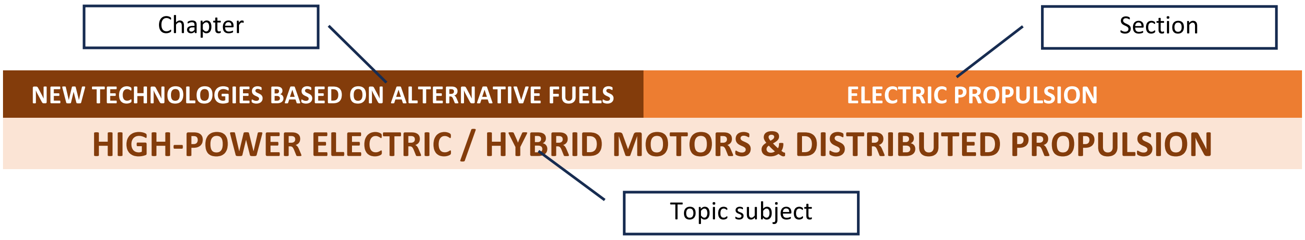
Finally, as such a document allows to start prioritizing the use of those technologies, careful attention must be made in not disregarding too fast some of them by exclusively concentrating of easy low-hanging fruits. Numbers are on thing, perceptions another. Despite its relatively small carbon footprint, aviation is already perceived as a major contributor and unfairly blamed for it. This societal perception should not be discarded when it comes to relying on certain technologies. Because it is easier, simply reducing carbon emissions or using SAFs on the long term may not be sufficient. The societal pressure may one day force aviation to stop emitting CO_2, even if the total life-cycle is carbon neutral.

To that extent, research must continue on most fronts, for short-term AND long-term solutions. The good news is that the whole industry is committed, and all players and stakeholders are active on the subject. These are exciting times and our industry has probably not seen such a level of innovative thinking since the beginning of the jet era, or even maybe since the beginning of aviation itself.

HOW TO READ THIS DOCUMENT

This document is split into two parts: **Efficiency Improvement Technologies** (with green headers and footers) and **New Technologies Based on Alternative Fuels** (with orange headers and footers)

Each individual topic has been treated almost independently and is identified in the page headers as follows:



Furthermore, each one of these topics is presented along the following structure such that a detailed assessment can be carried out :

- DESCRIPTION
  - Concept
  - Maturity
  - Environmental Impacts
- SUITABILITY
  - Constraints
  - Certification Aspects
  - Aircraft Segments Concerned
- APPLICABILITY
  - Market Acceptance and Barriers
  - Costs
  - Implications on Aircraft Designs
- REFERENCE DOCUMENTS

Note finally that reference documents and sources are specific to each section and indicated in brackets (such as [12]).

The ENAC Alumni logo on each page header brings back to the Table of Content.

ABBREVIATIONS & ACRONYMS

A4E	AIRLINES FOR EUROPE
AAFC	ALKALINE AMMONIA FUEL CELLS
ACE	ADAPTIVE CYCLE ENGINE
AFC	ALKALINE FUEL CELL
AFP	AUTOMATED DRY FIBER PLACEMENT
ALT	ATTACHMENT LINE TRANSITION
AMFC	ALKALINE MEMBRANE-BASED FUEL CELLS
APPU	AUXILIARY PROPULSION AND POWER UNIT
APU	AUXILIARY POWER UNIT
AR	ASPECT RATIO
ASK	AVAILABLE SEAT KILOMETER
ATAG	AIR TRANSPORT ACTION GROUP
ATSM	AERONAUTICAL TELECOMMUNICATION STANDARDS
BGA	BUSINESS AND GENERAL AVIATION
BL	BOUNDARY LAYER
BLI	BOUNDARY LAYER INGESTION
BPR	BY-PASS RATIO
BWB	BLENDED-WING BODY
CAEP	COMMITTEE ON AVIATION ENVIRONMENTAL
CFI	CROSS FLOW INSTABILITIES
CFRP	CARBON FIBER REINFORCED PLASTICS
CI	COST INDEX
CO	CARBON MONOXIDE
CO_2	CARBON DIOXIDE
CO_3^2	CARBONATE
CROR	CONTRA-ROTATING OPEN ROTOR
CS	CERTIFICATION SPECIFICATIONS
DBD	DIELECTRIC BARRIER DISCHARGE
DC	DIRECT CURRENT
DEP	DISTRIBUTED ELECTRIC PROPULSION
DLR	GERMAN AEROSPACE CENTER
EASA	EUROPEAN UNION AVIATION SAFETY AGENCY
EGTS	ELECTRIC GREEN TAXIING SYSTEMS
EIS	ENTRY INTO SERVICE
EMC	ELECTRO-MAGNETIC COMPATIBILITY
EMI	ELECTRO-MAGNETIC INTERFERENCES
ENAC	ECOLE NATIONALE DE L'AVIATION CIVILE
ESM	ELECTRICALLY EXCITED SYNCHRONOUS MACHINE
EU	EUROPEAN UNION
EUROCAE	EUROPEAN ORGANISATION FOR CIVIL AVIATION
EWIS	ELECTRICAL WIRING INTERCONNECTION SYSTEM
FAA	FEDERAL AVIATION ADMINISTRATION
FADEPC	FULL AUTHORITY DIGITAL ENGINE AND PROPELLER
FAR	FEDERAL AVIATION REGULATION
FC	FUEL CELL
FMS	FLIGHT MANAGEMENT SYSTEMS
FPR	FAN PRESSURE RATIO
GE	GENERAL ELECTRIC
GHG	GREENHOUSE GAS
GTF	GEARED TURBOFAN
H_2	HYDROGEN
H_2O	DIHYDROGEN OXIDE (WATER)
H_2S	HYDROGEN SULFIDE
HBPR	HIGH BY-PASS RATIO
HLFC	HYBRID LAMINAR FLOW CONTROL
HP	HIGH PRESSURE
HT	HIGH TEMPERATURE
IADP	INNOVATIVE AIRCRAFT DEMONSTRATION PLATFORMS
IATA	INTERNATIONAL AIR TRANSPORT ASSOCIATION
ICAO	INTERNATIONAL CIVIL AVIATION ORGANIZATION
IM	CAGE INDUCTION MACHINE
KW	KILOWATT
LFC	LAMINAR FLOW CONTROL
LH_2	LIQUID HYDROGEN
LHSS	LIQUID HYDROGEN STORAGE SYSTEMS
LHV	LOWER HEAT VALUE
LNH_3	LIQUID AMMONIA
LP	LOW PRESSURE
LPA	LARGE PASSENGER AIRCRAFT
LSP	LIGHTNING STRIKE PROTECTION
LT	LOW TEMPERATURE
M	MACH
MCFC	MOLTEN CARBONATE FUEL CELL
MEA	MORE ELECTRIC AIRCRAFT
MFC	MICROBIAL AMMONIA FUEL CELLS
MJ	MEGAJOULE
MLG	MAIN LANDING GEAR
MSN	MANUFACTURER SERIAL NUMBER
MW	MEGAWATT
MTOW	MAXIMUM TAKE-OFF WEIGHT
NASA	NATIONAL AERONAUTICS AND SPACE
NH_3	AMMONIA
NLF	NATURAL LAMINAR FLOW
NLG	NOSE LANDING GEAR
NOx	NITROGEN OXIDES
O^2	OXYGEN
OEM	ORIGINAL EQUIMENT MANUFACTURER
OH-	HYDROXIDE
OLED	ORGANIC LIGHT-EMITTING DIODE
OPR	OVERALL PRESSURE RATIO
PAFC	PHOSPHORIC ACID FUEL CELL
PEMFC	PROTON EXCHANGE MEMBRANE FUEL CELL
PGB	POWER GEAR BOX
PMSM	PERMANENT MAGNET SYNCHRONOUS MACHINE
PV	PHOTOVOLTAIC
RTM	RESIN TRANSFER MOLDING
SAE	STANDARD AEROSPACE EQUIPMENT
SAF	SUSTAINABLE AVIATION FUELS
SBW	STRUT-BRACED WING
SFC	SPECIFIC FUEL CONSUMPTION
SHP	SHAFT HORSE POWER
SOFC	SOLID OXIDE FUEL CELL
SOx	SULFUR DIOXIDE
SRM	SWITCHED RELUCTANCE MACHINE
STC	SUPPLEMENTAL TYPE CERTIFICATION
STOL	SHORT TAKE-OFF AND LANDING
TAS	TRUE AIR SPEED
TAW	TUBE-AND-WING
TBW	TRUSS-BRACED WING
TIT	TURBINE INLET TEMPERATURE
TRL	TECHNOLOGY READINESS LEVEL
TSI	TOLLMIEN SCHLICHTING INSTABILITIES
UHBPR	ULTRA-HIGH BY-PASS RATIO
VCE	VARIABLE CYCLE ENGINE
VTOL	VERTICAL TAKE-OFF AND LANDING

EFFICIENCY IMPROVEMENT TECHNOLOGIES

This Chapter reviews the key decarbonization technologies aiming at reducing fuel burn (and therefore CO_2 emissions) through aircraft weight reduction, aerodynamics improvements or engine efficiency increase.

These improvements would apply to existing kerosene-powered aircraft but could, in many cases, be implemented in complement to a change of fuel.

These technologies are often referred as continuous improvement.

DESCRIPTION

Concept

In aircraft design, weight plays against fuel consumption. Weight per passenger has constantly reduced over the last twenty years, mainly due to the implementation of composite materials instead of metallic structures.

Composite materials can drastically cut down the weight of an aircraft, which leads to better performance and improved fuel efficiency. Fiber-reinforced matrix systems are often stronger than traditional aluminum previously used in most aircraft, and provide a smoother, more aerodynamic surface, which also improves performance and fuel efficiency. Composite materials do not corrode as easily as other structure types, and they do not crack from fatigue the way aluminum does. Instead, they flex, which makes them last longer than metal, leading to lower overall maintenance costs.

There are many types of composites used in aviation:

Glass fiber or fiberglass is manufactured with varying physical characteristics and cost. It is also available in varying weights from less than 30 g/m2 to over 350 g/m2.

Carbon fiber or CFRP (Carbon Fiber Reinforced Polymer) is a very strong reinforcement material. It combines low weight, high strength, and high stiffness. CFRP is used in critical aircraft primary structure areas such as spars, wings, fuselage, etc.

Kevlar, a product of the DuPont Corporation, is a high-strength material, very effective in applications requiring resistance to abrasion and puncture. However, its use in primary structures is often limited by the relatively low compression strength and difficulty in handling.

Figure 1 - Electroimpact machines lay down thin strips of carbon fiber infused with epoxy resin (Source: The Ledger)

The **resin component** in a composite helps maintain fiber orientation, transfer loads, and protect the structure against the environment. While a composite's stiffness, flexibility, and tensile strength are more affected by the reinforcement material, its heat resistance, shear and compressive strength are more dependent on the resin system. Three types of resin systems are available: polyesters, vinyl esters, and epoxies.

Technological advances are on multiple fronts, including resin transfer molding (RTM), thermoplastic composites, hybrid metal-composite structures and 3D-printed parts in metal, plastic and composites.

The **RTM technology** is already flying (A330/A340/A350 spoilers, A350 passenger doors, etc.) and has now been advanced to high-pressure RTM (HP-RTM), achieving a 30% cost reduction. RTM is a closed-mold process for manufacturing high performance composite components. The next step for RTM is through VaRTM (vacuum-assisted RTM) which significantly reduces defects and tooling costs.

Thermoplastic composites are getting a lot of attention these days as the aerospace industry increasingly uses them to replace various metallic and thermoset composite parts. By definition, thermoplastics are plastic polymer materials that become pliable or moldable at a certain elevated temperature and solidifies upon cooling. Thanks to their higher impact resistance, unique processing possibilities, lightweight properties, strength and environmental advantages, thermoplastic composites can help reduce fuel costs while increasing environmental sustainability.

Unlike traditional thermoset composites – which require lengthy production times and large, costly autoclave ovens – thermoplastics are produced out-of-autoclave and can be stamp-formed in their required shape in just a few minutes. Whereas the forming of thermoset composites is based on solidification through chemical reactions, thermoplastics are formed through physical principles based on remelting and no chemical reactions are needed during its forming processes. As a matter of fact, thermoplastics can be heat-molded and reshaped again and again, making them recyclable and environmentally friendly.

These new highly engineered materials, and their methods of manufacture, have the potential to:

- Reduce manufacturing cycle time by 80 percent;
- Decrease the weight of aerospace structures by as much as 50 percent compared to metallic solutions and up to 20 percent when compared to thermoset solutions;
- Incorporate sustainability improvements resulting in fewer emissions, a fully recyclable product and lower landfill output.

The production method revolves around the following: Automated Dry Fiber Placement (AFP), using heated tools supported by robots and cobots, out-of-autoclave (OoA) processes for thermosets and thermoplastic AFP including in situ consolidation, processes digitalization (Digital Infusion Centre), etc.

Finally, new production methods (**hybrid-metal** or **3D printing**) should allow more complex parts to be produced in composite, further reducing the aircraft weight.

Maturity

Full scale prototypes of structural elements have been produced with out-of-autoclave processing and tested for quality. A thermoplastic fuselage is also becoming a reality thanks to welded thermoplastic stringers. TRL 6 could be achieved before 2025 for some major structures (fuselage sections, wings).

Environmental Impacts

In general, every kilogram of weight reduction can save up to 3.5 liters of kerosene per year. Composites can therefore lead to several percentages of fuel reduction at aircraft level.

For thermoplastics more specifically, the following advantages could be obtained:

- Up to 20% lighter compared to thermoset composite solutions.
- Manufacturing cycle time reduced by 80%.
- Up to 15% reduction in energy usage.
- At least 25% reduction in scrap.

SUITABILITY

Constraints

The greatest disadvantage of composite materials is that they do not break easily, which means that it is difficult to identify if the aircraft structure has been damaged. Because shears and dents are more visible on aluminum, it makes it easier to detect a need for repair. Composite materials are also more difficult and more expensive to repair than metals, although it can be argued that the long-term savings of using a more resilient material off-set this additional cost.

Another issue is that the resin used in composite materials weakens at temperatures around 65°C, making it necessary to take extra precautions against fires. Burning composite materials can release toxic fumes and micro-particles into the air, both of which are serious health risks. At temperatures above 150°C, structural failure can occur.

Production of composites in the aerospace industry is not new and is well understood. However, a few limitations or constraints exist today:

- Highly specialized manufacturing processes are required
- High-quality mold needed
- Manufacturing and material costs make composites more expensive to produce
- Some large complex parts cannot be manufactured with molds or lay-up and will require new manufacturing techniques, such as using 3D printers

Large carbon-fiber parts, such as a fuselage section or a wing box, are made up of many components such as skin panels, stringers, frames, and bonds. They include numerous openings for doors and windows, local reinforcements for point loads and stress concentrations, and varying skin thicknesses that are tailored to resist aerodynamic loading, internal

pressure, or bird strikes. The assembly of composite components requires accurate control of laminate thickness, ply orientation, layer boundaries, and drop-off placement so that each part meets stringent producibility requirements.
Composite parts are laminates made by manual or automated deposition of tens or hundreds of layers (plies or tapes) of various shapes and fiber orientations.
Most composite manufacturing methods can lead to fiber deformation, which impacts production quality and part performance. For example, hand layup of prepregs or dry materials inside a curved mold is prone to deformation such as ply wrinkling, warping, and bridging, which may affect the strength, stiffness, and fatigue resistance of the final product. Fiber placement or tape laying on large fuselage panels or wing skins can produce uncontrolled deviation of fibers. Forming processes used for spars and stringers may generate stresses and strains inside and between ply layers.

Finally, composite materials can be expensive, although it can be argued that the high initial costs are typically offset by the long-term cost savings.

Certification Aspects

Composite materials do not break easily, meaning that it is difficult to tell if the inner structure of the material has been damaged. This explains why specific certification and compliance measures have been introduced by regulators. Because composites have been used in aviation for decades and their use gradually increased, the certification requirements have constantly evolved and are now well known and established.

Aircraft Segments Concerned

All aircraft segments have applications of composites.

APPLICABILITY

Market Acceptance and Barriers

Repairability is the main issue with composites. Over time, several techniques have been developed for various types of damages on composite structures. Repair cost and downtime remain high and repairs generally reduce the overall longevity of composite structures.

Recycling is also a growing issue. Typically, composites are composed of layers of materials and resins that are heated and compressed, making it very difficult to separate these elements during the recycling process. Equally, a large amount of material is wasted during the manufacturing phase.
It is estimated that by 2035, unless recycling increases across the aviation industry, an astonishing 23,500 tons per year of end-of-life carbon fiber will accumulate if left unrecycled.
Research programs are looking at recycling technologies for carbon fiber composites and have developed new processes for fiber recovery from these materials:

- Normally, when carbon fiber is recycled, it is broken down into individual filaments which are short and entangled with each other, making them difficult to reuse in the same way they would have been originally as they are no longer aligned.
- New fiber realignment processes are studied which can take the fluffy recycled fibers and process them into a form that still contains the high fiber content needed for high performance components.

Costs

The material cost for composites is 50 to 60% higher than aluminum on a per kg, per square-meter basis. Machine costs for composites is 35 to 45% higher, resulting in total manufacturing costs being 50 to 60% higher than aluminum, by taking into consideration other factors such as waste, time to produce, required manpower, etc.

Over time, this cost difference is expected to reduce with new manufacturing techniques and more composite applications across the industry.

Implications on Aircraft Designs

On planes built from highly conductive aluminum, even the worst-case 200,000-ampere lightning jolt can be quickly conducted away. But for aircraft made with less-conductive carbon fiber composites or nonconductive fiberglass, lightning strike protection (LSP) is critical.
LSP must provide a continuous conductive path of low resistance over the entire aircraft exterior, with additional protection in zones where lightnings are most likely to attach. To create a conductive path, metal in the composite aircraft's outer skin — typically a fine, lightweight mesh or foil embedded in a surfacing film, or a wire embedded within the outer laminate ply — is placed in contact with metal bonding strips or other structures that connect the outer conductive surface to a metallic ground plane, such as an engine or metal conduit in the fuselage.

There are no other specific implications on aircraft design beyond those evoked above and the normal considerations for a lighter material in domains such as the required stiffness of certain structures, adjustment of the center of gravity, extreme loads, etc.

DESCRIPTION

Concept

The objective is to design a fuselage without windows thus without the necessary window frames to compensate for the discontinuities and structural weaknesses created by the cutouts where the glass is installed. Cabin windows could be replaced by OLED screens. The aim is to save the weight of the reinforcements surrounding the cutouts i.e. the window frames and the transparencies themselves which are assumed to be heavier than a sheet of aluminum alloy of the same size. Instead, the fuselage design would remain undisturbed.

Nevertheless, these weight savings will be counterbalanced by the weight of the OLED screens if installed on the sidewall panels and associated cameras and video systems used to offer an outside view to passengers.

Another weight reduction potential would come from a reduction in drag due to the removal of discontinuities on the fuselage exterior surface.

Research paper [1] browses a general overview of a windowless cabin including weight saving calculations.

Figure 2 - Illustrative Concept from Rosen Aviation

Maturity

The technology exists both for the structure and the flexible OLED screens, so solutions are ready to be applied on aircraft. Demonstrators have already been displayed. The only question that remains is the acceptability by the flying public.

Environmental Impacts

The environmental impacts are based on fuel savings resulting from weight saving as described in reference [1]:

- *Weight savings are evaluated by comparing the central fuselage section for the windowless and the common configuration of an A320 …/… According to available data, the weight saving is around 600kg, about 30%.*
- *Considering the environmental aspect, the CO_2 emission is about 2.5 kg per liter of fuel that means that the windowless concept would produce 570 kg less CO_2 than a traditional configuration. It represents just one percent*

point of the total emission, but when multiplied by the number of aircraft in service, it could spare four million kilos of CO_2 each day: the equivalent of one million cars.

SUITABILITY

Constraints

No particular technical issues are anticipated, technical solutions exist.

Operational constraints may result from the passenger perception of a windowless cabin and the feeling of claustrophobia [1]. About 80% of passengers would not travel in a windowless plane, because they would expect to feel claustrophobic. Hence the necessity to introduce screens reflecting the outside environment. Then, the question of dispatching the aircraft with inoperative cameras or screens before the flight must be considered even if no direct safety effect is identified.

Long-term economic effects seem positive considering fuel savings.

Production constraints or limitations are not anticipated.

Certification Aspects

Basically, certification (CS25) does not require the installation of windows in the passenger cabin. The only required windows (viewing means) are inside or near the emergency exits in order to check the outside conditions before exiting the aircraft in case of emergency.

On the Operation side, airlines require passengers to open the window shades during cabin preparation for take-off and landing. This common airline practice would be to ensure that natural light would shed the cabin in case of emergency.

In some cases, flight crew can ask cabin crews to check through the windows in case of suspected kerosene leakage or engine damage. This is also a known practice that has no corresponding requirement in the regulations.

Despite above comments, one needs to consider that no application for certification of such designs has yet been done. Thus, the authority may reassess the safety benefits of cabin windows at the occasion of such a certification exercise and issue Special Conditions due to the novelty of the design. These Special Conditions may require some compensations to ensure that the main safety benefits of cabin windows can be maintained, such as identification of damages on the wing or engines, fuel leaks, preparation for emergency evacuation, etc.

One consequence might be to consider cameras and screens as safety equipment, leading to their certification at the same level as other critical systems.

Flammability of screen materials will also be a certification topic that may lead to some additional design costs.

Aircraft Segments Concerned

All aircraft categories could be potentially using such approach. Fuel savings will be more significant on larger aircraft. This technology could potentially be first introduced on Private Jets.

APPLICABILITY

Market Acceptance and Barriers

Market acceptance by airlines, airports and passengers may come from the large potential for new applications using the screens (advertisement, practical info, e-commerce, …) However, at this stage, most passengers do not seem to support windowless cabins.

Certification and public acceptance will be one of the key pre-requisites for the technology to be implemented, but it must be examined in light of above positive points.

Costs

No input

Implications on Aircraft Designs

We can anticipate a simplification of the fuselage design with elimination of cutouts and associated reinforcements. The effect on the primary structure is seen as positive.

On the contrary, we can anticipate a complexification of cabin systems with the introduction of numerous screens and cameras of latest technology, and materials compliant with the requirements of interior compartments.

REFERENCE DOCUMENTS

[1] Aircraft Preliminary Design: a windowless concept
Sara Bagassi, Francesca Lucchi, Franco Persiani University of Bologna – DIN, Industrial Engineering Department Via Fontanelle 40, 47121, Forlì, Italy

AIRCRAFT ELECTRIFICATION

DESCRIPTION

Concept

Beyond its propulsive function, an aircraft is equipped with additional systems needed for the safety, maneuverability, communications, navigation and more. Most of those systems require power and energy to execute their functions and are currently taking their power source from the aircraft engines through some distribution and power management systems. This is the case for the flight control systems (cockpit controls, actuators controls, avionics calculators and bus, etc.), the environmental control systems (temperature, pressure and oxygen control in cockpit and cabin), the de-icing/anti-icing systems, the landing gear systems, etc.

Those systems are complex, mainly electric, hydraulic or pneumatic and they represent an additional on-board weight (estimated at approx. 14% of the empty weight for a single-aisle aircraft). They may also induce an additional drag effect depending on their embodiment in the aircraft, which could deteriorate aircraft performance.

In the end, it is identified their power consumption for a full flight cycle may represent up to 5-10% of the total aircraft fuel consumption.

Therefore, improving aircraft systems is mainly centered on their electrification (i.e. embedding electrical power source and replacing pneumatic or hydraulic systems by electrical system) in order to decrease their impact on fuel consumption, as well as their on-board weight by simplifying their physical integration.

Maturity

As of today, only a partial electrification of aircraft systems has been developed and embodied on commercial aircraft, while it is commonly accepted that the aviation industry progressively tends towards “More Electric Aircraft (MEA)”.

Some examples exist today with, for instance, the replacement of one of the hydraulic distribution systems on the Airbus A380 by an electrical one, leading to a weight reduction of about 500kg.

Another important step in the most recent aircraft development is the Boeing 787 which became the first “bleed-less” commercial aircraft, meaning that the former bleed system, which decreased engine performance, was replaced by two electrical compressors. The same aircraft also introduced more electrification systems for the anti-icing or the engine start.

However, the total removal of hydraulic or pneumatic systems remains an important challenge because of their current good performance levels and ease to execute certain primary functions.

In any case, the main objectives of the aircraft electrification remain to reduce the total weight, to facilitate systems integration and ease the maintenance in-service.

But without some technological breakthrough, most studies conclude that it will not be possible to achieve more than a 20-30% consumption reduction per pax.km by 2035, in comparison with current aircraft technologies and configurations.

Environmental Impacts

The aircraft electrification leads to reduce the empty weight of the aircraft and therefore reduce the fuel consumption – and the related pollutant emissions (CO_2, NOx…) – over a flight cycle.

In addition, electrical systems are considered more environment friendly, as they allow to remove some harmful fluids such as Skydrol, used in some hydraulic systems.

They are also easier to maintain in-service and necessitate fewer additive fluids which reduce their environmental impact.

Some global studies indicates that fully electrified aircraft, where only the propulsion functions are ensured by the engines, may result in a weight reduction of about 10% and a fuel reduction per pax.km of around 9%.

SUITABILITY

Constraints

While aircraft electrification allows to better control the correct quantity of power required to make systems function, it also leads to a significant increase of the required embedded electrical sources in the aircraft. This may lead to an important increase of the electrical system weight which needs to be balanced against the savings made by eliminating other systems. As an example, Boeing estimates at only 3% the overall benefit of the 787 electrification on the fuel consumption.

On the other hand, the increase in power levels to be handled by the new power management systems will require the development of reliable and mature high-power components as well as the development of new complex integrated routings and systems now called Electrical Wiring Interconnection System (EWIS).

Also, in order to better control currents and weight, some studies suggest to increase the network voltage to 500-1000V. This would create other challenges due to electric arcs and partial discharge phenomenon, impacting the systems reliability and increasing fire risks.

In addition, the full aircraft electrification leads to significantly increase the total number of electrical components. This densification could trigger issues with the electro-magnetic interferences and compatibility (EMI-EMC) requiring to ensure they will not adversely affect each other as well as the other aircraft systems.

Finally, one of the major issues remains the thermal management. Indeed, the electrical systems need to be locally monitored and cooled down and those issues may require to introduce additional mitigation measures such as new air entry points, which could themselves lead to other issues such as an increased drag.

Certification Aspects

The aircraft electrification raises concerns on the safety assessment of the failure conditions for each dedicated systems and each interconnected system. Redundancy remains an important key factor in the reliability of aircraft systems and the continuity of the primary functions in case of failure. It may become challenging to ensure the independence of all electrical systems and that a failure of one of them would not affect the others.

This is also the case when addressing the increased fire risk. The difficult management of the thermal control and the significant increase in EWIS integration lead to envisage the probability of an in-flight fire, without necessarily the possibility of adequate detection and firefighting means.

It is to be expected that a stronger maintenance oversight will be required to ensure and prevent fatal damages to the systems.

Another challenge is to demonstrate of the absence of adverse electromagnetic interferences between all systems and to ensure the integrity of each function and each information transmitted through the aircraft over the flight and over multiple flight cycles, in different environmental conditions.

Aircraft Segments Concerned

While general aviation is already using some state-of-the-art technologies towards full electrification, most benefits of full-electric aircraft would be obtained in the commercial aircraft segment, which requires many complex additional systems relying today on the engine power source.

APPLICABILITY

Market Acceptance and Barriers

No specific market barriers are identified at this stage since these developments concern the aircraft system technology with no impact on the passenger experience.

In addition, such electrification steps aim at easing the aircraft maintenance while reducing fuel consumption. This has an overall positive impact on operations, provided those new electrical systems demonstrate an in-service reliability comparable to today's systems.

Costs

While some retrofits limited to specific individual systems might be technically feasible, these technologies will be developed for the new aircraft generations and will require large development and certification costs, which could offset the operational cost benefits.

Implications on Aircraft Designs

The main challenge for full aircraft electrification revolves around system segregation and redundancy constraints. In addition, it requires a greater interaction with the structural design teams to ensure electrical systems will be designed appropriately to react to forces applied to the aircraft. Identification of new fire risk zones must also be defined.

Finally, 'MEA' technologies are only just beginning and more harmonization and industry standards will have to be deployed to get to much higher level of electrification.

Reference documents

[1] Référentiel ISAE-SUPAERO - Aviation et Climat. Version 1.0. S. Delbecq, J. Fontane, N. Gourdain, H. Mugnier, T. Planès et F. Simatos, 2021.

[2] W. Cao, B. C. Mecrow, G. J. Atkinson, J. W. Bennett, and D. J. Atkinson. Overview of electric motor technologies used for more electric aircraft. IEEE Trans. Ind. Electron., 59(9):3523–3531, 2012.

[3] Investigation on the Selection of Electric PowerSystem Architecture for Future More Electric Aircraft. Jiawei Chen, Member, IEEE, Chengjun Wang, Student Member, IEEE, and Jie Chen, Member, IEEE

[4] Electrical Power Generation in Aircraft: review, challenges and opportunities. V. Madonna, Student Member, IEEE, P. Giangrande, and M. Galea., Member, IEEE

[5] Clean Sky 2 - 2020 Highlights – 2020

[6] ACARE - Strategic Research & Innovation Agenda - 2017

DESCRIPTION

Concept

The objective is to reduce or eliminate the need to run the aircraft engines during ground operations, thus reducing fuel consumption.

Two main solutions can be considered: onboard systems and external systems.

Onboard systems are entirely located in the aircraft and are usually based around the concept of an electrical drive comprising an electric motor, a power converter and an electric energy source. External systems use an external vehicle to tow the aircraft. [1]

Onboard systems generally consist of an electric motor installed on a wheel of either the Nose Landing Gear (NLG) or the Main Landing Gear (MLG). Electric power supply is ensured by the APU, which implies that this system still generates CO_2 emissions but significantly less than engine taxiing (unless APUs become electric). Zero emission solutions are also considered, based on either batteries or fuel cells. Wheeltug® and Safran® have tested their solutions on 737 and A320.

Figure 3 - Wheeltug system

External systems are generally based on a modified towing tractor ("Tug"). Diesel engines on Tugs are gradually replaced by fully electric or hybrid-electric motors. Tugs used for pushback only are not considered here. Some like Taxibot® are partially automated and designed to tow the airplane in all ground operations [2]. Taxibot is steered by the pilot through a tiller as in normal taxiing, which is a significant feature as it partially reinstates aircraft autonomy …/… Such feature is obtained through a unique towbarless NLG interface clamping mechanism mounted on a rotating turret platform …/… Sensors installed onto the platform detect the steering angle of the NLG and steer all wheels of the tow tractor. Braking is operated by the pilot using the braking pedals as for normal taxiing. Nevertheless, Taxibot® operation still requires a driver for pushback and return after the airplane take-off.

Maturity

Taxibot® was certified by EASA for the 737 in 2014 and the A320 in 2017, it is currently operated by Lufthansa Engineering and Operational Services. It also got FAA certification in 2018.

For the on-board systems, Wheeltug® seems the most advanced solution and has already received up to 1000 orders. However, despite an announcement that the FAA accepted the certification plan in 2017, no further information indicates the STC was certified, as expected by end 2021.

On the Safran® side, in July 2018, they were targeting an entry into service by 2021-2022, on an A320neo but Airbus finally rejected the project.

Environmental Impacts

According to aviationbenefits.org, and compared to a typical dual-engine taxiing operation, Electric Green Taxiing Systems (EGTS) would cut CO_2 emissions by 61%, NOx emissions by 51%, unburned hydrocarbons by 62% and CO emissions by 73% during ground operations.

SUITABILITY

Constraints

The effect on in-flight fuel consumption induced by the additional weight often counterbalances the fuel savings realized on the ground.

Techno bricks are available but integration on the aircraft remains the main difficulty, with potential effects on the life limits of the landing gears. Electrical power source and cable routings with high intensity and voltage are also a potential difficulty depending on the retained solution.

Certification Aspects

E-taxiing systems are part of the aircraft definition and will be certified through a change to the aircraft type design, most probably via an STC process. As an aircraft system, onboard systems will have to comply with all applicable CS/FAR 25 requirements, one of the most critical being the safety requirements (25-1309). Consequences of the system malfunctions during the critical flight phases of take-off & landing, will have to be assessed and will determine the Design Assurance Level to be met.

Another aspect to be considered will certainly be the fire risk after MLG or NLG retraction, within the landing gear bay. Fire protection may be required.

High-intensity electric cables routed to the electric motors on the MLG or NLG may create potential shock hazard to maintenance personnel. Specific procedures will have to be developed.

Certification difficulties will be technical and should not constitute a showstopper, but the induced design costs might be detrimental to the project.

Aircraft Segments Concerned

All aircraft segments could benefit from such technologies. However, trade-off analyses must be carried to determine the benefits of the ground fuel savings vs. the extra fuel consumption due to the additional weight carried. For that reason, single-aisles aircraft operating on short distances are primary targets. Widebodies are typically used on long-haul routes which makes the taxi fuel saving marginal compared to the extra fuel consumption during the flight.

APPLICABILITY

Market Acceptance and Barriers

Various technologies are available and acceptance by airlines, airports, passengers is not an issue if significant fuel savings can be achieved. Benefits associated to noise level reduction and emissions on airports must also be considered.

Different solutions of integrating electrical taxiing systems on aircraft have already been explored and tested, and it seems that the most promising is on MLG wheel(s). Anticipated difficulties are linked with the proximity of brakes that generate elevated temperatures during braking sequences and in case of direct drive, the motor must be able to withstand high speed variations during take-off and landing phases. On the other hand, geared systems would involve sophisticated mechanical systems, increasing failure potential.

Costs

No Input

Implications on Aircraft Designs

Main implications of the MLG solution are on the landing gear structure, electric power supply, cables routing and the overall maintenance.

Reference documents

[1] State of the Art of Electric Taxiing Systems
M. Lukic1, A. Hebala1, P. Giangrande1, C. Klumpner1, S. Nuzzo1, G. Chen1,2, C. Gerada1, C. Eastwick1, M. Galea1,2
1 University of Nottingham, Nottingham, United Kingdom
2Univeristy of Nottingham, Ningbo, China

[2] Electric Taxiing Systems
Milos Lukic, Student Member, IEEE, Paolo Giangrande, Member, IEEE, Ahmed Hebala, Stefano Nuzzo, Member, IEEE and Michael Galea, Senior Member, IEEE

DESCRIPTION

Concept

Overview on Turbofans

Before introducing ultra-high-by-pass-ratio and geared turbofans, classical turbofans are presented.

A turbofan engine (Figure 4 [22]) is composed by a primary core (or engine core) operating as a classical gas turbine, but it has a ducted fan that energizes a so-called bypass flow.

The core is composed by compressors stages, located before the combustion chamber, that lead the air ingested at its optimum condition for the combustion of kerosene, by the combustion chamber where kerosene is injected and burnt, and finally by turbines stages and the nozzle where the mixing is expanded and then ejected.

The energy brought to compressors comes from the turbines which retake it from the airflow expanded. This energy is transmitted by rotation movement of shafts connecting both turbines and compressors. Most turbofans have two shafts (or spools) for two groups of compressor-turbine stages named Low Pressure (LP) and High Pressure (HP) stages.

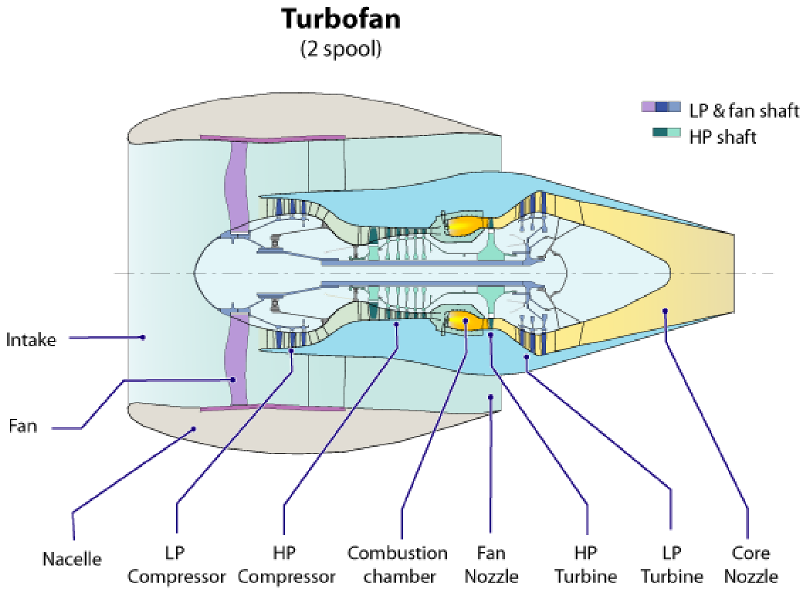


Figure 4 - Turbofan layout

However, note that tree spools turbofans also exist, especially for high thrust application. Rolls Royce is specialized on this engine architecture that we can see on Airbus A330 - A340-500/600 - A350 XWB - A380 - B777 and B787.

The breakthrough of the turbofan is the use of a ducted fan allowing a By-Pass Ratio. The Bypass Ratio (BPR) is defined as the ratio between the bypass and the core mass flow rates: $BPR = \frac{\dot{m}_{fan}}{\dot{m}_{core}}$

In a practical sense, the higher it is, the larger the secondary flow hence the secondary duct area, leading to an engine shorter but with a larger diameter (Figure 5, pictures from [34] on the left, and [29] on the right).

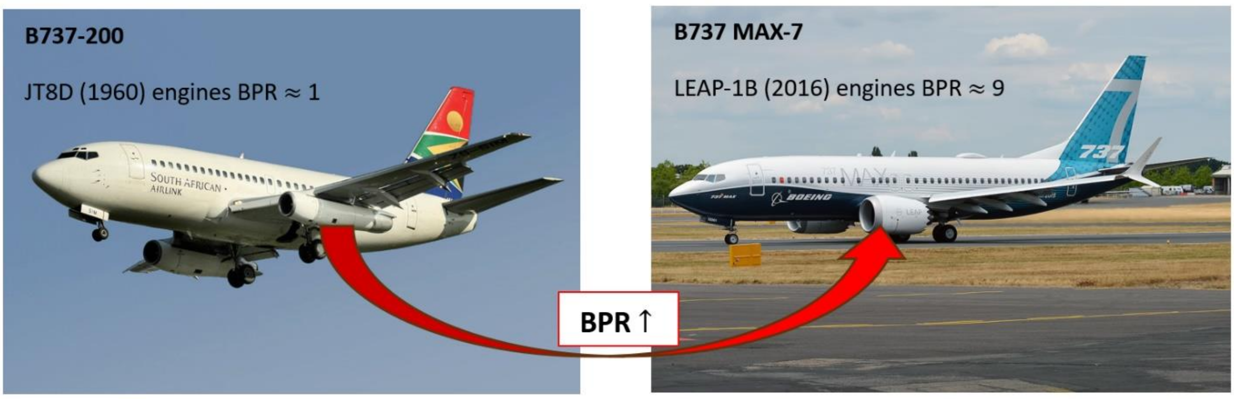


Figure 5 - Comparison of BPR between 737-200 and 737MAX-7 engines

On fighter jet engines, the BPR is very small, less than 1:1 and on classical commercial aircraft turbofan engines approximately 9-12:1. We say that such small BPR engines produce thrust with a small mass flow rate very accelerated, whereas high BPR engines produce thrust with a high mass flow rate slightly accelerated [1,2].

Concerning engine performances, we define two main metrics: the thrust and the specific fuel consumption (SFC).

The thrust is the parameter that defines how powerful an engine is, hence, how heavy the aircraft it powers can be. Assuming a constant mass flow rate for each flow, that the difference between the fuel flow added and the bleeds and leaks are compensating each other, and that there are no pressure forces (both nozzles and inlet are well designed):

$$Thrust = \dot{m}_{fan}\left(V_{fan_{nozzle}} - V_o\right) + \dot{m}_{core}\left(V_{core_{nozzle}} - V_o\right)$$
$$= \dot{m}_{core}V_{core_{nozzle}} - \dot{m}_o V_o + BPR.\dot{m}_{core}V_{fan_{nozzle}} \quad (Eq.1)$$

with:

- $\dot{m}_{fan}$: mass flow rate going through the fan, so the bypass stream (in kg/s)
- $\dot{m}_{fan_{nozzle}}$: mass flow rate going through the fan nozzle (in kg/s)
- $V_{fan_{nozzle}}$: flow speed going through the fan nozzle (in m/s)
- $\dot{m}_{core}$: mass flow rate going through the main core (in kg/s)
- $\dot{m}_{core_{nozzle}}$: mass flow rate going through the main core nozzle (in kg/s)
- $V_{core_{nozzle}}$: flow speed going through the main core nozzle (in m/s)
- $\dot{m}_o$: mass flow rate going through the inlet of the turbofan (in kg/s)
- V_o: flow speed before entry in the turbofan, aircraft velocity in flight (in m/s)

In other words, the thrust of an aero engine depends on the quantity of air ingested times the speed at which it is ejected.

The environmental challenge we face today consists of increasing or at least keeping the same engine performance levels while reducing significantly the fuel consumption. To study the fuel consumption, the specific fuel consumption is used. It is defined as:

$$SFC = \frac{\dot{m}_{fuel_{injected}}}{Thrust} \quad (\text{Eq. }2)$$

The preferred way to express this fuel consumption is to use the engine efficiencies. This allows to see how the consumption evolves with them, and also assess the impact of the flight speed (V_o) and the fuel energy content (FHV):

$$SFC = \frac{V_o}{\eta_{th}\,\eta_{prop}\,FHV} \quad (\text{Eq. }3)$$

with:

- η_{th} : The thermal efficiency of the turbofan, how efficiently chemical energy is converted into kinetic energy. This includes compressors, the combustion chamber, and the turbines behaviors. To increase it, thermodynamic cycle improvements are needed. This can be achieved mainly by an increase in overall pressure ratio (OPR) with accordingly an increase in turbine inlet temperature (TIT) and component performance improvements (compressors, turbines). Note that the combustion efficiencies are today already higher than 99% [2].
- η_{prop} : The propulsive efficiency of the turbofan, how efficiently kinetic energy is converted into propulsion. To increase it, the lowest as possible difference between jet velocities of both stream and free stream is required. This can be achieved by a higher BPR.
- FHV : the fuel heating value in J/kg.

In short, for a given fuel and flight speed, a turbofan engine can reduce its fuel consumption by improving both thermal and propulsive efficiencies. To do so, the main levers are [2]:

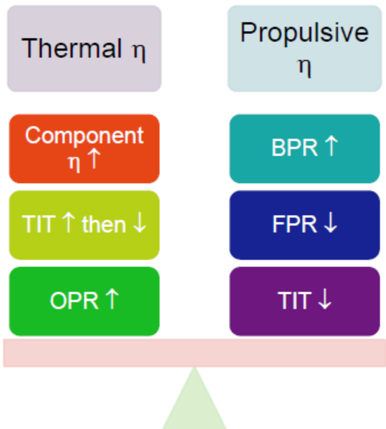


Figure 6 - Levers to increase engine efficiencies (with FPR as the Fan Pressure Ratio)

Both concepts of Ultra-High By-Pass Ratio and Geared Turbofan aim at saving fuel and therefore minimizing the engine environmental impact. Both concepts are related but it has been chosen to create two separate topics to simplify explanations.

Ultra-High By-Pass Ratio (UHBPR) Turbofan

A first idea to reduce SFC consists in increasing the propulsive efficiency of the engine by increasing the BPR. This implies an increase in fan diameter and so the nacelle size, to ingest more airflow. Moreover, until certain limits due to material constraints, very advanced fan blade spanwise chord distribution can be designed such that more air coming from the inlet can be injected in the bypass duct instead of the core.

Since the 1960s, ratios have climbed from an initial value of 2:1, reaching 4:1 to 6:1 in the 1980s (Low/Medium BPR), up to 8:1 in the late 1990s (Large BPR) and 9:1 to 12:1 (High BPR) on today's aircraft [2]. The Figure 7 [2] below shows this evolution.

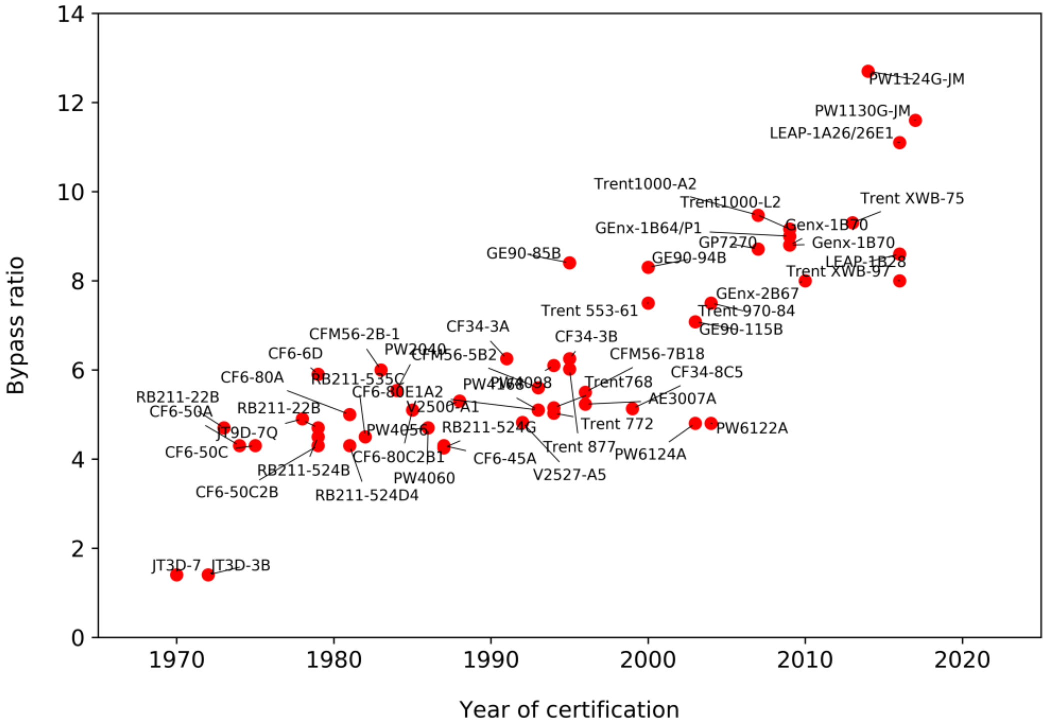


Figure 7 - Evolution in Bypass Ratio over time

In fact, considering the engine only and other thrust parameters remaining constant, increasing the BPR results in the engine producing more thrust with the same fuel flow.

But as the BPR increases, the fan size and weight increase and more mechanical work on the low-pressure shaft is required to make it turn. This implies that more energy is extracted by turbines to the core flow velocity with a negative effect on thrust.

Nevertheless, the mass flow rate through the fan is much higher than through the core so, even if the velocity of the core flow is the highest, its thrust component contribution decrease is relativity compensated by the increase of BPR: the thrust increases for the same fuel injected (Eq.1) so SFC decreases (Eq.2). In other words, at a fixed the thrust level, the overall consumption decreases (Ep.2) [2].

In other terms, by increasing the BPR, as the core flow is faster than the bypass flow, the equivalent exhaust jet velocity decreases leading to a significant increase in propulsive efficiency: SFC decreases (Eq.2).

The aim of the UHBPR is to increase much more the BPR to keep increasing the propulsive efficiency and to achieve even lower SFC.

We consider that the range of BPR could go as high as 20:1 [20] but the limit would be at approximately 15:1 [2,40]. In fact, for higher BPR, drag and the weight penalties will be too significant compared with the savings: the SFC at aircraft level must be considered, not just the SFC of the engine in isolation (Figure 8 [43]).

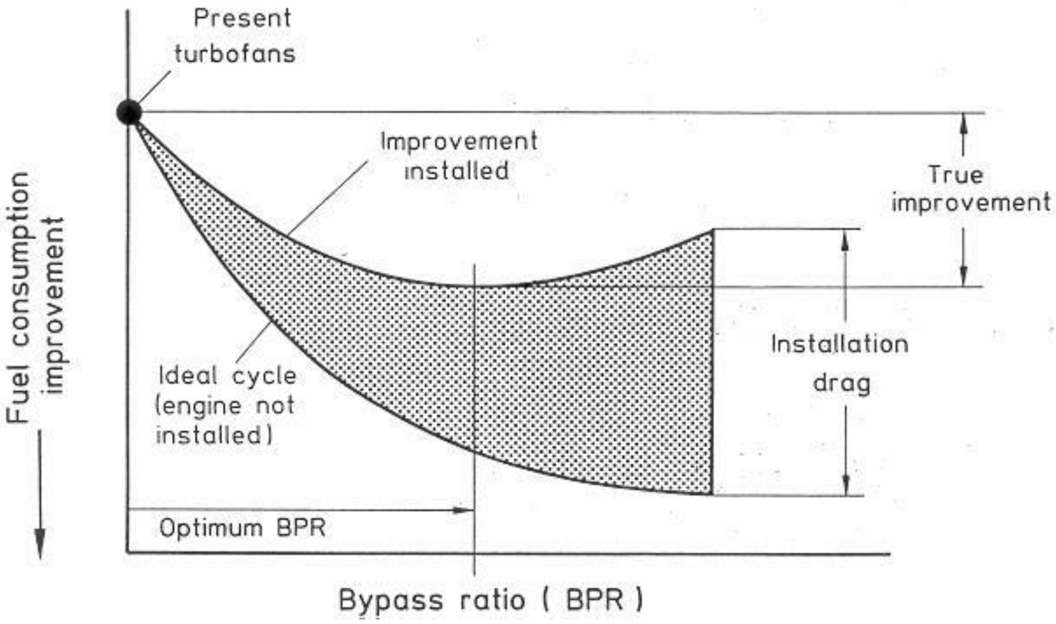


Figure 8 - Existence of an optimum BPR with SFC, integration effects of turbofans

Finally, another advantage will be the reduction in the jet engine noises as the equivalent exhaust jet velocity will be lower [2,4,33].

Geared Turbofan (GTF)

A second idea to reduce SFC consists in designing the compressor and turbine stages such that they can rotate at their optimal speed. This increases the thermal efficiency of the engine. To do so, the geared turbofan decouples the fan from the other turbomachines.

The Geared Turbofan is a variant of a conventional turbofan where a reduction gearbox is installed on the low-pressure shaft, between the fan and the low-pressure compressor. It is often a planetary gear train with a reduction ratio of 3:1 or higher [7].

It isn't a new concept. The British Aerospace BAe 146 produced until 2002 was fitted with four Textron Lycoming ALF 502R-5 geared turbofan engines. The Bombardier Challenger 600 originally was fitted with the ALF 502L geared turbofans. The TFE731, a geared turbofan engine, first ran in 1970, and its variants powers popular airplanes such as the Learjet 35, 40,45 and 55, Dassault falcon 900DX, Hawker 800,850XP and 900XP, and a few Cessna Citations. Not forgetting the LF 507 (80s) on Avro RJ and the IAE V2500 (90s) which powered the Airbus A320 family, the McDonnell Douglas MD-90, and the Embraer KC-390 [21].

This technology (Figure 9 [2]) allows to decouple the fan whose rotation speed is limited by a maximum blade tip speed, and the low-pressure compressor and turbine (that are on the same shaft). In fact, if the fan turns too fast, shock waves can occur at fan blades tips as sonic condition are reached. This penalizes its efficiency and can cause unknown damages on blades affecting the flight safety [2].

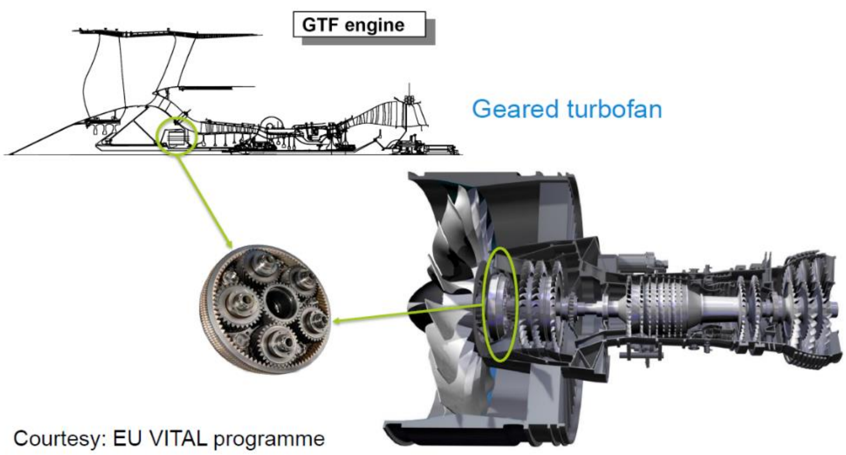


Figure 9 - GTF concept

More precisely, without the gearbox (see savings in Figure 10 [9]):

- The LP compressors will be less efficient, both in percentage of the OPR and in intrinsic efficiency, as it turns far slower from its optimal speed. Hence, a higher number of stages (and larger size) will be required to reach the performance requirements [2,21].
- The LP turbines must also get larger both in number of stages and in size to produce the required power to make turning this larger fan and so reach the performance requirements [2,6].

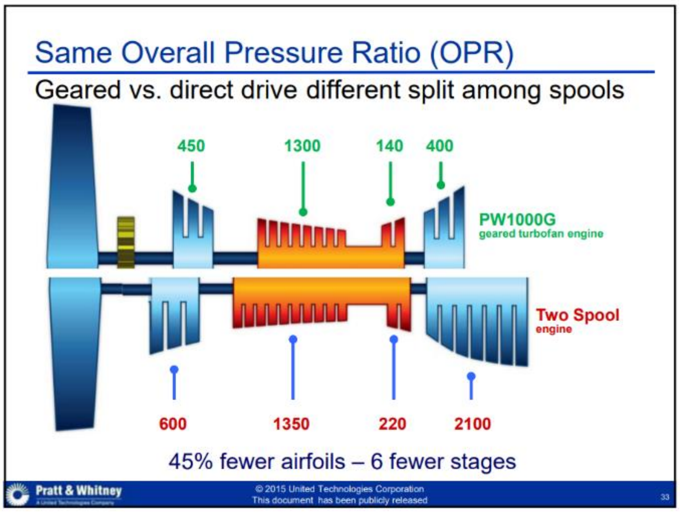


Figure 10 - Pratt & Whitney view on GTF weight and integration savings

The geared architecture is an enabler to keep increasing the fan diameter without significantly penalizing rotation speed hence efficiencies of other components, then of the overall cycle [2 ,5].

Moreover, as each component (compressor and turbine) is more efficient, fewer and smaller stages are required leading to weight savings [2]. In addition, as the fan turns slower, it produces less noise than other turbofans [39].

Finally, it is important to note that, very likely, this concept will allow engine manufacturers to design higher BPR turbofans as the fan will not anymore constrain the low-pressure shaft rotation speed. This is why both UHBPR and GTF engine concepts are related.

Maturity

Ultra-High By-Pass Ratio Turbofan (UHBPR)

Today, Rolls Royce is the only engine manufacturer who started the assembly of a demonstrator, at the beginning of Spring 2021, to reach a BPR over 15:1 [11].

Its demonstrator called "UltraFan" is a geared turbofan with a fan diameter of approximately 3.55m, so larger than the GE9X, already known as the largest commercial aircraft engine. In comparison, an A320 fuselage diameter is approximately 3m95. It is being developed within the framework of Clean Sky's ENGINE ITD, and the flight testing is one of the major flagships of Clean Sky's Large Passenger Aircraft (LPA) Innovative Aircraft Demonstration Platforms (IADP) [37].

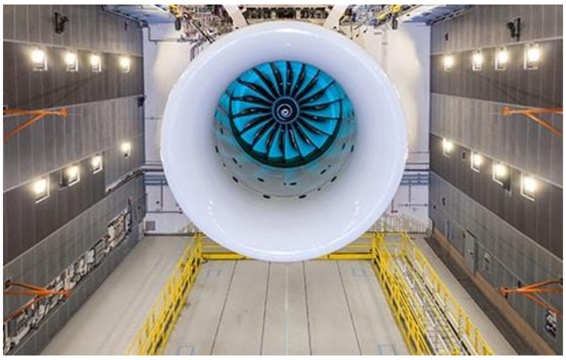


Figure 11 - UltraFan in testing facility – Testbed 80

On May 18th 2023, the first tests were successfully completed in Derby (UK) (Figure 11 [28]) after that the record-setting PGB (power gear box) had been sent from Dahlewitz (Germany) in March 2022 [10,11].

The UHBPR's Technology Readiness Level (TRL)[2] can't be clearly expressed as the global engine is made by several systems with each one its own TRL. However, for this entire design successfully ground tested by Rolls Royce, a TRL of 6 can be assumed. The entry into service is announced for the 2030s [28].

[2] *Way to classify the level of development of a given technology. Based on NASA model, this can be found in [18] page 49.*

Geared Turbofan (GTF)

The pioneer in this domain is Pratt & Whitney in partnership with NASA, MTU and former Fiat Avio [13,38].

Pratt & Whitney, MTU and Fiat Avio began their first preliminary studies into a geared turbofan in the 1990s [5]. Their first GTF entered into service in 2013 and today more than 1600 aircraft fly with this technology [7] (see timeline in Figure 12 [2]).

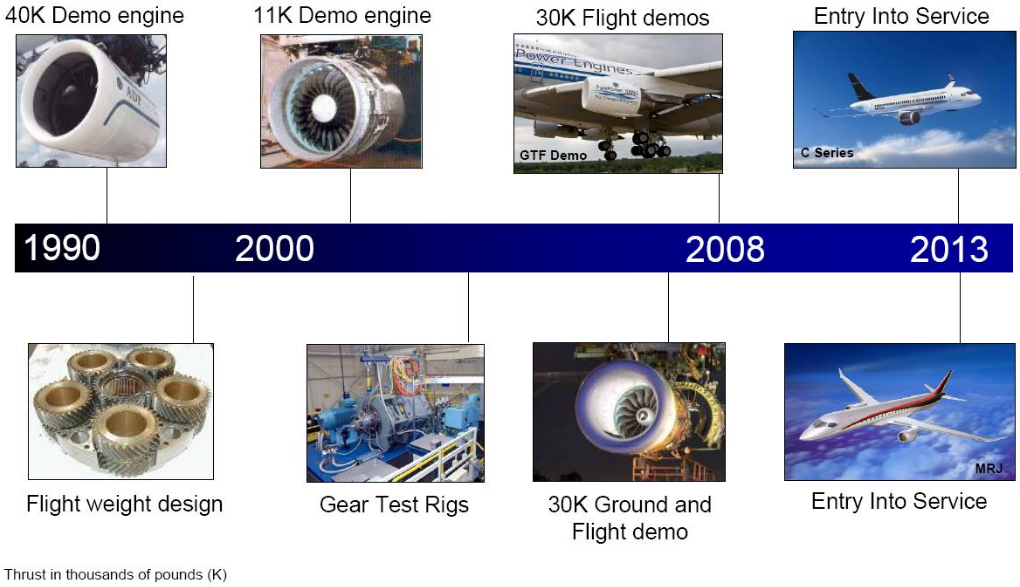


Figure 12 - GTF timeline of Pratt and Whitney

The TRL of such configuration depends on the power transmitted by the gearbox due to several constraints:

- For regional and single-aisle jet aircraft, they have been certified and used since nearly one decade with the Pratt & Whitney GTF family called PW1000G series. The power transmitted is in the order of 15-25MW (22MW for one of the two PW1100G-JM on the A320neo at take-off [35]) so there is not any problem of readiness for such power range.
- However, for the UltraFan more than 60MW [15] are required (the gearbox individually was tested to deliver 64MW [15]). As the first tests were successfully completed, a TRL of 6 can also be given.

Summary

To get a first look at those technologies, Table 1 below shows for each one some engines already in service, upcoming, and future concepts with their EIS and TRL.

Technology	Engine	BPR	EIS	TRL	References
HBPR	GE GEnx	8 - 9.3:1	2012	9	[19,26]
	GE GE9x	10:1	2020	9	[17]
	CFM LEAP-1	8.5 - 12:1	2016	9	[19,31,41]
HBPR GTF	PW1100G Series	9 - 12:1	2016 / 2013	9	[7,39]
	P&W Advantage	/	2024	/	[14]
UHBPR GTF	RR UltraFan	15:1	2030s	6	[12, 15,17,28]

Table 1 - Engines readiness level and entry into service
/ = No input

The aircraft segments concerned, based on [12] classification (table 2.1 page 33 of their report) for each in-service engine are as followed.

Regional jets

Single-aisle jets

Twin-aisle jets

Environmental Impacts

It is difficult to study the respective environmental impacts of each engine improvement individually as they are introduced at the same time with many others (new materials for engine core, …). Nevertheless, the following table shows the overall savings of some engines using such technologies. Table 2 compares the new engines with the previous generation which powered the same aircraft segment (reminded between parenthesis from the literature of [42]). The color codes used are the same as the previous Table 2.

As order of magnitude, each new engine generation is approximately 15-20% more fuel efficient than the previous they replace, and, at the aircraft level, each generation is 15-25% more fuel efficient [17].

For NOx and noise emissions, very few data have been found.

Technology	Engine	Fuel	CO_2	NO_x	Noise	References
HBPR	GE GEnX	-15% (CF6-80C2)	-15% (CF6-80C2)	-40 to -50% (CF6-80C2)	-30% (CF6-80C2) -50% (aircraft)	[23,24]
	GE GE9x	-10% (GE90-115B) -5% (Trent XWB 97)	-10% (GE90-115B)	-50% (any engine on twin-aisle)	/	[17,24,25]
	CFM LEAP-1	-15% (CFM56-7B)	-15% (CFM56-7B)	Until -50% (ICAO CAEP/6)	/	[19,24,27,31]
HBPR GTF	PW1100G Series	-12% to -15% (current CFM)	15% (CFM56-7B)	-50% (CFM56-7B)	-20% (current CFM)	[7,30,31]
	P&W Advantage	-1% (current PW1000G series)	-1% (current PW1000G series)	/	/	[8]
UHBPR GTF	Rolls-Royce Ultrafan	-10% (Trent XWB) -25% (Trent 700)	-25% (Trent 800)	/	/	[12,15,17,32]

Table 2 - Engine main environmental impacts

SUITABILITY

Constraints

The following Table 3 describes for each technology the main identified constraints:

	UHBPR	GTF
Main characteristic	Large fan diameter (hence large nacelle)	Power gearbox
	Identified Constraints	
Technical	The nacelle size and position affect wing shape, structure, and aerodynamics: - Increase of the nacelle drag and of the wing loading (addition of structural weight to strengthen it). - Integration of all equipment needed by engines (harnesses, piping, …) in a smaller volume. - Integration of the accessory gearbox. The One Engine Inoperative certification requirements will require a different aircraft surface control and tail sizing.	Mechanical component reliability. Additional dynamic behaviors due to LP shaft which rotates at a higher speed. New design of high-speed LP compressor and turbine. Heat dissipation to prevent critical effects on materials. Even if the gearbox efficiencies are very high (more than 99.5%), 0.5% of 20MW still represent significant heat to be dissipated.

Certification	Sufficient roll clearance must be kept for crosswind landing and flat tires, while vertical ground clearance must be enough to avoid engine scraping in the event of nose gear collapse. The spanwise location must also consider passenger door escape slide, loading ramps, suction and blowing zones, turbine disk bursting zones, nose gear water spray cone. One Engine Inoperative and Foreign Object Damage requirements.	The technology has already been proven for many years over a thousand of single-aisle aircraft. For high power requirements, gearboxes might need several risk assessments before getting certified.
Operational	Engine size might be a problem when taxiing and at airport gate due to the lower clearance.	Reliability and maintenance.
References	[38,39,41]	[9,39]

Table 3 - UHBPR and GTF main constraints identified

An illustration of engine integration issues is shown in Figure 13 (provided by [2]) to summarize main elements from the previous Table 3.

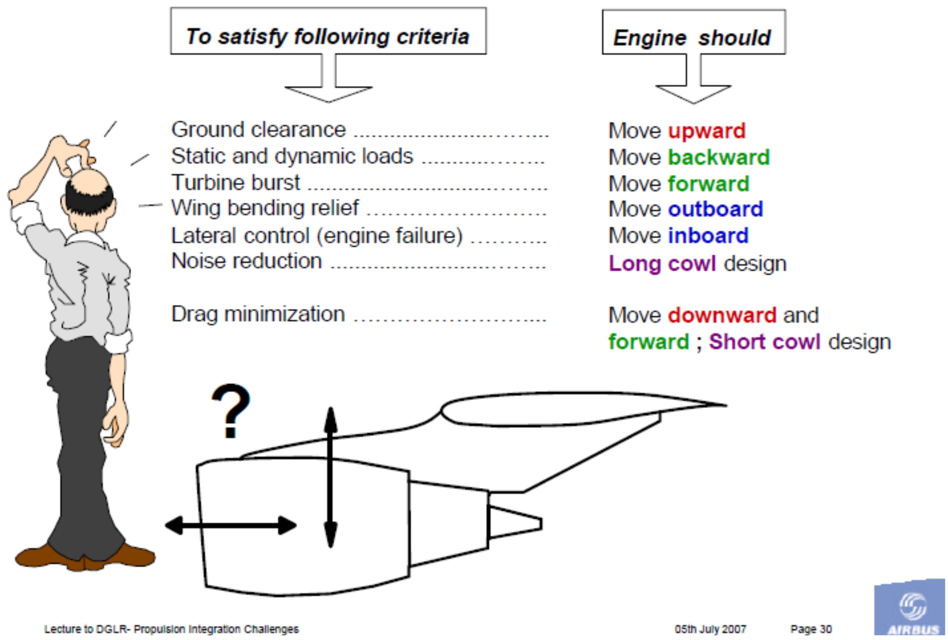


Figure 13 - Integration challenges of turbofans underwings

More quantitative elements on the impact of turbofan sizes are shown in Figure 14 [2].

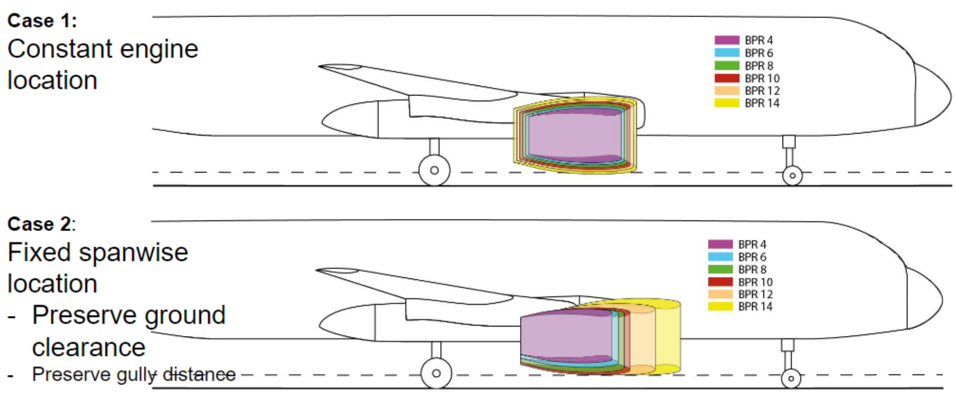


Figure 14 - Schematic view of BPR effect on ground clearance

Aircraft Segments Concerned

GTF is already implemented on regional and single-aisle jet aircraft. It and can be further extended in the future to larger aircraft considering the previous constraints of power transmitted by the gearbox. As turbofan are less efficient than turboprops at low speeds and low operating altitudes, smaller regional applications are not concerned.

However, for the UHBPR turbofan, the range of applicability is significantly reduced if classical under-wing mounting is considered (discussed latter in Implications on Aircraft Designs).

APPLICABILITY

Market Acceptance and Barriers

For airlines, as fuel cost represents nearly 15-25% of their total costs, the shift to these technologies offers significant fuel savings and therefore fuel cost reduction.

For airports, ground and gate clearance must be considered. More studies will be required to understand how the infrastructure needs to be adapted to safely cope with these new engines.

Costs

The implementation of both concepts is possible for new aircraft, retrofit is technically feasible and successful (A320neo, 737MAX) but the demonstration of safety, especially when dealing with larger engines, could sometimes cost higher than market expectations. Strong coordination between aircraft and engine manufacturers will be required.

Implications on Aircraft Designs

Particularly, large-fan engine implementation is a significant challenge due to the different constraints and limitations evoked above.

While today the highest BPR mounted under the wing is approximately 12:1, the classical under wing mounting might not allow to go further as the ground clearance isn't enough on all aircraft [39]. Many studies describe for mid-term either a compromise between aircraft and engine manufacturer but resulting probably in a less efficient solution than what was planned, or new engine locations as the only way to go.

According to the constraints previously identified and, in the need to fulfil ambitious environmental targets and mitigate the aviation sector impact, HBPR geared turbofan represent a smoother technology change, compared to futuristic aircraft designs featuring electric, distributed and boundary layer ingesting propulsion [38]. Knowing that, today, a significant number of last generation engines are still in operation [42] (due to the long lifecycles of aircraft programs), a first replacement globally with today's engine generation is certainly a first step to consider for short/mid-term.

Nevertheless, for the long term, a real shift towards these new engine concepts will be crucial to meet carbon-neutral engagements. Hence, disruptive aircraft designs could be introduced in the next decades, enabling at the same time many other savings (drag reduction, use of new fuel, etc.)

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DESCRIPTION

Concept

Introduction

According to the EASA Notice of Proposed Amendment of 2015, the Open Rotor is “a Turbine Engine featuring contra-rotating fan stages not enclosed within a casing” [4]. In other words, it looks like a turbofan of which the fan is replaced by unducted rotors (often one or two) designed in a particular way.

The concept dates back from the World War 2 with the Douglas XB-42 (Figure 15), an experimental bomber aircraft designed for a high top-speed [13,23] powered by a piston engine, with turbocharger to reach excellent performance at high altitude, powering two contra-rotating propellers. The propulsion system was not rigorously an open rotor, as the engine core was a piston engine and not a turbine, however the idea of making rotors rotating in opposite directions to generate thrust was born.

The first XB-42 was delivered to the USAAF on 6 May 1944, performance was excellent: as fast as the De Havilland Mosquito B.XVI but with defensive armament and twice the bombload over short distances [23].

Figure 15 - View of the contraprop and cruciform tail [23]

Two prototype aircraft were built, but the end of World War II changed priorities and the advent of the jet engine gave an alternative way toward achieving high speed.

Commercial version has several decades of history. In fact, when the 1973 oil crisis hit, interest in “propfans” soared and NASA-funded research began to accelerate [24]. The “propfan” concept was outlined by Carl Rohrbach and Bruce Metzger of the Hamilton Standard division of United Technologies in 1975 and was patented by Rohrbach and Robert Cornell of Hamilton Standard in 1979.

The idea was to achieve the low fuel consumption of the turboprop while keeping the cruise performance of the turbofan. During 1980s, several manufacturers did their own studies and tests. At that time, there were many names to define such engine concept: Propfan, unducted fan, contra-rotating open rotor (CROR), or open rotor.

This first version of what we call today an Open Rotor, the GE36 UnDucted Fan (UDF), was developed in 1986 by General Electric Aviation with Snecma (today Safran). There were flight tests on both MD-80 (Figure 16) and Boeing 727 aircraft (Figure 17).

Figure 16 - Boeing 727 / GE UDF aircraft [25]

Figure 17 - MD-80 / GE UDF aircraft [26]

The engine consisted of a modified F404 gas generator and counterrotating propulsor system, mechanically decoupled, and aerodynamically integrated through a mixing frame structure. The utilization of the existing F404 engine minimized engine hardware, cost, and timing requirements and provided an engine within the desired thrust class [15].

The power turbine provided direct conversion of the gas generator horsepower into propulsive thrust making rotating the two rotors to generate thrust. In fact, the jet exhaust thrust contribution was not significant compared to the unducted fan as most of the energy inside the gas produced was extracted through the turbine. There was no gearbox and associated hardware, significantly simplifying the design and its operation. A cross section is shown in Figure 18 [15].

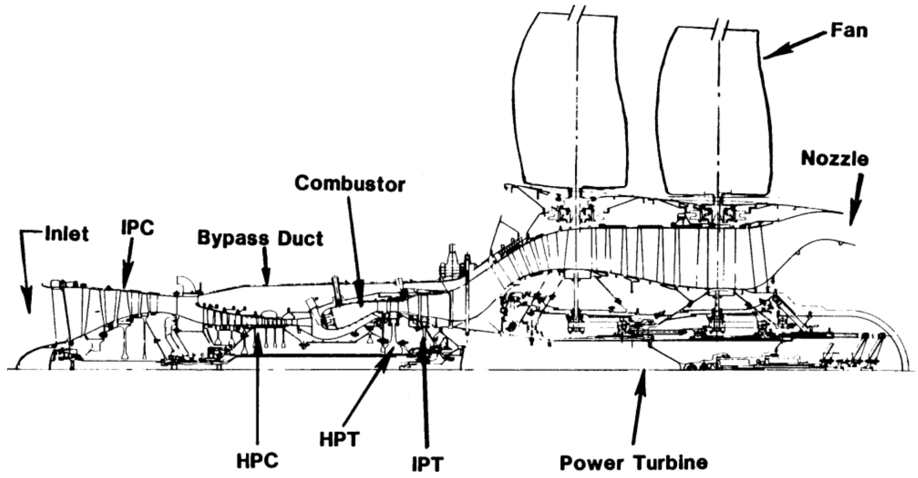

Figure 18 - GE36 UDF cross section

Finally, counterrotation utilized the full propulsive efficiency by recovering the exit swirl between blade stages and converting it into thrust [15]. It demonstrated a 15-20% fuel burn reduction compared to contemporary turbofans [9,27], and more precisely for the UDF MD-80 aircraft, they concluded in 1988 a 30% reduction compared to the turbofan powered version [28] with JT8D-200.

With this concept, engineers solved the low-cruise speed issue of turboprop around Mach 0.6, to reach more than 0.8 avoiding wave drag on blades, i.e. when sonic flow conditions on blades' tip are reached, significantly decreasing their efficiency. This cruise speed was satisfactory as competitive with commercial turbofan fitted aircraft. However, faced with a market where fuel prices were dropping, the program was ended in 1989.

Advantages

The concept of Open Rotor is one of the most promising ways today to reduce aviation impact on global warming. Research accelerated more particularly since last decade and recent successful projects demonstrated further improvements encouraging the development of future engines based on this concept.

In fact, this design allows further improvement of the overall engine efficiency compared to today's turbofan. To decrease even more the engine fuel consumption, there are two levers: the thermal efficiency and the propulsive efficiency. They are introduced as follows in the engine specific fuel consumption (SFC):

$$SFC = \frac{V_0}{\eta_{th}\,\eta_{prop}\,FHV}$$

with:

η_{th} : The thermal efficiency of the turbofan, how efficiently chemical energy is converted into kinetic energy. This includes compressors, the combustion chamber, and the turbines behaviors.

To increase it, thermodynamic cycle improvements are needed. This can be achieved mainly by an increase in overall pressure ratio (OPR) with accordingly an increase in the turbine inlet temperature (TIT) and components performance improvements (compressors, turbines). Note that the combustion efficiencies are today already higher than 99% [29].

η_{prop} : The propulsive efficiency of the turbofan, how efficiently kinetic energy is converted into propulsion. To increase it, the lowest as possible difference between jet velocities of both stream and free stream is required. This can be achieved by a higher BPR.

FHV : the fuel heating value in J/kg, energy released in Joule by the combustion of 1 kg of fuel.

In short, for given fuel and flight speed, a turbofan engine can reduce its fuel consumption by improving both, the thermal and propulsive efficiency. To do so, the main design levers are summarized in Figure 19 [29].

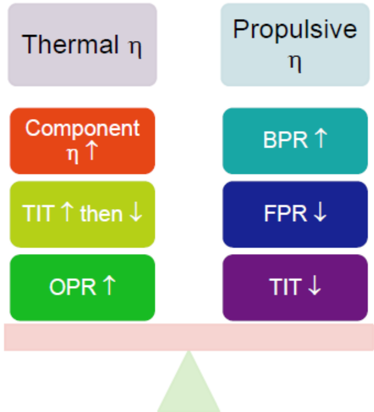

Figure 19 - Levers to increase engines' efficiencies

They were introduced in the Ultra-High Bypass Ratio and Geared Turbofans sheet [30] however some of them are again explained here for the purpose of the Open Rotor.

To increase the propulsive efficiency, turbofan tends toward higher By-Pass Ratios (BPR). It is the ratio between the secondary and the primary stream mass flow rate. This is a consequence of the secondary stream slower than the primary one. However, penalties of the engine mounting, associated to larger and larger fan aiming at reaching higher and higher BPR, become a showstopper above 15:1 where there are no longer benefits at aircraft level (see [30]). More precisely, the engine-only consumption is one thing, but the consumption at the aircraft level is another.

In this situation, the duct associated to this larger fan becomes heavy and generates more drag. At aircraft level, this suppresses the engine benefits by increasing the aircraft drag, and weight as the wing structure must be adapted to sustain heavier engines, which bring, in turn, additional drag (in cruise the drag is balanced by the thrust produced by the engines which is directly linked to the weight of the aircraft by the lift over drag ratio).

Therefore, the advantage of Open Rotor is to suppress the duct around the fan and to make rotating larger blades to increase even more the BPR (more than 30:1). Then, the propulsive efficiency and finally the overall engine efficiency (the core efficiency remains the same) can be improved, minimizing the installation impact on the aircraft. Figure 20 [7] illustrates these propulsive efficiency dependencies:

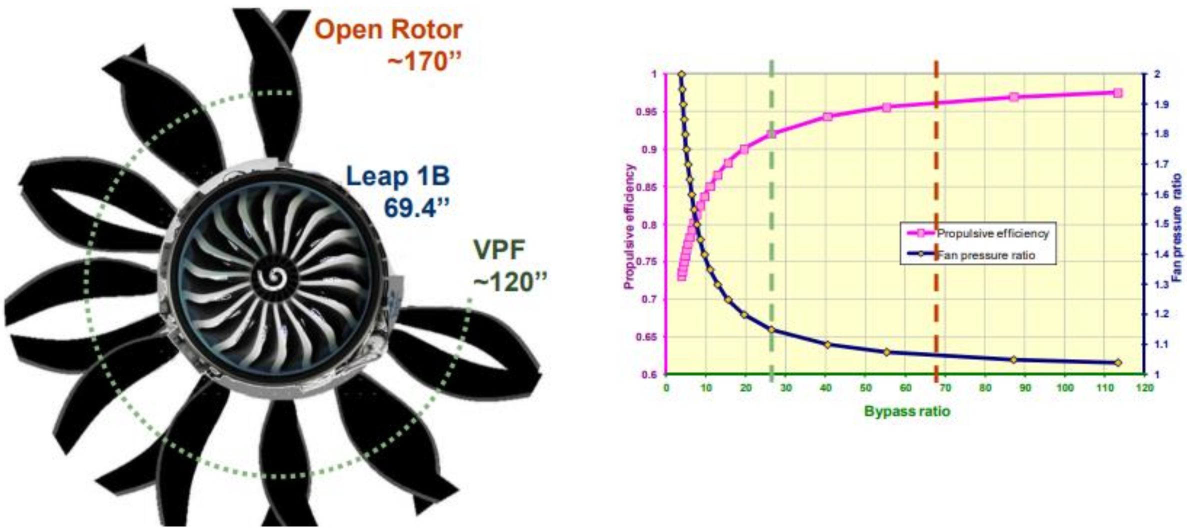

Figure 20 - Propulsive efficiency with By-pass Ratio and Fan pressure Ratio [7]

Design

The design of an Open Rotor is, as described previously, characterized by a turbine featuring contrarotating fan stages not enclosed within a casing [4]. It can also be called Counter-Rotating Open-Rotor (CROR).

Perhaps different design approaches, the general conception is based on a main core whose architecture is a gas turbine with a third shaft where a working turbine is fitted making rotate the disks of blades. The rotations speeds are often driven by a differential gearbox at the output of this turbine [13]. The blades are located either at the front or at the back of the powerplant (many configurations exist Figure 21) and generate thrust like propellers of a turboprop.

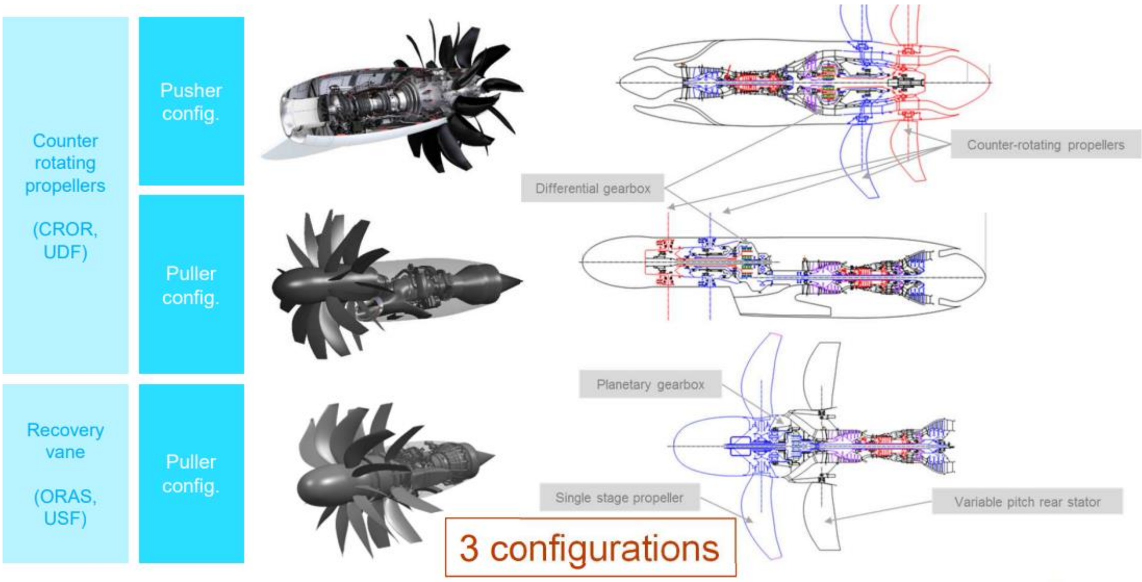

Figure 21 - Different configurations of Open Rotor [7]

This concept allows the powerplant to reach more than 30:1 of BPR, with high thermal and propulsive efficiency without wasting energy in wave drag of blades; in fact, to avoid wave drag generated by strong shock waves at the tips of the rotor blades:

- The rotation speed of the third shaft is low compared to the other ones as it rotates with a working turbine decoupled.
- A differential gearbox with reduction ratio is used [7] to ensure a low rotor rotation speed. This furthermore let the working turbine turn at its optimal speed.
- Instead of using one large disk of blades, two are installed allowing to make shorter blades, which results, with the introduction of the gearbox, in reducing even more the tangential tip speed.
- Complex aerodynamic blades design with swept leading edge and composite materials.

To summarize, Open Rotor allows significant fuel consumption reduction by improving the propulsive efficiency. From a practical viewpoint, it takes both benefits of a high cruise speed from the turbofan-fitted aircraft, and the low consumption of turboprops.

Maturity

The Counter-Rotating Open Rotor (CROR) propulsor concept has been studied in Europe and the US for decades, with surges in research and development aligning with high fuel prices, and less interest when fuel prices were low [14].

Figure 22 - SAGE2 in testing [6]

After the UDF GE36 of General Electric, that reached a TRL of 7 with expensive flight testing until end of the 1980s, more recently in the EU Clean Sky research project called Sustainable And Green Engine, the CROR propulsion system has been shown to be capable of further fuel burn improvement over turbofans engines for short- to medium range aircraft at a negligible speed penalty.

In fact, on May 30th, 2017 Safran ran the SAGE2 (Figure 22), a Full-Scale Open Rotor Ground Test Demo at their test facilities in Istres (France) during more than 70 hours. Hundred starts have been executed, and tests demonstrated key technologies like multi-variable power control, a pitch actuation system and an advanced power gearbox integration [7].

The concept demonstrated a TRL of 5, which was very promising.

With both experiences from General Electric and Safran (Figure 23), their joint adventure, CFM International, decided in 2021 to go further with the RISE (Revolutionary Innovation for Sustainable Engines) program.

Figure 23 - General Electric and Safran experiences on Open Rotor [17]

Figure 24 - CFM open Fan project [17]

One of their announcements is the design of a commercial Open fan (Figure 24), the most ambitious architecture, for an entry into service by mid of 2030s.

Environmental Impacts

With the significant increase in BPR, the open rotor offers double-digit improvements in reduction of fuel consumption, and therefore CO_2 emission, compared to the old generation of engines still in operation today (CFM56, CF34...) – over 30% savings [16] –, and with latest engines (LEAP, PW1000G series, …) – 10-20% savings [9]. It would also represent some 5% potential savings vs 2037 advanced turbofans [14].

Engine	Fuel	CO_2	References
SAGE2	-30% (current CFM56)	-30% (current CFM56)	[1,2,3,11]
RISE Open Fan	-20% (LEAP) More than -35% (current CFM56)	-20% (LEAP) More than -35% (current CFM56)	[2]

Table 4 - Some environmental impacts of Open Rotor.

Concerning noise, Open Rotor due to unducted blades will be noisier than turbofans. However, by decreasing rotors rotating speed and by optimising blades aerodynamic design, this effect can be mitigated. For instance, SAGE2 demonstrated that is it Compliant with Chapter 14 with some margin.

SUITABILITY

Constraints

The following Table 5 describes the main constraints identified for the Open Rotor. Some of them are dependent on the chosen aircraft design. For instance, for a classical tube-and-wing aircraft, the different possibilities for engine mounting are shown in Figure 25, highlighting ground-clearance challenges.

Main characteristic	Larger diameter: 4.5m (SAGE2 [5]) So more than twice of newer turbofan on short/middle range aircraft, around 30% larger than GE9X
Identified Constraints	
Technical	Rotor weight and its impact on aircraft structure Aircraft integration, ground clearance Aerodynamic interference, Wing aeroelasticity, wingspan loading and structure, Different surface control and tail sizing
Certification	Sufficient roll clearance must be kept in case of crosswind landing and flat tires The spanwise location must also consider passenger door escape slide, loading ramps, suction and blowing zones, nose gear water spray cone Due to the larger diameter, it will inevitably be more susceptible to the ingestion of foreign objects (birds, ice released from the fuselage, tire debris…) An uncontained engine rotor failure or so-called blade-off containment (a propeller debris release) must not damage the fuselage (passenger safety, and flight control integrity) De-icing of blades
Operational	Clearance of: - runway - taxiing, and airport gate Maintenance and ground handling complexity
References	4,5,7,11

Table 5 - Open Rotor main constraints identified

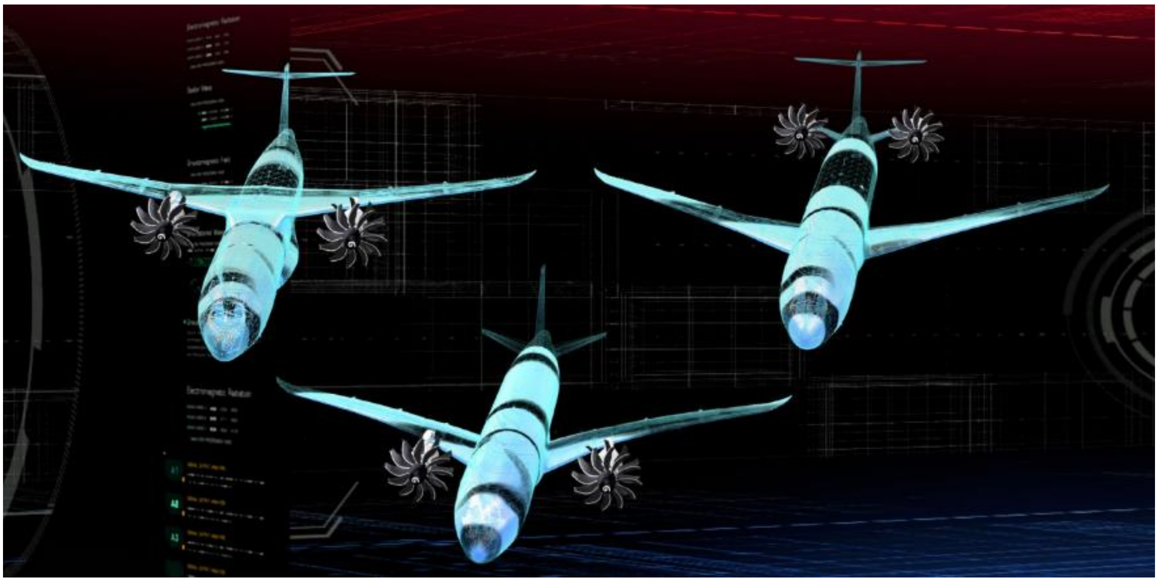

Figure 25 - Open Rotor integration possibilities on classical tube and wing aircraft design [17]

The noise challenge associated with such unducted rotors is today secondary. In fact, the industry is already confident with recent testing about the compliance to ICAO Chapter 14, even with some margin [14].

Moreover, there is evidence that the cruise speeds possible to reach with such an engine concept is commercially satisfying, i.e. between Mach 0.75 and 0.80 [14]: much higher than classical turboprop and competitive with turbofans (in the same Mach range).

Finally, the use of one rotor instead of 2 (for example in the CFM Rise Open Fan program) should reduce some these technical and certification risks. The announcement of a flight demonstration contributes to the confidence in timing and investment [14].

Aircraft Segments Concerned

Due to the significant size of engines to derive most benefits from the open rotor concept, only single-aisles and widebodies are concerned.

APPLICABILITY

Market Acceptance and Barriers

As Open Rotors look like turboprops for passengers (propellers), there could be some potential passenger reluctance who could associated it to old technology (there are today preconceived ideas about turboprops in some regions). Cabin noise will also have to be comparable to today's turbofans.

For airlines, the shift to these technologies offers significant and appealing fuel savings, for a small and manageable impact on operations (speed, ground handling).

Concerning airports, clearances will have to be considered (taxiing, gates, etc.) More studies will be required to understand how the infrastructure need to be adapted to safely cope with these new engines.

Engine manufacturers have acquired a significant experience, with recent testing and launch of new programs being encouraging.

Costs

Size constraints will probably be a major constraint for retrofitting current aircraft generation. Thus, this technology is most likely to be implemented onto new aircraft programs, specifically designed for integrating these large and heavier engines. Development costs will therefore be in the order of magnitude of a new engine program, several hundreds of millions until more than a billion of dollars.

Implications on Aircraft Designs

Today, more than 80% of the ASK and CO_2 emissions come from single-aisles with short flights and small/medium twin-aisles [18], therefore, technical improvements should be focused on these aircraft segments. Nevertheless, the Open Rotor is larger than 4m so more than twice larger than the latest engines fitted on them.

Consequently, its integration on aircraft can be a showstopper if classical tube-and-wing configurations with low-wing mounting are considered. This is why new aircraft designs are likely to be a key element to solve this issue.

There are a variety of options for integrating this engine: under the wings in either a low- or high-wing configuration, at the back of the aircraft (Figure 26), or on top of the fuselage for a blended-wing body

Figure 26 - Open rotor at the back of the aircraft [11]

design (Figure 27). All these configurations must be studied so that the best benefits can be extracted from this engine concept [19, 20, 21, 22].

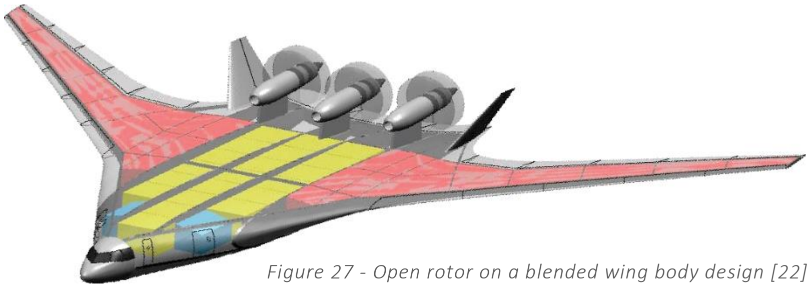
Figure 27 - Open rotor on a blended wing body design [22]

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DESCRIPTION

Concept

A Variable Cycle Engine (VCE) or Adaptive Cycle Engine (ACE) can be defined as one that operates with two or more thermodynamic cycles. It is a type of aeroengines whose thermodynamic cycle can be adjusted by changing some components' shape, size or position, and the cycle parameters, such as pressure ratio, mass flow, bypass ratio and thrust. It can be varied between those of a turbojet and a turbofan, making it to combine the advantages of both. These measures may enable the engine to obtain the optimal thermodynamic cycle, and to acquire a good adaptability to various flight envelopes.

The engine can work as a turbojet when the aircraft requires high specific thrust, such as take-off, acceleration and supersonic cruise. It also can work as a turbofan when the aircraft requires low fuel consumption, such as standby and subsonic cruise. The most important advantage expected from using VCE in future supersonic transport is a substantial range improvement as compared to a conventional engine. These range improvements are mainly achieved by reducing the subsonic specific fuel consumption by around 15% (relative to a turbojet) and improving the fuel consumption at off-design by the extensive use of variable geometry. The future VCE will have a low-emission combustor and afterburner.

The disadvantages are mainly an increase in the engine weight and a more complex control system, therefore impacting the engine reliability. The performance of any VCE depends critically on the attainment of the predicted technology level improvements.

Development programs exist to produce prototypes of three-stream adaptive engines that are light weight and flight ready. By relying on a third stream of air that can be dynamically modulated between the engine's core and the bypass stream, an adaptive engine can provide increased thrust during take-off and increased fuel efficiency during cruise conditions.

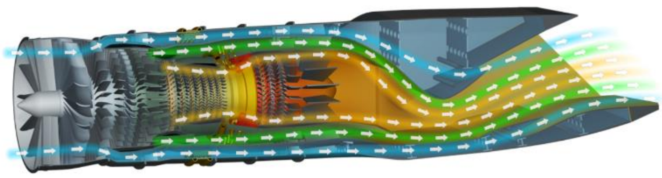

Figure 28 - Schematic illustration of an Adaptive Engine Transition Program (AETP) design, U.S. Air Force

Maturity

In March 2022, GE started tests for its XA100 adaptive cycle engine designed to equip fighter aircraft such as the F35. To date, no other major scale project exists for commercial aircraft applications.

Environmental Impacts

A gain of about 15% in fuel efficiency is claimed for supersonic aircraft using this technology. No reference could be found for gains in commercial aviation applications.

SUITABILITY

Constraints

- Engine complexity and control systems
- Engine weight

Certification Aspects

No input

Aircraft Segments Concerned

Primary target is supersonic aircraft.

APPLICABILITY

Market Acceptance and Barriers

No input

Costs

No input

Implications on Aircraft Designs

No input

DESCRIPTION

Concept

Pratt & Whitney Canada has commanded the Business and General Aviation (BGA) turboprop market since it introduced its PT6 turboprop more than 50 years ago, producing over 50,000 of these engines. While the PT6 is widely considered as a reliable engine with great market shares, it is not known in the market as an advanced engine [2].

Many manufacturers have been working to improve this type of engines and make it even more sustainable, low fuel and low noise. Two main concepts are promoted today:

- The Catalyst, from GE, within the Clean Sky's MAESTRO (More Advanced and Efficient Small TuRbOprop engine) project. It is based on the philosophy of using the experience from commercial engines to create "all-new" turboprops with "low risk and high value" [12].

Figure 29 - GE Catalyst Advanced turboprop engine [12]

- More recently, the Tech TP from SAFRAN, within Clean Sky2 initiative [11], a demonstrator to keep learning, innovating, and testing even more efficient designs.

Figure 30 - Safran Tech TP advanced turboprop [11]

The General Electric Catalyst engine was announced in November 2015 to power the future Beechcraft Denali (certification expected to be achieved at the end of 2023). It is based on GE's experience with CT7 compressor configuration, advanced blade design from GE9X, and cooled turbine from the GE Passport.

Its main characteristics are the use of an authority digital engine and propeller control (FADEPC) which is common in jets but has never been used in commercial turboprop planes, and the integration of twelve 3D-printed parts in titanium alloy replacing 855 parts: frames, combustor liners, sumps, exhaust case, bearing housings, stationary components in the flow path, and heat exchangers. More than 35% of parts are 3D printed which would result into a 5% weight saving according to GE [6, 7].

The power is around 1240 SHP and could be extended to 850–1.600 SHP [3, 6].

The Tech TP from Safran is a Clean Sky 2 turboprop demonstrator program started in 2015. It aims at validating the technologies required to develop a new-generation turboprop engine that will feature a compact, lightweight architecture as well as offering lower fuel consumption and CO_2 emissions compared to current engines [8, 9].

While the core of the Tech TP is identical to that of the Ardiden 3 (helicopter engine core of 1700-2000 SHP), the other components of the demonstrator have been designed or adapted to the needs of the program: a specific gear to drive accessories, speed reduction and power transfer to the propeller, an air inlet specially designed to promote flow inside the nacelle and a nozzle improving residual thrust. Moreover, it integrates a FADEPC which, as explained before, has never been used in commercial turboprop planes.

In 2023, a new step was passed with an engine converted into a hybrid-electric configuration, called the Tech TP ACHIEVE. It incorporates technologies from Clean Sky ACHIEVE (Advanced mechatronics devices for a novel turboprop electric starter-generator and health monitoring system) project, resulting in more efficient and more sustainable operating modes [11].

It allows to drive the propeller electrically, enabling new operating modes such as taxiing without using power directly from the main turbine engines or in-flight electric assistance. This saves fuel and reduces noise and emissions, resulting in more sustainable operations [11].

Maturity

The first run of the GE Catalyst™ engine on the Flying Test Bed began in December 2020. In parallel, GE Aviation Turboprop also delivered its first flightworthy engine for the Beechcraft Denali. In September 2021, 16 test engines have accumulated more than 2,600 hours of operation in ground tests and completed four certification tests [7]. For these reasons, we can estimate a TRL of 6.

The Tech TP demonstrator's first ground test was carried out in June 2019 in Tarnos (France) [8, 9], and in January 2023 a first run of the hybrid electric configuration was achieved [11]. Consequently, a TRL of 5 is estimated.

Environmental Impacts

Both GE Catalyst™ and Safran Tech TP turboprop offers about 20% of fuel consumption reduction, hence CO_2 emissions, compared to current engines [2, 8, 9, 11].

SUITABILITY

Constraints

Advanced turboprops can be seen as innovative engines that also use latest technologies already test proven. Hence, technically speaking, the main constraints might concern the hybrid configuration of the Safran Tech TP, and the 3D printing parts for the GE Catalyst.

Certification Aspects

Both 3D printing parts for the GE Catalyst and the Safran tech TP hybrid electric configuration will require particular certification processes as these are technologies emerging very quickly on the market and are quite new.

Aircraft Segments Concerned

The aircraft segment concerned is the Business and General Aviation segment, and short-range commuter aircraft segment, which have a cabin capacity of up to 19 passengers [1, 10]. Even if this segment represents a very small part of aviation CO_2 emissions (0.02% in 2018 [5]), it will be key to help decarbonize these segments.

No more application and expectation of development have been found as both concepts from Safran and GE produce less than 1800SHP. In fact, 1800 SHP can be estimated as a power threshold between 19-seat-or-less aircraft engines and the regional aircraft segment between 19-100 seats [5].

APPLICABILITY

Market Acceptance and Barriers

This concept is fully compliant with existing airline operations, so no specific issue in terms of acceptance is expected. However, the implementation of these technologies will however depend on the development of concurrent technologies addressing the same segments, such as electric engines.

If those technologies mature concurrently, the market may decide to opt for the most sustainable, fully decarbonized one, in this case electric propulsion.

Costs

No input

Implications on Aircraft Designs

None

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DESCRIPTION

Concept

Introduction to boundary layer concept

Any object moving inside fluid faces a drag force implying a loss of its energy. For aircraft, this force dimensions the fuel required for a given mission and is the main driver of aircraft design as the fuel required determines wing geometry, weight, payload-range and so forth. More intense efforts have been deployed since the last decade to investigate laminar wing design, transition control, separation control in order to decrease this drag. Each percent of aerodynamic improvement is difficult to obtain but essential to reduce fuel burn.

Before investigating further the boundary layer ingestion (BLI) concept, it is important to understand the boundary layer and its effects.
The Boundary layer (BL) is a layer where the flow velocity of a fluid around an object is affected by the viscosity of the surface. For instance, you probably already experienced that it is not a good idea to play with a light boat model close to the shores of a river due to the very strong water vortexes... as you may have experienced loss of control. The boat is then inside the disturbed flow of the boundary layer that forms along the side of the river.

To see what a boundary layer looks like, a well-known experiment consists in electrolyzing water, producing a column of hydrogen bubbles with a wire (placed vertically) inside a flow of water. It is then possible to observe how this column of bubbles behaves when it encounters an obstacle. The simplest obstacle is a flat plate aligned with the flow and the result of the experiment, at given flow condition, is shown in Figure 31 [2].

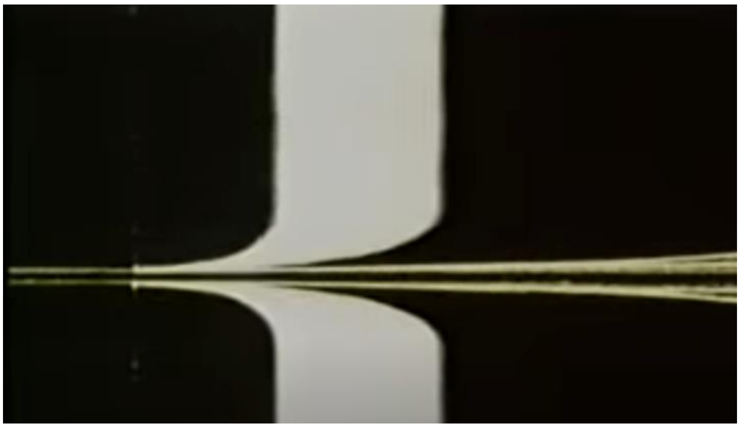

Figure 31 - Boundary layer on a flat plate, water with hydrogen bubbles [2]

Near the surface, due to the viscosity, the flow is slowed down so the bubbles are delayed in comparison to the other far away from the plate, explaining the curved shape of the bubble column of Figure 31.

Moreover, above a certain vertical distance all the bubbles are at the same position, it means they all have the same velocity. Therefore, depending on the vertical distance with respect to this wall, different axial velocities inside the flow can be found. Above a certain distance, the flow is not anymore (or in a very negligible way) impacted by the surface: we are outside the boundary layer and the velocity is nearly the freestream velocity.

The low velocity inside the BL implies that the flow around an aircraft is very sensitive to pressure forces. If the pressure that faces the flow increases more and more along the path, the velocity inside the boundary decreases until a given point where a flow separation can happen with reverse flows. This is for example what occurs during the stall of an aircraft when increasing too much the angle of attack (Figure 32 [3]).

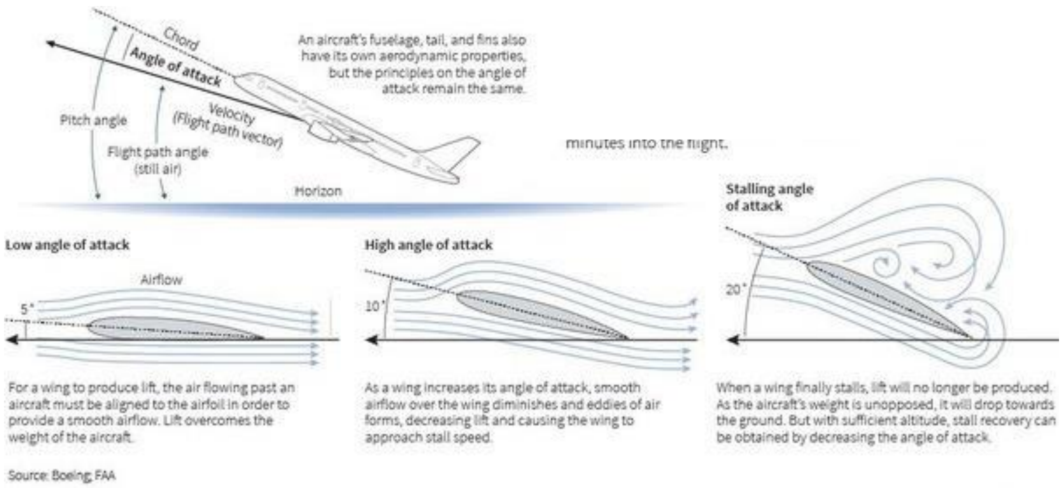

Figure 32 - Simplified schematic of flow patterns on aircraft wing with angle of attack until stall

This phenomenon can be easily and progressively observed experimentally using a diffuser shape to create an increase in pressure inside the flow along its path (for subsonic flow). The result (Figure 33 [2]) shows that near the wall, the bubble progressively slows down until coming back: this is flow reversal.

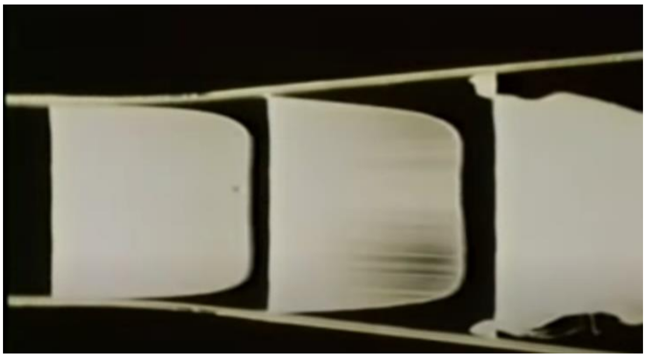

Figure 33 - Boundary layer inside a diffuser, water with hydrogen bubbles

More in details, the flow complexity from its laminar regime to turbulent and in the extreme case of a flow separation is illustrated in the Figure 34 [1] below.

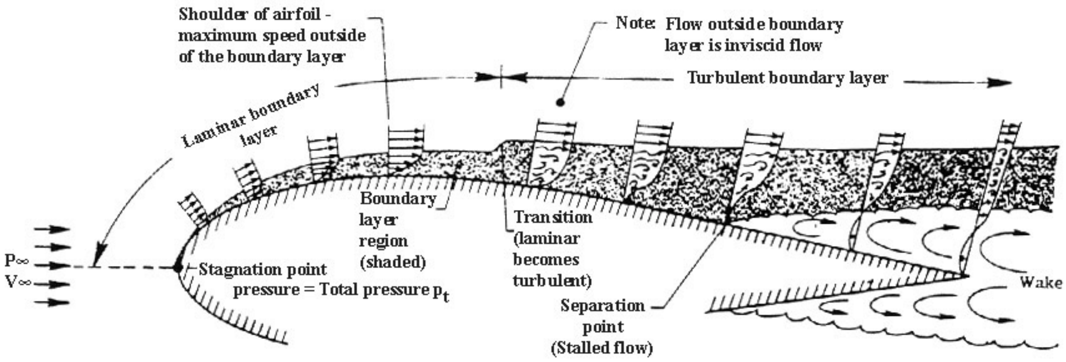

Figure 34 - Flow complexity around a wing section

The aerodynamic boundary layer equation was first defined by Ludwig Prandtl at the third Congress of Mathematicians in Heidelberg, more than a century ago on August 12 1904. In 10 min, he changed the world of aerodynamics and this is still a fundamental theory today.

Boundary layer ingestion

As previously explained, the boundary layer is the location of an important gradient of air speed above aircraft surfaces and studies proved that its ingestion inside an engine is beneficial for the fuel consumption. In fact, this comes from re-energizing the aircraft wake, allowing lower energy waste [1,4].

More precisely, it can be demonstrated that less power is required for aircraft engines to sustain the cruise condition (i.e. where the thrust setting required is equal to the drag force) with boundary layer ingestion [4].

This is illustrated using the two idealized situations in Figure 35 [4].

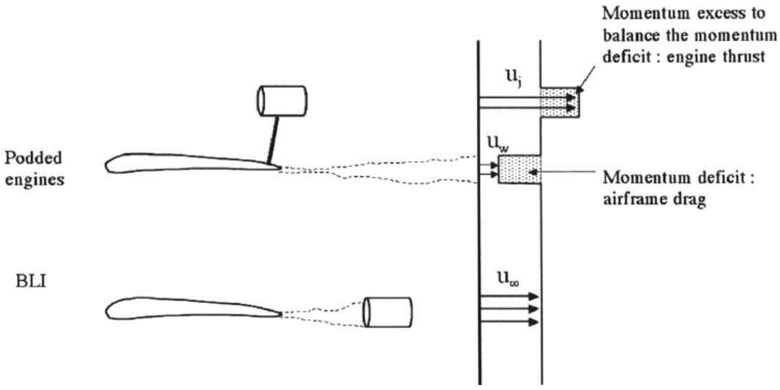

Figure 35 - Illustration of boundary layer ingestion effect on wing downstream flow velocity pattern

In fact, the difference in energy input between the two situations occurs because, for a specific force, less power needs to be added to a flow that enters the engine with a lower velocity [4]:

Consider a flow that enters an engine at velocity V_0 and exits at velocity V_j . The force created by an engine, whose inlet and exhaust are well-designed (no pressure force) and assuming that fuel flow injected is compensated by air leakage toward the outside, is:

$$Thrust = \dot{m}\left(V_{jet} - V_0\right) = \dot{m}\Delta V$$

The power put into the flow is:

$$Power_{flow\ acceleration} = \dot{m}\left(V_{jet}^2 - V_0^2\right) = \frac{F}{2}\left(V_{jet} + V_0\right) = F\left(V_0 + \frac{\Delta V}{2}\right)$$

For a constant mass flow $\dot{m}$ and a constant propulsive force F (because in cruise to maintain horizontal flight the thrust is equal to the drag force on the aircraft, so it is a consequence of the aerodynamics design), ΔV is then constant. A decrease in V_0 results in a decrease in required power.

In other words, for lower engine inlet velocity, i.e. for the case of ingesting boundary layer fluid, the nacelle generates less aerodynamic losses [5] which is interpretated in the engine thrust formula with the term $-\dot{m}V_0$:

- For a same propulsive force, less power is required.
- For a same power, more thrust can be produced.

Propulsive fuselage and its advantages

It is important to note that the term propulsive fuselage refers in literature to concepts of rear engines (not always at the very end of the fuselage after the tail cone) that swallow the BL which growths along the aircraft fuselage (Figure 36 [5]). Therefore, it is fundamentally using BLI, however it is to be distinguished with distributed propulsion (see below, *Difference between propulsive fuselage and distributed propulsion*).

Figure 36 - Single-aisle turboelectric aircraft with an aft boundary layer propulsor STARC ABL

As described above, when using an engine with BLI, for same propulsive force, less power is required or for the same power, more thrust can be produced.

Hence fuel burnt and the specific fuel consumption of this propulsive fuselage aircraft design reduce, by definition of the specific fuel consumption (SFC):

$$SFC = \frac{V_O}{\eta_{th}\,\eta_{prop}\,FHV}$$

with:

η_{th} : The thermal efficiency of the turbofan, how efficiently chemical energy is converted into kinetic energy. This includes the compressor, combustion chamber and turbine behaviors.

η_{prop} : The propulsive efficiency of the turbofan, how efficiently kinetic energy is converted into propulsion. To increase it, the lowest as possible difference between jet velocities of both stream and free stream is required. This can be achieved by a higher BPR or, in our situation, by decreasing the engine's inlet flow velocity V_0. In details, for a single stream exhaust engine (but the reasoning for a two-stream exhaust engine also applies):

$$\eta_{prop} = \frac{2}{1 + \frac{V_{jet}}{V_0}}$$

FHV : the fuel heating value in J/kg, energy released in Joule by the combustion of 1 kg of fuel.

As the engine's inlet velocity V_0 decreases, the SFC decreases. Moreover, there is an improvement (thus an increase) in the propulsive efficiency η_{prop} (defined above): both improve SFC.

Therefore, the main advantage of propulsive fuselage aircraft design is a reduced engine fuel consumption.

But there are also other advantages:

- Reduction of velocity deficit in the aircraft wake as well as a reduction in the propulsor wake, thereby reducing aircraft drag hence fuel consumption [12].
- Reduction of the engine pylon weight
- Less one-engine-out condition [12] in aircraft design, i.e. nearly null yaw moment to compensate with the vertical stabilizer when one engine shuts down.
- No disk burst possibly hitting the fuselage for a tail cone fixed aft engine.
- If the aft engine has propellers, it could be used as thrust reverser [12]:
    - Eliminating the need to tug the aircraft out of its parking area, reducing operational costs substantially
    - Reducing the aircraft landing distance.
    - Allowing steeper aircraft descent, thus reducing the noise footprint near airports on approach
- Downsizing of the underwing turbofans with the thrust contribution of the additional engine [10].
- Adapted to recover part of the drag generated by external bodies on aircraft and significantly improving the performances. For instance, preliminary aircraft design studies for tube-and-wing hydrogen aircraft could involve external hydrogen tanks able to fit enough energy for the design mission. Therefore, to compensate and surpass the additional weight of these tanks, such aft engine could be used [9].

Difference between propulsive fuselage and distributed propulsion

In literature, both concepts of propulsive fuselage and distributed propulsion can be found, and it might be confusing. Figure 38 [6] and Figure 37 [7] show distributed propulsion design:

Figure 38 - ESAero's ECO-150

Figure 37 - VTOL Lilium Jet for autonomous air transportation of 5 passengers

Figure 36 [5] above shows a propulsive fuselage design and Figure 39 [8] below a combination of both distributed propulsion and propulsive fuselage concepts.

Figure 39 - NASA N3-X Distributed Turboelectric Propulsion System

As introduced previously, the propulsive fuselage refers to concepts of rear engines that swallow the BL that grows along the aircraft fuselage (Figure 36 [5]). In a distributed propulsion, engines can be installed at the trailing edge of the wing or more forward towards the leading edge, and the term "fuselage" from "propulsive fuselage" is not therefore adapted.

Moreover, a distributed propulsion often refers to several small electric engines, with the objective to reduce drag over a larger span, to perform different flight control [6], and to decrease the power required by each engine (Figure 39 [8]).

Finally, most propulsive fuselage concepts often concern turbofans using kerosene or alternative fuels such as hydrogen, even if electric motors can be considered.

Although distributed propulsion is based on the same physic principles of BLI discussed above, it is not covered here but in the Electric Propulsion section.

Maturity

Many studies exist about BLI, propulsive fuselage, and their benefits (Figure 40):

- NOVA concept plane, ONERA
- Starc ABL, NASA
- Concept plane, Cambridge University
- D8 NASA / MIT
- CENTRELINE

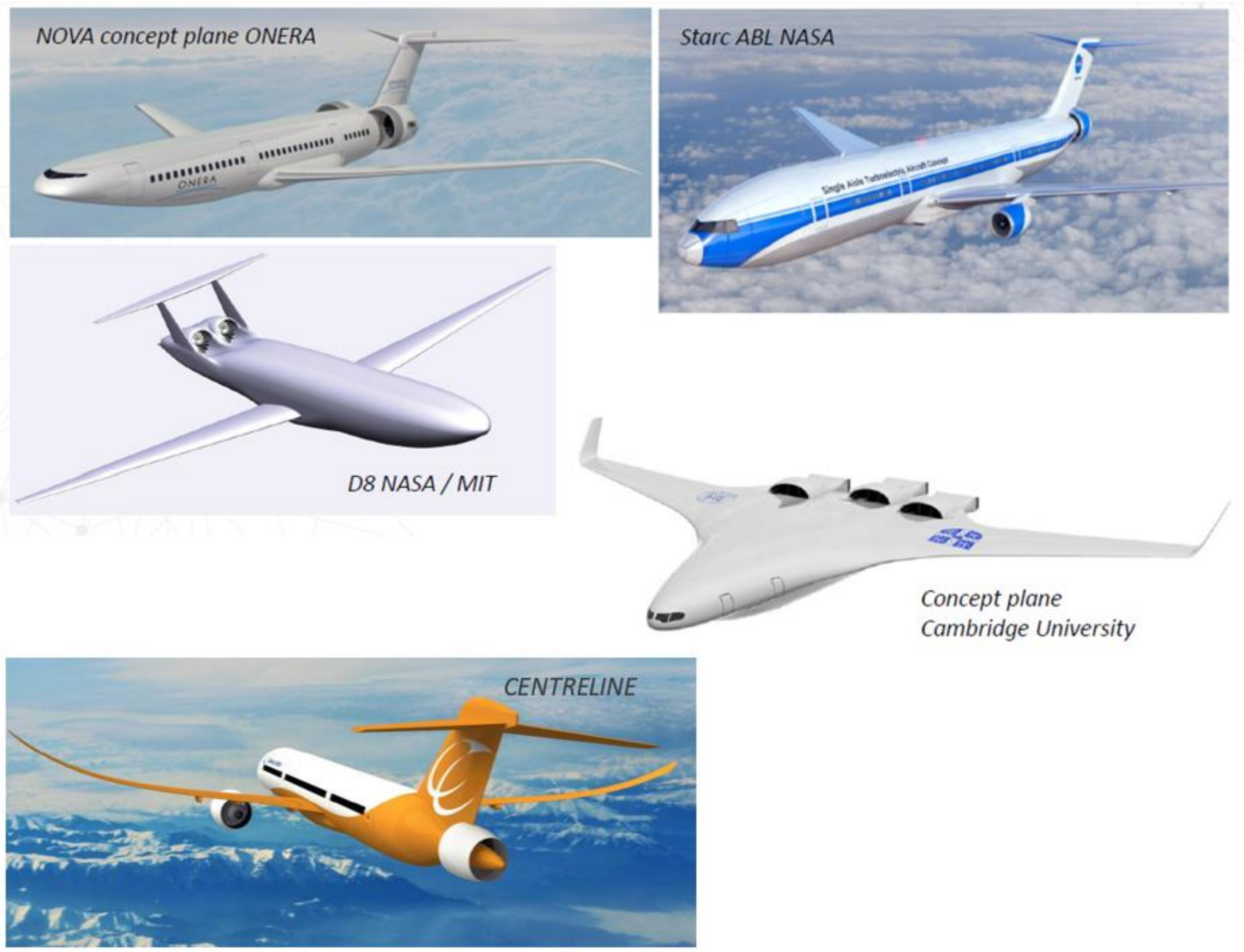

Figure 40 - Most cited BLI aircraft design

Figure 41 - APPU Project presentation

Moreover, the very promising Auxiliary Propulsion and Power Unit (APPU) project (Figure 41 [12]) has been carried out, for 3 years from June 2020 to August 2023, by the University of Delft in the Netherlands, in partnership with TKI (Ministry of Economic Affairs, Netherlands), SAFRAN, Airbus and Rotterdam The Hague Innovation Airport.

The proposed APPU is a novel system that replaces the traditional APU of the A320, with a multifunctional state-of-the-art gas turbine fueled by hydrogen, powering a variable-pitch open-rotor propulsion system at the aft end of the fuselage in a BLI configuration. No conclusions were published, however according to the number of new technologies (hydrogen, open rotor, BLI) introduced, we may estimate a TRL of 2/3.

Very few data are available concerning TRL of all the other concepts, however the most advanced design identified is the Starc ABL of NASA planned to achieve a TRL of 6 by 2025 for an EIS in 2035 [10]. Note that the CENTRELINE project should have reached a TRL of 4 in 2022 [11].

Environmental Impacts

According to the thrust increase / drag reduction of BLI, aircraft with a propulsive fuselage design will have their mission emissions significantly reduced. This implies less CO_2, NOx and water vapor.

Depending on the source [4, 9, 10], studies show fuel consumption reductions of 1% to 15% for a given mission compared to a reference aircraft, so approximately the same percentage in CO_2 and water vapor emissions.

Concerning noise, the aft engine could be used to process steeper descent as it would act as an air-brake (see above). This would help reduce the noise footprint near airports while approaching. However, the disturbed flow swallowed could produce additional vibrations and noise from the fan of the engine [4].

SUITABILITY

Constraints

Most of the constraints of propulsive fuselage are technical and operational.

Boundary layer ingestion

The effect of Boundary Layer Ingestion (BLI) is very difficult to compute, it requires a very precise energy analysis of a flow simulation around the aircraft and inside the engine which is long and costly [1, 5]. It is important to find a simplified method to access the most important benefits at aircraft level.

Moreover, as the boundary layer thickens along a surface as the flow progresses, it is required to correctly assess (with optimization methods) the engine inlet size necessary to capture most of the flow velocity deficit and recovery power. Otherwise, the engine inlet will be either too large, so heavy and fuel consumption penalizing, or not large enough, so not as efficient as expected. For example, according to the design proposed by [10], less than 50% of the boundary layer captured leads to over 70% momentum deficit.

Implementation and operations

The implementation of such aft engines rises a lot of challenges:

- The maximum pitch attitude during take-off and landing (especially for engine fixed on the tail cone);
- The ground clearances in case of banking attitude during take-off, landing or ground maneuvers (especially for engine fixed on the tail cone);
- The aerostructural stability and the engine attachment to the structure;
- The aerodynamic interactions between fuselage, tail, tail cone and the engine inlet;
- Foreign Object Damage during take-off and landing (especially for engine fixed on the tail cone);
- Potentially more water ingestion as water can trickle along the fuselage;

Concerning operations, up to now, air inlets sucking the boundary layer have been carefully avoided in engines because that would drive too strong distortion for the fan, would reduce its efficiency (stall possibility), and would generate additional mechanical efforts due to vibration [1, 4, 5]. In fact, as the boundary layer thickens along a surface as the flow progresses, it is very sensitive to adverse pressure forces at the rear for the fuselage. The diffuser shape for engine inlet might then generate a flow separation, i.e., a disturbed flow which will affect more critically the fan [4]. However, recent studies [13] showed that specific S shape design for inlet can reduce such flow distortion.

Finally, some studies assessed that BLI impacts also the engine Brayton cycle as the overall pressure ratio which is linked to the thermal / core efficiency (see *propulsive fuselage and its advantages*) in a penalizing way [4]. Globally, both propulsive savings and thermal efficiency losses must be assessed to clearly identify the global saving.

Certification Aspects

Certification aspects concerned for propulsive fuselage aircraft design are mostly due to the implementation and the operation for these aft engines.

As discussed previously, especially for an engine fixed on the tail cone, three main certification challenges exist:

- The maximum pitch attitude during take-off and landing
- The ground clearances in case of banking attitude during take-off, landing or ground maneuvers
- Foreign Object Damage during take-off and landing.

For other designs with engines above the fuselage, these can be considered as not critical.

Finally, as evoked above, fan operations would require particular risk assessments.

Aircraft Segments Concerned

All aircraft could theoretically benefit from BLI. However, the additional complexity of the design must be balanced with the drag benefits, and for a propulsive fuselage, this favors an implementation on single-aisles and widebodies aircraft.

APPLICABILITY

Market Acceptance and Barriers

For airlines, as fuel cost represents nearly 15-25% of the total costs, the shift to these technologies would offer significant fuel savings. This would be counterbalanced by additional maintenance costs, that would need to be studied carefully to understand.

For airports, clearance considerations must be analyzed (taxiing, gate, etc.) and ground handling adapted. More studies will be required to understand how infrastructure and maintenance will need to be modified and if the change will be acceptable or not to deal safely with these new engines.

Costs

No input

Implications on Aircraft Designs

Propulsive fuselage technologies are very dependent on the aircraft design. If the wrong design is considered, the implementation and operation of these engines will become too complex, uneconomic or even affecting safety.

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DESCRIPTION

Concept

When the skin of the aircraft is in contact with an airflow, the airflow velocity on the skin is 0 but far from the skin, the airflow velocity is at the True Air Speed (TAS). Consequently, there is an area close to the aircraft skin where the airflow velocity is decreasing from TAS to 0. This area is called the boundary layer (BL) (see section on PROPULSIVE FUSELAGE & BOUNDARY-LAYER INGESTION). This transfer of energy is diffusive at beginning of the flow stream. The flow velocity is steady and smoothly changed inside the BL. This kind of airflow is named laminar flow. But this transfer becomes convective due to chaotic effects, the airflow including then several eddies and being not steady. This kind of flows is named turbulent flow. As the convection transfer is more efficient than the diffusion one, the velocity transition distance is smaller for a turbulent flow than for a laminar flow (Figure 42).

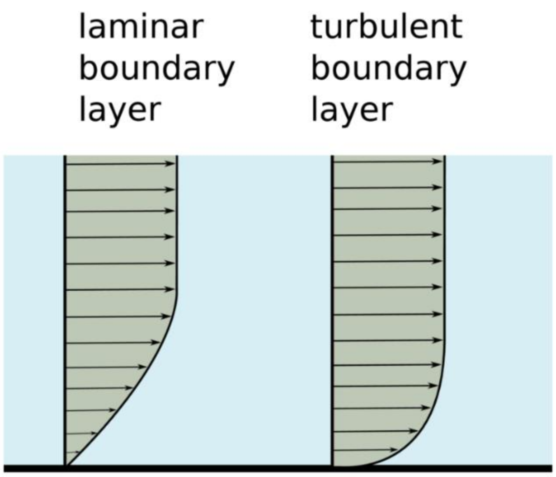

Figure 42 - Difference between laminar fluid flow and turbulent fluid flow, showing the different shapes of the developed boundary layer [10]

Moreover, this variation of velocity in the BL is generating a friction drag force on the skin of the aircraft. This friction force can be defined by [09]:

$$dF = \mu \cdot dS \cdot \frac{\partial V}{\partial n} \quad (1)$$

where:

- F is the drag friction force (N)
- S is the aircraft skin surface (m²)
- μ Is the coefficient of viscosity (Poiseuille)
- n is the distance to the aircraft skin (m)
- V is the velocity of the airflow at n distance (m/s)

The air flow velocity gradient, $\frac{\partial V}{\partial n}$ in the BL is greater for the turbulent flow than for the laminar one. So, according to eq. (1), the friction drag value is greater in turbulent zone than in laminar zone. According to [19], the drag due laminar flow represents around 20% of the drag due to the turbulent one. Moreover, the friction drag is around 48% of total drag on commercial aircraft [09]. For today's commercial aircraft, most of the wet surfaces (wings, tail, fuselage) could be considered to be covered by turbulent BL. Therefore, it is necessary to delay, as far as possible, the airflow transition from laminar to turbulent, in order to reduce significantly the total drag.

Three main types of instabilities are causing the turbulent flow transition (refer to Figure 43):

- Attachment Line Transition (ALT): The airflow stays in the plane of the airfoil but, after transition, the flow is not parallel to the shape of the airfoil and its trajectory is independent from the shape of the foil.

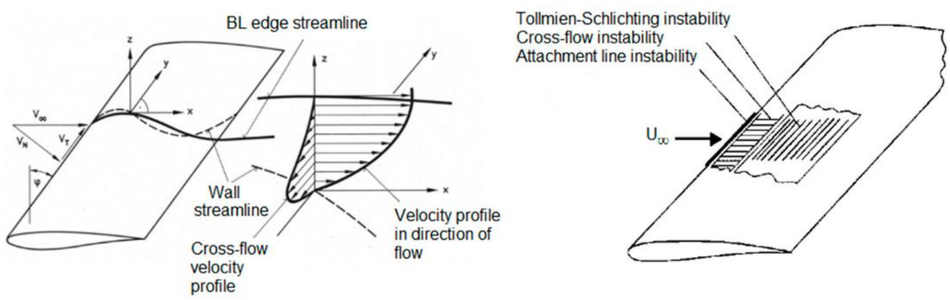

Figure 43 - 3D Boundary Layer on a Swept Wing and related Transition Mechanisms [08]

- Cross Flow Instabilities (CFI): The airflow trajectory has a component in the plane orthogonal to the TAS vector. This instability is most of the time a vortex.
- Tollmien Schlichting Instabilities (TSI): these instabilities are periodic waves that are propagating toward the direction parallel to the airflow.
- The ALT and TSI transitions occur only before 5-10% of the chord. [08]

Several technological development axes can be explored to delay this turbulent transition. Hereafter are the most relevant technologies.

Riblets

Riblets consist in a treatment of the aircraft skin (wing + fuselage + Tail). This treatment is adding some small-sized grooves (around 0.1mm) that are aligned with the airflow and guide it in a given direction. The flow needs therefore more energy to change its trajectory, so the eddies responsible for the turbulent flow are delayed (Figure 44).

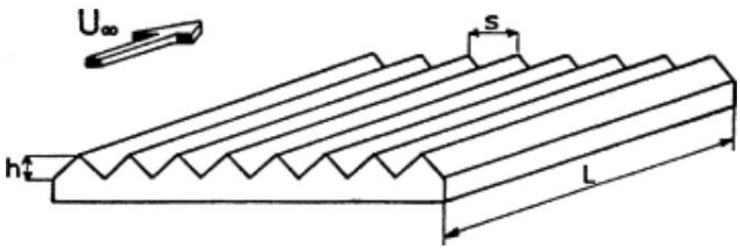

Figure 44 - Riblets surfaces are made of grooves aligned with the flow [11]

The installation of riblets contributes to around 1% reduction in fuel consumption [16]. The surface treatment is replaced periodically every 4-5 years. Moreover, maintenance should keep the surfaces as clean as possible as impurities (dust, insects) downgrade the riblets efficiency.

Natural Laminar Flow (NLF)

The NLF consists in a wing and fuselage geometry design delaying as much as possible the transition to turbulent flow. This geometry aims at reducing all surface imperfections such as door gaps, etc. In addition, the sweep angle of the wing is reduced to lower than 20° and its taper ratio is increased in order to reduce the sweep angle of a given value chord along the wing. The reduction of sweep angle delays largely the CFI type transition. But, due to this change, the cruise Mach number cannot exceed 0.75 [08, 07]. This Mach limitation can however be suppressed with forward swept wings. This configuration keeps delivering higher flow laminarity but rises some aeroelastic constraints that could be mitigated by the properties of Carbon Fiber Reinforced Plastics (CFRP) (Figure 45) [08].

The NLF is expected to reduce the total drag by around 3-15%. [08, 12, 20]. The resulting reduction of fuel consumption is expected to be around 4-10% [12, 16, 07].

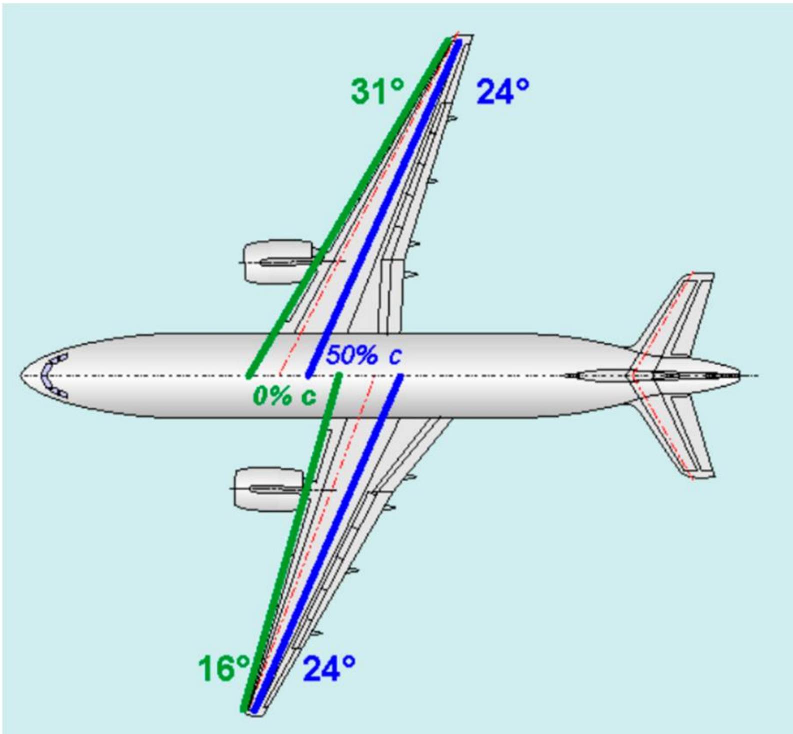

Figure 45 - Effect of taper on moderate aft sweep angle wing (aircraft right side) and on forward swept wing (aircraft left side) [08]

Hybrid Laminar Flow Control (HLFC)

HLFC aims at delaying the turbulent transition using some active controls on the BL airflow. Those controls are called active because they require the supply of external energy.

BL suction device

The Boundary Layer suction consists in aspiration of the airflow at skin level with dedicated pumps. This device stabilizes the airflow and, thus, can delay the turbulent transition (see Figure 46).

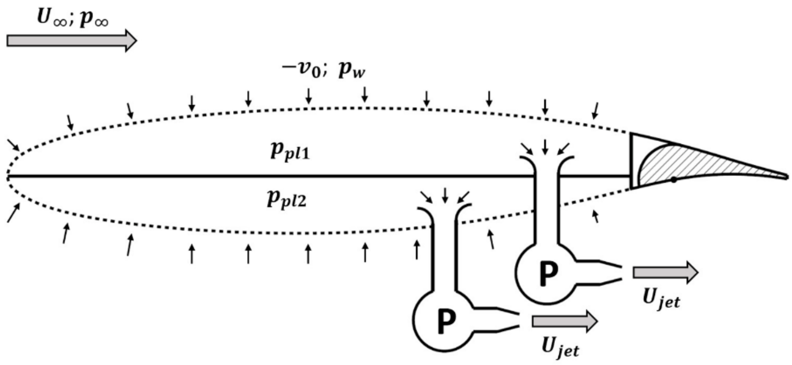

Figure 46 - Components of Suction System: aspiration can be on the whole wing (as above) or just limited to the leading-edge area [08]

This BL suction is proven to be efficient on ALT, TSI and CFI type of transition delays by several Lab test (ALTTA) and flight tests (A320 in 1998). It can delay the transition further to 40% of chord (Figure 47) [08]

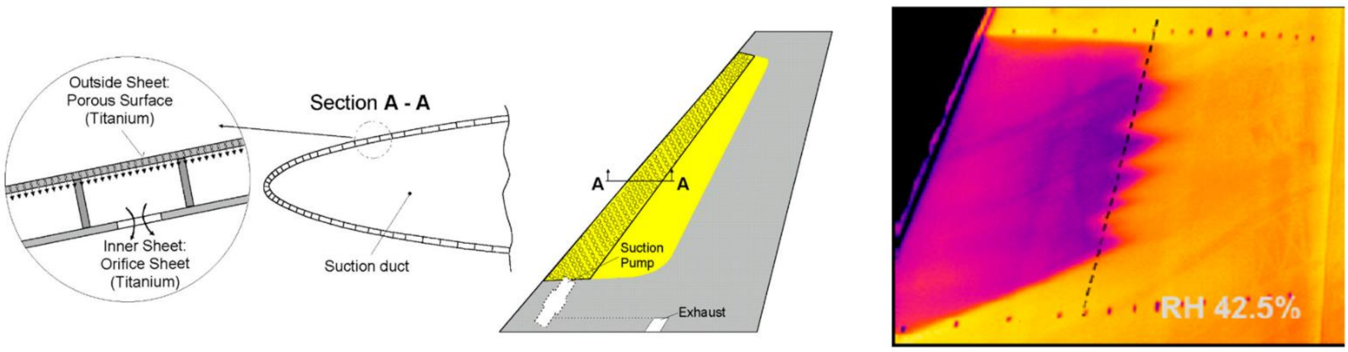

Figure 47 - Resulting laminar zone indication due to leading edge suction during wind tunnel tests, from ALTTA concept [08]

The BL suction application on the leading edge of the wings, the tail, and the fuselage, is expected to reduce the absolute drag by 10% [12] up to almost 30% [08].

The realistic assessment of the mission fuel reduction is around 5% [20]. On the other hand, the most optimistic approach [08] considers an HLFC application coupled with resizing of wing and tail. This brand-new design should result in an outstanding reduction of the mission fuel quantity of around 48% (Figure 48).

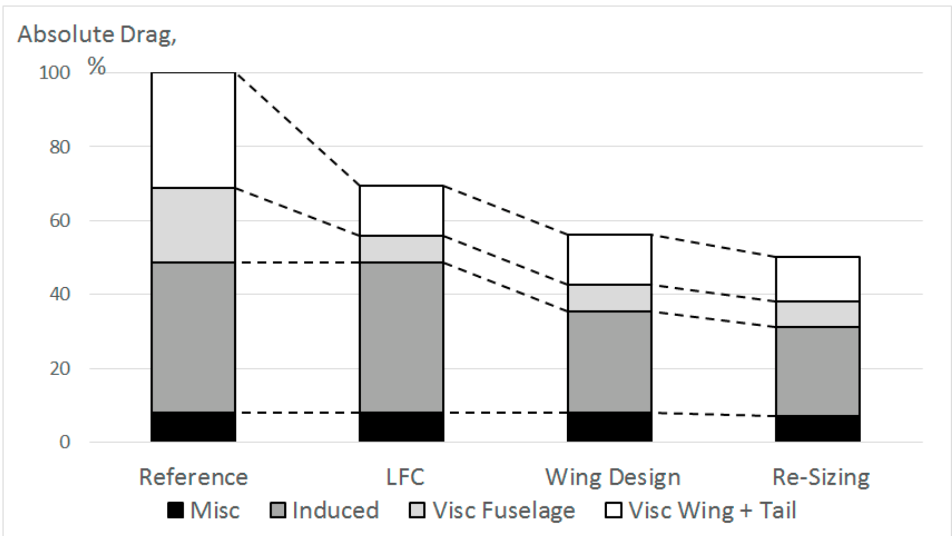

Figure 48 - Viscous Drag Reduction and Effect on Total Aircraft Drag [08]

Others Experimental and theorical HLFC devices

Except BL suction, others HLFC devices were considered to reduce drag. But most of them remains currently at the level of theorical or experimental concept. However, research is still ongoing on those subjects. Here below are mentioned some of the most relevant HLFC devices under research :

- **Cooling or heating surfaces, Researchers' opinions seem to diverge on the subject :**
  In theory it can be proved that to cool surfaces leads to stabilization of the BL hence it postpones the transition from laminar to turbulent [26] . In fact, by studying the sign of the curvature of the velocity distribution at the wall, in a zero-pressure gradient condition, an inflection point exists if the wall is hotter than the gas . This leads to destabilization of the boundary layer.
  However, the experience from [06] shown that heating the leading edge of a wing would induce an increase of the Reynolds number of the flow and a laminar area up to 31% of the chord was observed with a heating at $Re=2.3\ 10^6$. However, no flight test results on this method are available.
  Further experiments are required to clearly assessed this effect.
- **Electrogasdynamic methods of LFC**: those methods aim at generating a plasma corona close to the aircraft skin. To do so, research progress on the dielectric barrier discharge (DBD) [06, 26]. This kind of actuator is therefore capable of directly converting electrical energy into kinetic energy by accelerating the airflow plasma remotely with appropriate magnetic or electric field definition (Figure 49, Figure 50 from [26]).

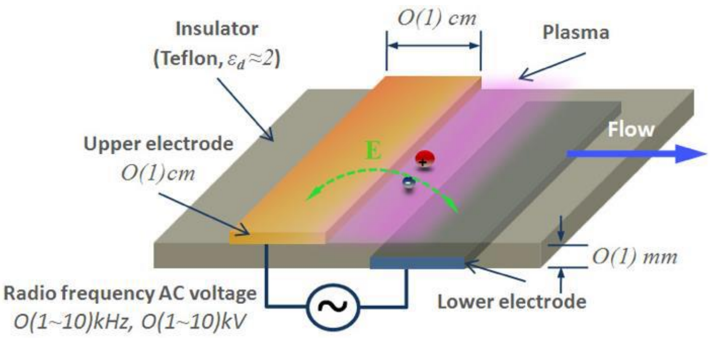

Figure 49 Principle of the plasma actuator

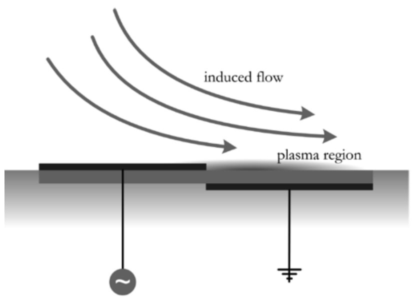

Figure 50 Acceleration of the airflow plasma

Therefore, momentum transfer to the ambient gas is possible without complicated mechanical devices . This successfully damps the amplitude of the TS waves and can delay transition for a significant distance downstream, lowering the skin friction drag of the body [26].

Another possibility is to remote the lift and the thrust by this technology, make something flying without wings and engines (refer to [05, 04]). Although this method is very futuristic, currently it was already proven in lab tests and on very light prototype. The main obstacle is the power necessary to produce the plasma corona that could be comparable to one required by the thrust (see Figure 51). It is also important to mention that the plasma corona generation could cause some ozone pollution in the atmosphere.

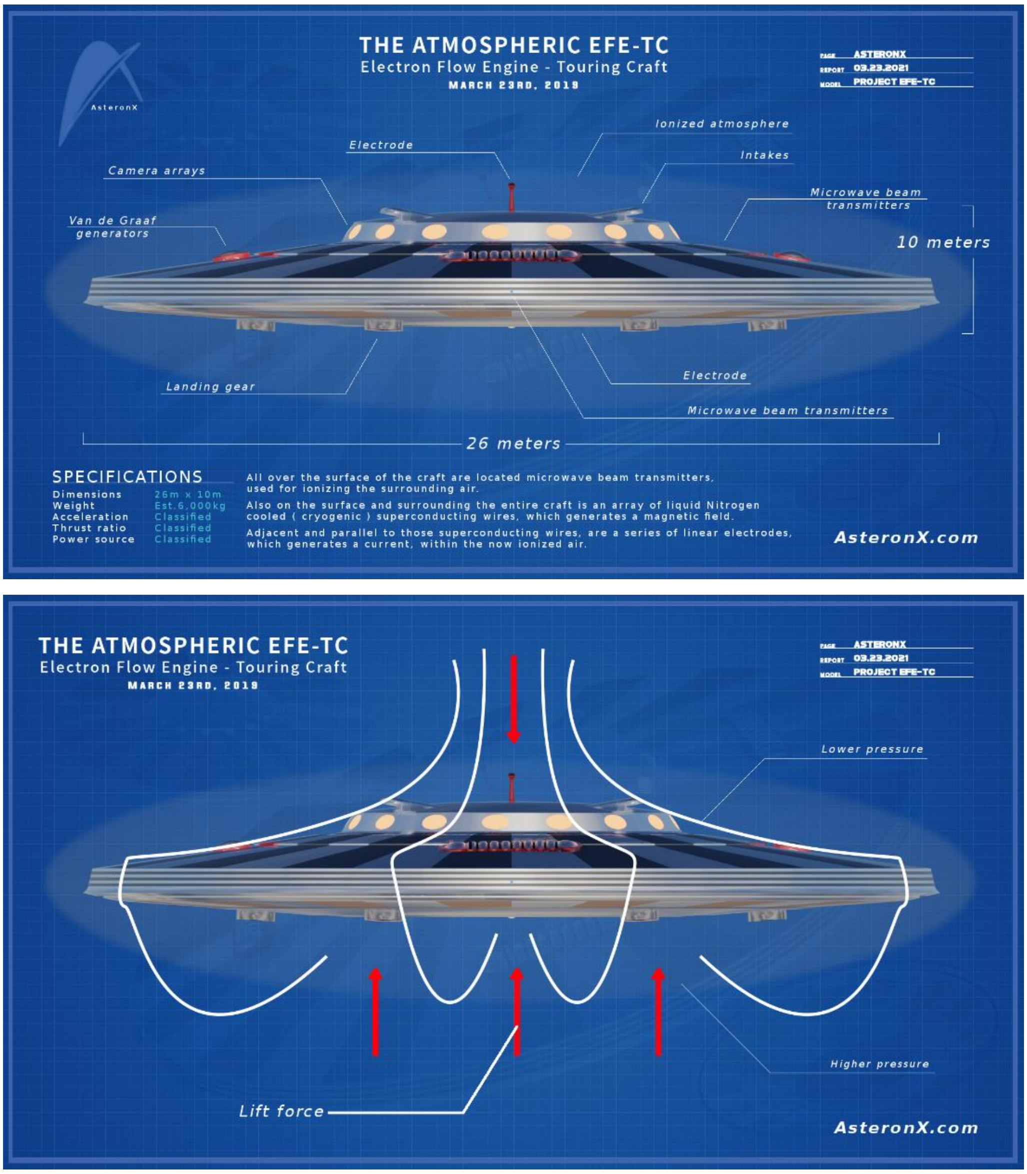

Figure 51 - Example of a plasma-based Magneto Hydro Dynamics air vehicle concept [02]

Some additional theorical studies and ground/flight tests should be undertaken on the two above HLFC methods in order to demonstrate their effective efficiency. Both are not further detailed in the following sections about industrial applications.

Blended Wing Body (BWB)

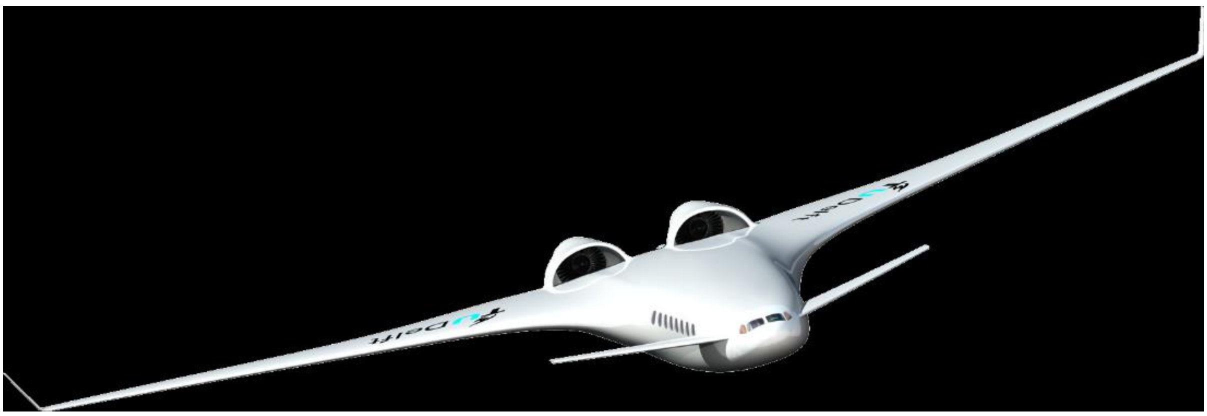

Figure 52 - Blended Wing Body (BWB) concept developed for the AHEAD project [17]

In classical tube-and-wings aircraft (TAW), the tube-shaped fuselage contributes to a slight portion of the drag. This fuselage drag is around 6% of the total drag [09]. Although fuselage drag remains small, it is not associated to any substantial lift. The fuselage drag is therefore substantially increasing fuel consumption.
The idea of blended-wing body (BWB) is to optimize the fuselage airfoil camber to increase the lift produced by the fuselage, and thus, decrease fuel consumption. The fuselage shape is changed from a cylinder to a sort of thick wing shape (Figure 53).

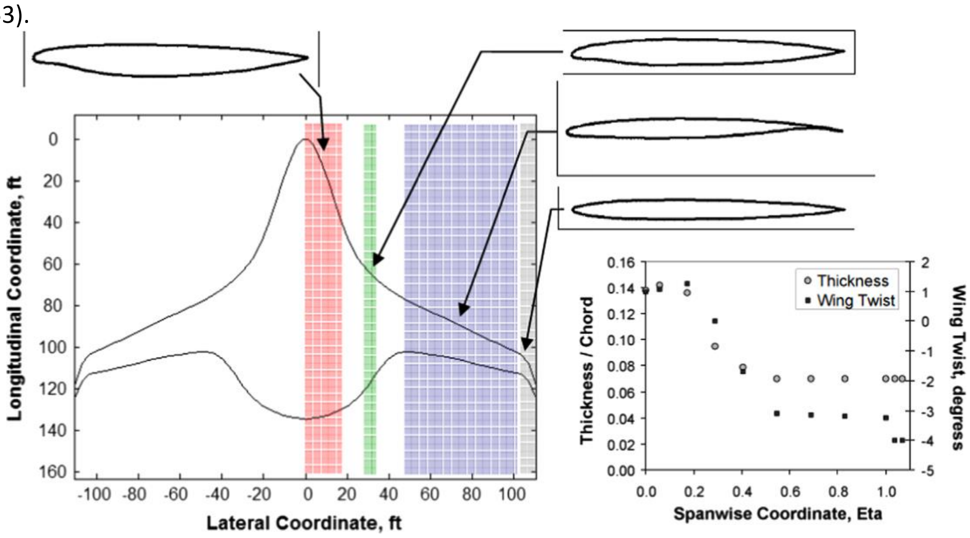

Figure 53 - Example of BWB cross section [24]

Actually, this concept already exists as a military bomber, the B2 Spirit (Figure 54) or the latest B21, but not as a commercial aircraft.

Figure 54 - B2 Spirit [22]

The main challenges for the BWB are:

- The structural loads of pressurization
- The limited emergency exit locations

The load induced by the pressurization of the cylinder-shaped fuselage is almost uniform on each part of the fuselage. However, for a BWB, this pressurization loads are completely function of the location in the fuselage. Indeed, this flat volume tends to become spherical like a balloon when it is pressurized. Consequently, the lateral borders of the fuselage have to sustain some shear load due to those variable constraint value (Figure 55).

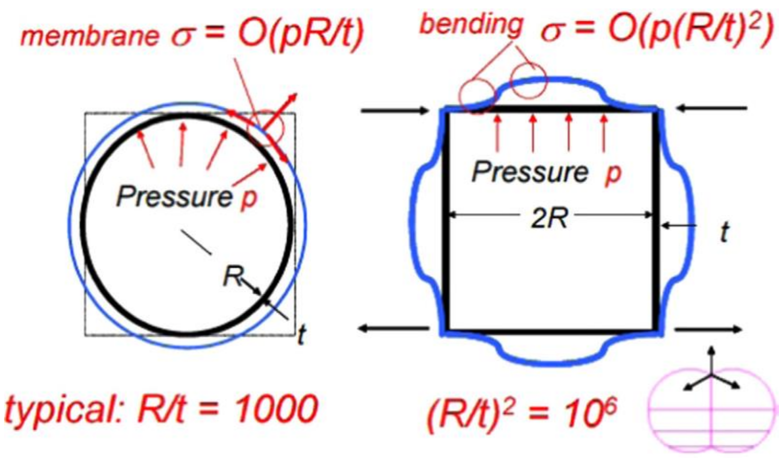

Figure 55 - High-bending stresses resulting from the effect of pressure on the box-like shape of the BWB vs TAW cylinder shape [24]

Thus, in the study [23], It was shown that it is possible to design a fuselage shell with sufficient safety margin comprising new materials and a Finite Elements approach. In the BWB concept, the fuselage includes a specific pressure that can sustain the relevant pressure load (Figure 56).

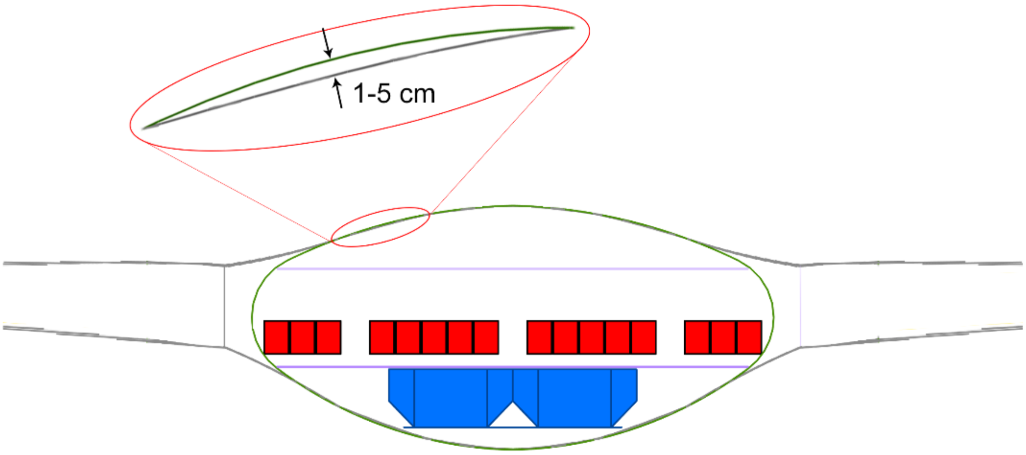

Figure 56 - Cross-section through the oval fuselage showing the cabin and cargo with a detail of the difference between the aerodynamic and pressure shell [25]

Emergency exits are also a challenge for the BWB aircraft when considering a high number of seats (above 400). Indeed, the thickness of the wing root prevents the installation of emergency exits at the junction of the fuselage and the wing. However, the study [24] has assessed that it was possible to design emergency exits complying with the relevant safety rules on a 1000+ seat BWB aircraft (Figure 57).

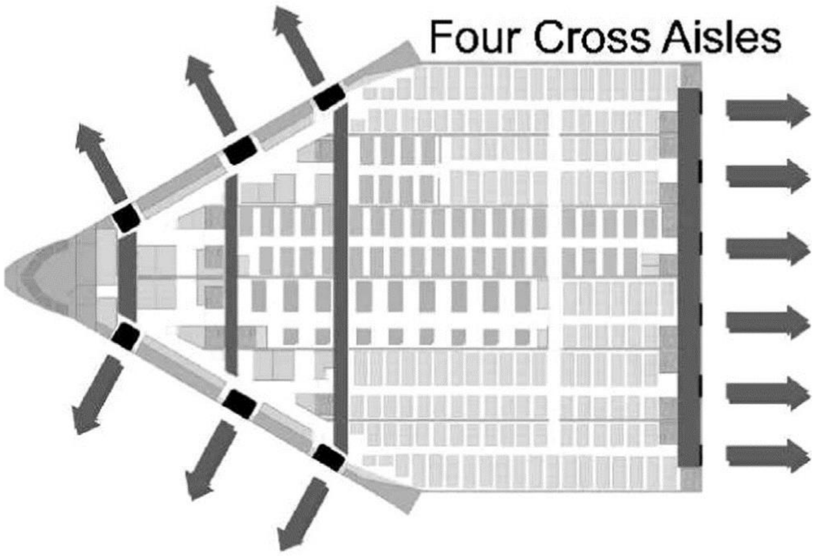

Figure 57 - Liebeck cabin concept to aid emergency evacuation [24]

The study [25] reports a comparison between both TAW and BWB concepts among three ranges of pax seat count:

- 156 seats for TAW150 and BWB150
- 248 seats for TAW250 and BWB250
- 368 seats for TAW400 and BWB400

Results of this study are summarized in the Figure 58. Although the space occupation remains similar between TAW and BWB, the best fuel saving is expected on the BWB250 with 24% lower fuel. It also assessed that the cumulated fuel burn per passenger kilometer could reach a 30% fuel saving.

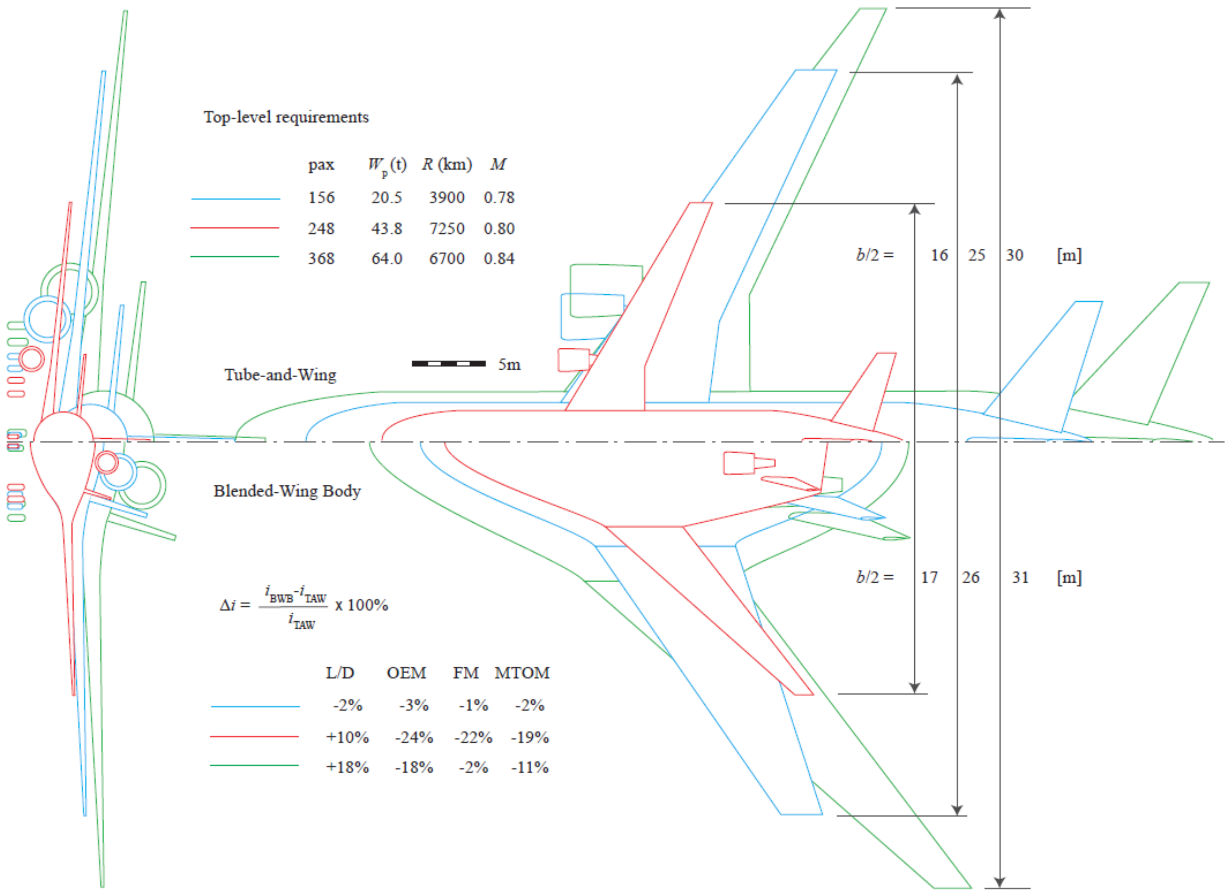

Figure 58 - Aircraft geometry and layout for tube-and-wing and blended-wing-body aircraft for three different top-level requirement sets along with the effect on the following performance indicators: aerodynamic efficiency during cruise (L/D), operating empty mass (OEM), fuel mass required to fly the harmonic mission (FM), and the maximum take-off mass (MTOM)[25]

Maturity

Riblets

The Riblets technology is almost available and can be provided by some industrial suppliers such as Lufthansa Technik and BASF, such as the AeroSHARK product [21] (Figure 59).

Figure 59 - AeroSHARK film installation [21]

Today, technological efficiency has been demonstrated and the technology is ready to enter into operations through retrofits. Technical Readiness level (TRL) is therefore at 8 [14, 16, 18].

Natural Laminar Flow (NLF)

NLF was demonstrated in flight test bed such as the BLADE (Breakthrough Laminar Aircraft Demonstrator in Europe) demonstrator (Figure 60) where some NLF areas were installed at the wingtip of an A340. Due to the moderate sweep angle, the cruise Mach had to stay lower than 0.74 instead of the usual Mach 0.82 [190].

NLF has not been yet implemented on most existing aircraft, except on very limited areas, such as, for instance, on the Boeing 787 nacelles [19]. Consequently, the TRL allocated to NLF is assessed at 3 [13]. According to [15], the NLF availability is expected during the 2025-2030 timeline.

Figure 60 - A340 Laminar Flow BLADE demonstrator first flight [16]

Hybrid Laminar Flow Control (HLFC)

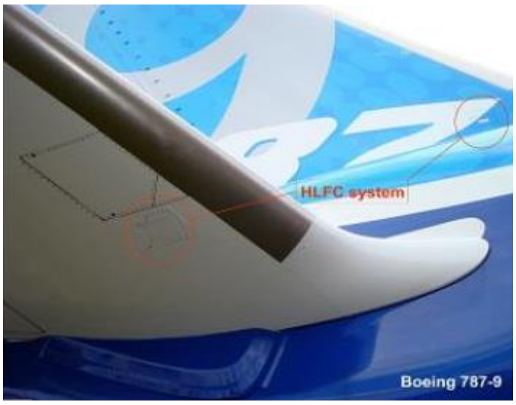

Figure 61 - HLFC on the fin of the 787-9 [01]

The BL suction was proven to be efficient. Moreover, such a device was partially installed on existing aircraft such as the fin of the 787 [19] (Figure 61). In some cases, it could be installed through retrofit. Thus, the TRL of BL suction is around 4 for a full implementation [12], which could be to be available by 2025-2030 [15].

Blended Wing Body (BWB)

This concept has been existing for a long time on several military aircraft without any pressurization. It has never been used in commercial aviation. This technology is expected to be available between 2025 [16] and 2035 [14]. The TRL of BWB is expected to be around 1 to 3 [18] because research works are still ongoing on those subjects.

Environmental Impacts

The implementation of these various technologies contributes to reduce the fuel consumption, hence emissions, as documented in the Description section above.

Riblets

There is no other environmental impact except for the plastic wastes as riblets films must be periodically replaced every 4 to 5 years.

Natural Laminar Flow (NLF)

NLF has no other environmental impact because it consists just in a redesign of the geometry of the aircraft.

Hybrid Laminar Flow Control (HLFC): BL suction device

To be efficient, Boundary layer suction requires a pump, implying some power supply which can be potentially responsible for some additional fuel consumption. According to [08], the power of the pump is completely compensated by the drag reduction because the power of the pump represents only 7% of the power saved by this device. We can therefore assume that BL suction has no other environment impact.

Blended Wing Body (BWB)

This technology does not introduce any other additional environmental impacts compared to the existing TAW.

SUITABILITY

Constraints

Riblets

This technology is almost available. So, most industrial and certification obstacles are almost cleared.

Natural Laminar Flow (NLF)

NLF with a moderate aft sweep angle is limited to a cruise Mach under 0.74 due to the wave drag constraints. This increases travel times for passengers. However, NLF with forward swept wing does not have any Mach limitation, however it raises some aeroelastic constraints. This requires to introduce some new challenging technologies on CFRP.
NLF is affecting the structural design of the aircraft. So, it cannot be implemented on existing aircraft through a simple retrofit.

Hybrid Laminar Flow Control (HLFC): BL suction device

The main challenges of the BL suction technologies are:

- the ability to develop efficient porous aircraft skin with associated aspiration systems,
- the treatment of the surface discontinuity, or impurities such as dust, rain, or ice that can clog the aspiration systems,
- the interaction with the propulsion, anti-ice, high-lift systems

Such device also requires some specific maintenance to clean all the impurities (dust, water or ice) that could impair the aspiration systems.

Blended Wing Body (BWB)

Although some military BWB already exist, no commercial BWB aircraft has yet been designed. The main challenges for this concept are:

- the lack of place for emergency exit at the junction between the fuselage and the wings,
- the flow instabilities due to the length of the fuselage cord,
- the structural reinforcements required by the pressurization loads.

However, current ongoing researches seem to propose viable solutions to those challenges.

Certification Aspects

Riblets

Riblets can be installed on the existing aircraft through retrofits [18]. The safety concern of losing riblet films in flight must be evaluated for engine ingestion, flight control masking, or any aerodynamic downgrade. Riblets installation could be certified as a Supplemental Type Certification (STC).

Natural Laminar Flow (NLF)

NLF are applied in the development stage of new aircraft programs. This requires a complete type certification process. NLF with forward swept wing includes some uncertainties on the aeroelastic properties of the wings. This could be complex to certify.

Hybrid Laminar Flow Control (HLFC): BL suction device

It should be possible to implement the BL suction on all existing aircraft. However, such an installation could be complicated as a new porous skin should be installed with an associated aspiration system. Those systems need an additional place that is currently used by the fuel tank or other systems in the fuselage. Consequently, this device could be implemented in some specific cases through retrofits and STC if no impact on the main structure. Otherwise, a new program and specific type certification are necessary.

Blended Wing Body (BWB)

The BWB requires a complete review of the hull structure. So, a new program type certification is required. The main obstacle foreseen for this certification remains the emergency exit configuration that must be compliant with the current CS25 rules.

Aircraft Segments Concerned

Riblets

According to [18], riblets are most efficient on long-haul aircraft.

Natural Laminar Flow (NLF)

NLF is applicable from regional aircraft [13] up to single-aisles and long-range aircraft.

Hybrid Laminar Flow Control (HLFC): BL suction device

According to [12], the BL suction technology should be efficient on long-range and large passenger aircraft.

Blended Wing Body (BWB)

As stated in the concept description, the optimal configuration of BWB is obtained for 250-seaters, so for large single-aisles or small long-range aircraft.

APPLICABILITY

Market Acceptance and Barriers

Riblets

No information about market acceptance or barriers could be found. However, today, there is no noticeable barriers identified for the riblets technology.

Natural Laminar Flow (NLF)

The reduction of cruise Mach could downgrade the attractivity of this technology in terms of travel offering.

Hybrid Laminar Flow Control (HLFC): BL suction device

No information about market acceptance or barriers could be found. However, today, there is no noticeable market barriers identified for the BL suction technology. As listed in section “Constraints”, there are several technical barriers to be cleared before any industrial implementation.

Blended Wing Body (BWB)

The lack of BWB windows could slightly affect attractivity for passengers. However, this could be compensated with inflight entertainment systems or roof windows.

Costs

Riblets

No information about the cost of this installation was found. The periodic replacement of riblet films would increase maintenance costs of this technology. However, we can assume that the implementation cost should be minor as it is simple to apply and the technology is very mature.

Natural Laminar Flow (NLF)

This technology requires large initial investments linked to the design of new programs with challenges in terms of aerodynamics and aerostructures.

Hybrid Laminar Flow Control (HLFC): BL suction device

Although the BL suction could possibly be implemented through retrofits, the initial investment for this technology remains high, because it implies major changes on a large part of the skins and several insertions of an aspiration system.

Blended Wing Body (BWB)

The BWB is a new concept that requires several experimentations and a new type certification. The initial investment for this technology is expected to be substantial.

Implications on Aircraft Designs

Riblets

Riblets are not affecting the aircraft structure and it is comparable to a painting process.

Natural Laminar Flow (NLF)

The NLF with swept forward wings implies new technology in material (CFRP) and in the artificial stabilization of naturally unstable aircraft. Canard controls could replace the vertical tail plane due to the shift of wing location afterward (Figure 62).

Figure 62 - Grumman X-29 displaying forward-swept wing configuration, Source: NASA Photo Number: EC87-0182-14, Public Domain, https://commons.wikimedia.org/w/index.php?curid=1479146

Hybrid Laminar Flow Control (HLFC): BL suction device

The BL suction requires some aspiration systems and the replacement of large areas of the wing and fuselage surfaces. These devices have to be implemented close to the existing aircraft systems such as powerplant, fuel tanks, anti-ice, high lift. These interactions could make the implementation more complex.

Blended Wing Body (BWB)

This technology requires a complete review of the structure, flight control laws, configuration of the pax seats, cargo, engines, and the fuel tank locations.

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DESCRIPTION

Concept

The induced drag mainly depends on the lift value. In fact, the airflow around an aircraft wing foil is causing a high pressure under the foil area named inboard / high pressure surface, and a low pressure above the foil named outboard / low pressure surface. At wingtip, high pressure air from inboard can rotate around the wingtip to go to the low pressure of the outboard. This rotation is generating vortexes at each wingtip (see Figure 63).

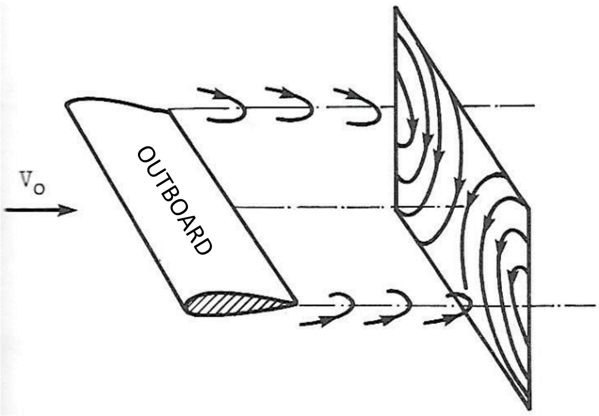


Figure 63 - Generation of the wingtip vortex [01]

This vortex exists at the wingtip and after the trailing edge of the foil, but extends also before the leading edge of the foil. Consequently, the downwash, W_i , in the plane orthogonal to the airflow direction is updating slightly the angle of attack by ϕ , value of this induced angle (Figure 64).

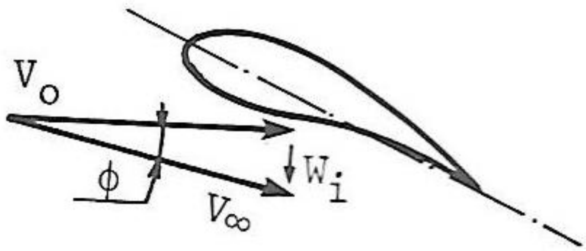


Figure 64 - Induced Angle definition [01]

The value of induced angle is given by the Prandt formula here below:

$$\phi_{rad} = \frac{C_L}{\pi\lambda} \qquad \text{(Eq 1)}$$

with:

- ϕ_{rad} is the value of ϕ in radian unit
- C_L is the aerodynamic coefficient of lift

λ Is the value of the aspect ratio (noted also AR in this document): $\lambda = \frac{b^2}{S}$; b is the wingspan and S is the reference surface.

This change of the angle of attack modifies the aerodynamic coordinates system by a pitch rotation. This causes the lift force to have a component on the drag axis, called induced drag (Figure 65).

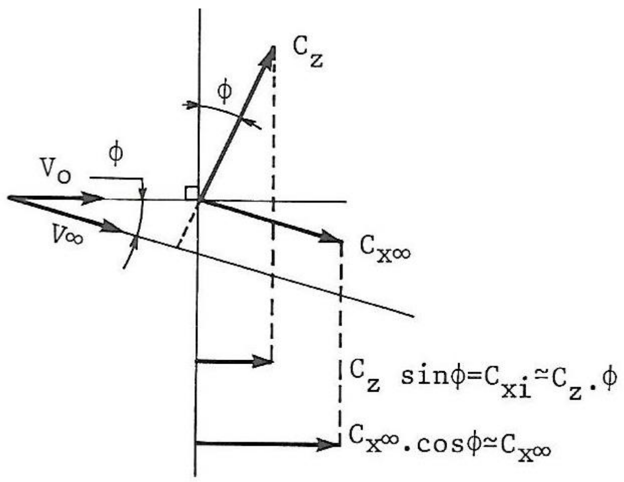


Figure 65 - Induced drag definition (Cz is the lift and Cx the drag) [01]

Therefore, according to the lifting-line Theory of Prandtl for an elliptic lift distribution on the wing, the induced drag coefficient, C_D, is detailed by the below formula resulting from (Eq 1) and the Figure 65 [01]:

$$C_D = \frac{C_L^2}{\pi\lambda} \qquad \text{(Eq 2)}$$

The induced drag represents 37% of the total drag of an aircraft [01]. This is the second contributor to total drag just behind the friction drag. Consequently, the induced drag reduction is a major lever to lower fuel consumption.
There are two main ways to reduce the induced drag:

- The reduction of the vortex intensity by dihedral angle
- The increase of the aspect ratio, λ, with higher wingspan value, b

Several systems have been designed to reduce the induced drag.

Classical winglets

Figure 66 - Learjet Longhorn 50 series equipped with winglets [06]

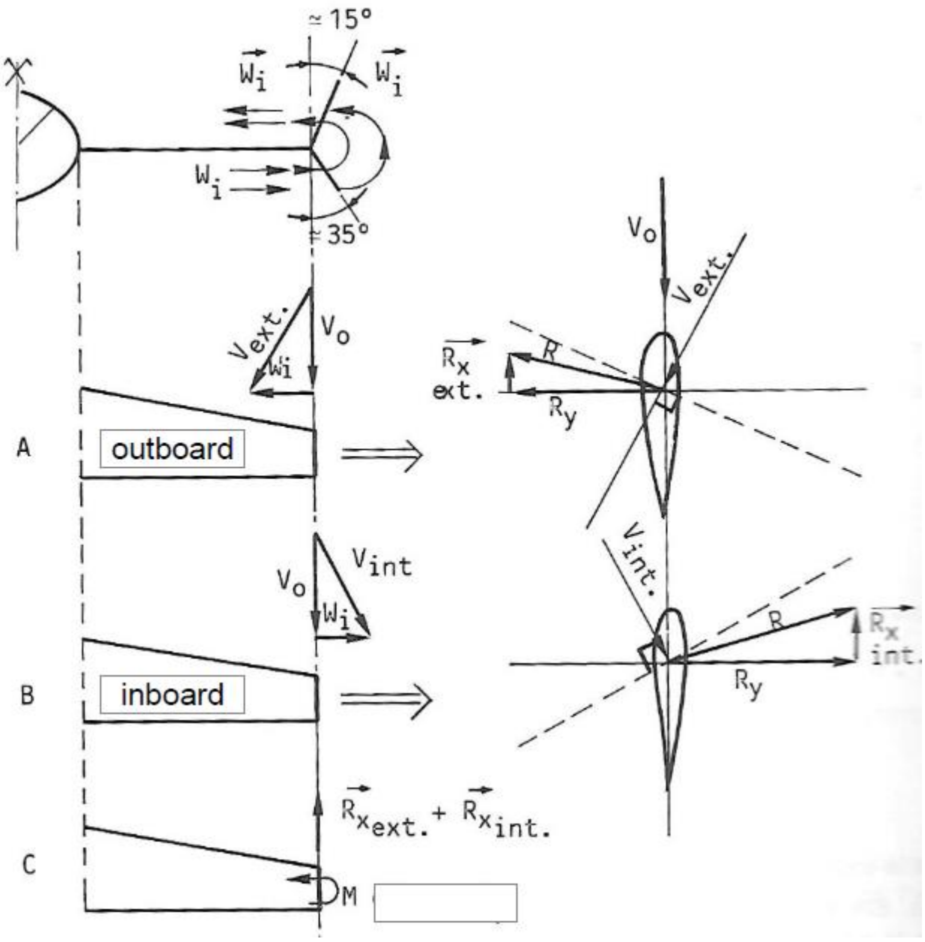
Winglets are small wings that are inserted at the wingtips. This technology was actually introduced in the 1970s [16]. For example, winglets have equipped the Learjet Longhorn since 1978 (see Figure 66).

Those small wings are perpendicular or with an angle compared to the main wing plan, like in Figure 67. Such wingtip devices were widely used on most aircraft during the last 40 years, and have proven very efficient in terms of fuel burn reduction.

In Figure 67, there are two winglets, one toward inboard and another toward outboard. The subparts A and B show that the vortex airflow on the outboard and inboard winglets provides the component forces, $R_{x_{ext}}$ and $R_{x_{int}}$ at opposite side of drag:

$$C_{Dwinglet} = \frac{C_L^2}{\pi\lambda} - C_{ext} - C_{int} \leq \frac{C_L^2}{\pi\lambda} \qquad \text{(Eq 3)}$$

With C_{ext} and C_{int} the aerodynamic coefficients associated with $R_{x_{ext}}$ and $R_{x_{int}}$.



So, this contributes to a decrease of the induced drag by a projection of the lift in the direction of translation of the aircraft : an additional component to the thrust. Due to this decrease, Eq 2 becomes:

$$C_{Dwinglet} = \frac{C_L^2}{e\pi\lambda} \quad \text{(Eq 4)}$$

e is the Oswald's efficiency factor or span efficiency factor (e>1). Here below the indicative values of this *e* factor are given in Figure 68, for several type of wings.

Figure 67 - Classical winglet description [01]

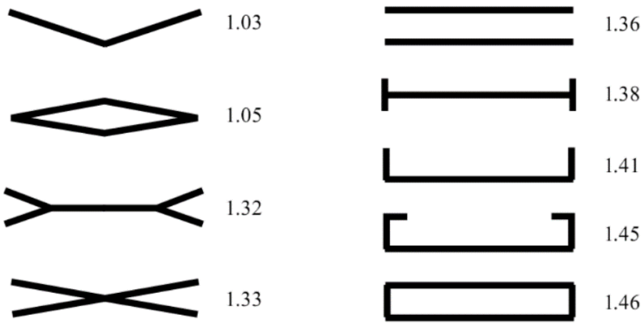


Figure 68 - Indicative values of e, the span efficiency factor for several basic shapes of wing [13]

Consequently, the winglet is equivalent to an increase of the aspect ratio, λ by a factor *e* [13]. It is commonly admitted that such classical wingtip devices can reduce fuel consumption by around 1.5% [01].

Blended winglet

Figure 69 - Blended Winglet of A350XWB
Source: Laurent ERRERA from L'Union, France — DSC_8030-F-WZGG - MSN 003 (Uploaded by Russavia)

Classical winglets are inducing an abrupt change of the dihedral angle from wing to winglet as it can be seen in Figure 66. However, blended winglets change the dihedral angle very smoothly, as presented in Figure 69.
This causes the vortex normally appearing at the junction between the classical winglets and the main wing, to appear at the edge of the blended winglets. Another effect of the smooth change of the dihedral angle is the reduction of the inboard pressure and the increase of the outboard pressure at the edge of the winglets. Consequently, the pressure difference between inboard and outboard is reduced, so the resulting vortex intensity is reduced. The induced drag thus decreases and the lift-to-drag ratio increases. Most of the latest installed winglets are blended winglets. Those can be installed in new aircraft programs but also as retrofits to existing aircraft.
Blended winglets reduce fuel consumption by 3% to 6% [11].

Foldable wingtips

In the scope of reducing the induced drag, foldable wingtips associate the reduction of the vortex intensity and the increase of the aspect ratio. Actually, since World War II, folding wings have been used by military aircraft to reduce storage space inside carrier ships (Figure 70).

Figure 70 - Corsair F4U-4 folding its wings
Source: Wikipedia

This concern of storage space or ramp space at the airport also applies to foldable wingtips on commercial aircraft. Folding wingtips are unfolded in flight. So, the in-flight aspect ratio increases, reducing the induced drag according to Eq 2. However, on the ground, wingtips are folded. So, the wingspan is reduced, and the aircraft is able to comply with limited space airport facilities in terms of gate and taxiways.

It must be added that folding wingtip devices require an actuator to fold and unfold the wingtips (Figure 71).

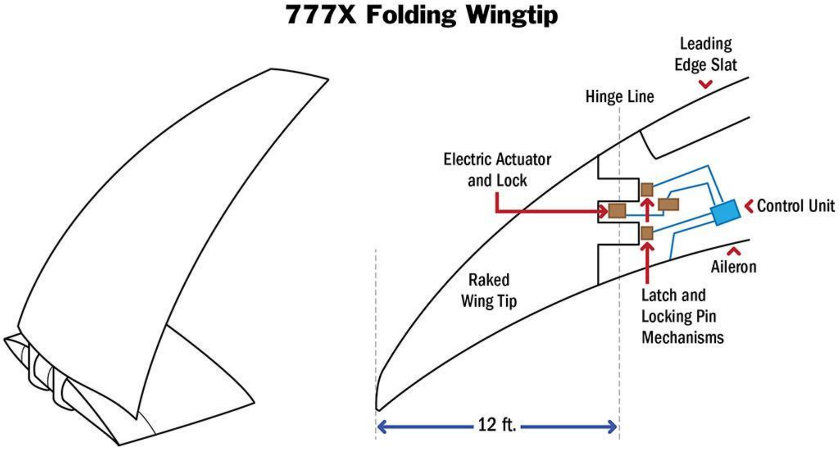


Figure 71 - 777X Folding Wingtip, Source: Jon Ostrower, the Air Current

According to [08], the Boeing 777X (Figure 72) equipped with folding wingtips is designed to use 20% less fuel than the previous-generation 777, though it is still able to use the same category of airport gates.

Figure 72 - 777X with its wingtips folded [08]

In this example, wingtips are unfolded and locked in this position during the flight. So, in addition to the high aspect ratio, the only benefit is maintaining the access to existing airport facilities.
Actually, there could be other benefits from folding wingtips, when this folding device is actuated in flight. In [14], the suitability of folding wingtips was analyzed for a use with an in-flight actuator called FOLDing wingtips sERving as cONtrol effectorS (FOLDERONS). Figure 73 details several options of hinge actuator in flight.

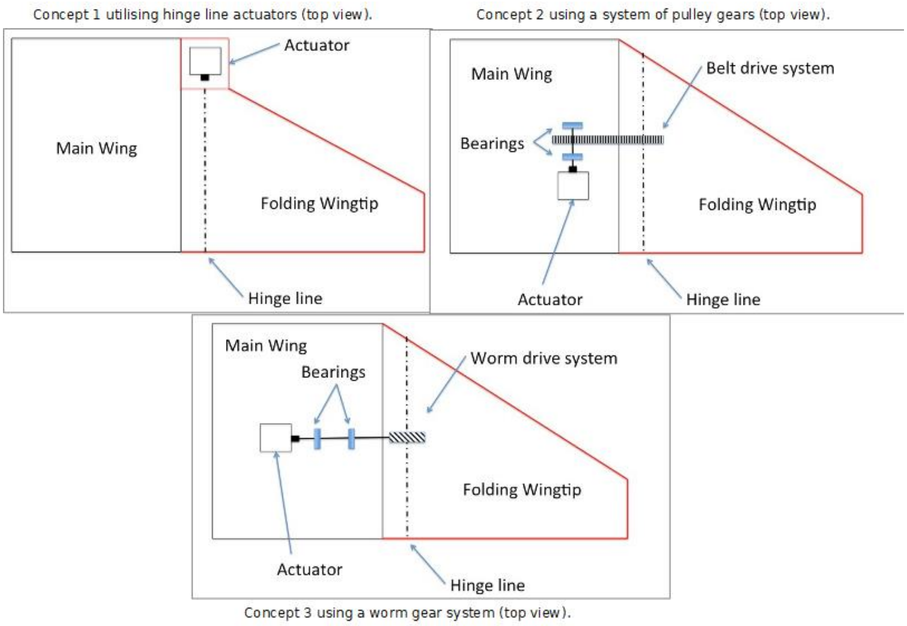


Figure 73 - FOLDERONS Hinge actuator concepts [14]

From the study [14], it appears that FOLDERONS are not able to replace ailerons as the roll moment is lower than the one of ailerons. However, high aspect-ratio wings tend to reduce the ailerons efficiency. So, FOLDERONS could help provide the necessary improvement of the aileron efficiency.

In addition, FOLDERONS can also be used like winglets with a variable fold angle. Today's winglets are designed with a fixed fold angle optimized for given flight conditions. In Figure 74, it is noticeable that fixed winglets are not optimized on the whole range of the polar curve.

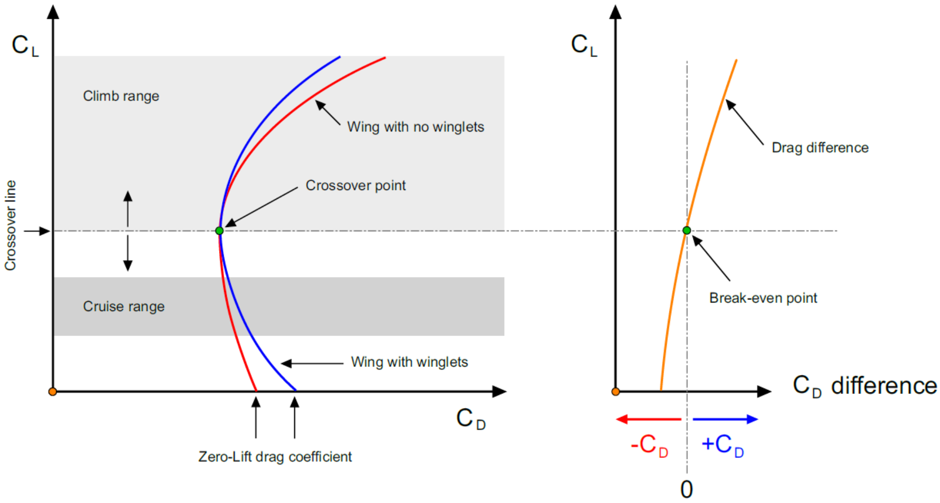


Figure 74 - Comparison of drag polars for a clean wing and a wing with winglet installed (C_D is the drag coefficient and C_L is the lift coefficient). On the left image, grey areas represent the climb range and the cruise range of the wing. The right image shows the drag difference, where negative C_D means drag increment and positive C_D means drag reduction. The C_D difference is the C_D delta between the wing with winglets and the wing without winglets [09]

However, study [09] suggests that an optimized control of the fold angle of the folding wingtip during the whole flight provides some noticeable improvements to the total drag.

Both arguments mentioned above are in favor of generalizing the control of the fold angle during the flight in order to improve the controllability and the drag reduction. Of course, this activation of the hinge control in flight must be compensated by the expected benefits of the variable fold angle wingtips.

Strut/ Truss-Braced wing

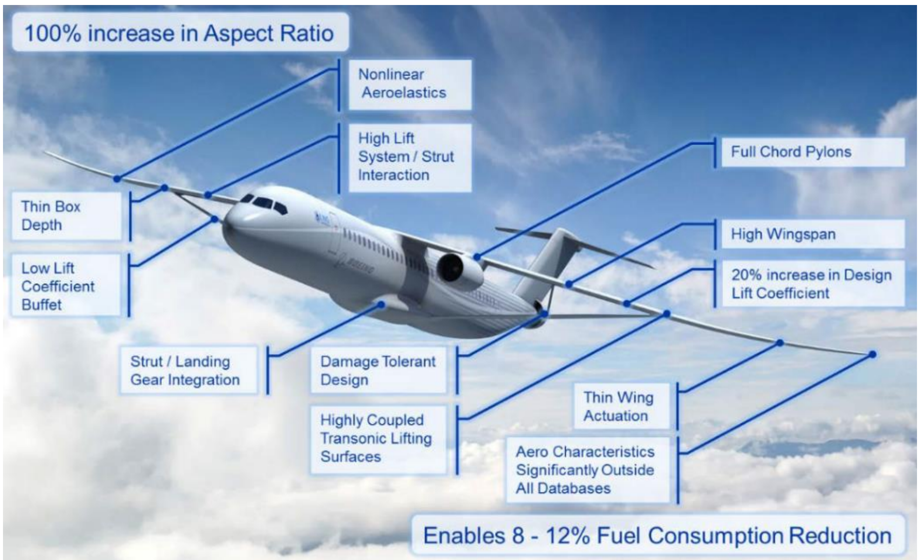


Figure 75 - Transonic Truss-Braced Wing (TTBW) [07]

According to Eq 2, the induced drag is reduced by increasing the aspect ratio, λ, with higher wingspan. However, this higher wingspan is increasing the lever arm at wing root (due to the shear efforts between lift and weight), and thus the weight due to the resulting structural reinforcements needed to compensate this additional torque. The concept of strut or truss-braced wing is based on the reduction of this wing root torque by adding one or several struts along the wing to reduce the load of the wing. Based on a high-wing configuration, those struts transfer the lift load from the wing to the lower part of the fuselage (Figure 75). Thanks to this concept, the wingspan can almost be doubled. Based on Eq 2, the induced drag is expected to be therefore decreased by half.

This concept was used on several existing aircraft such as the Hurel-Dubois HD.31, HD.32, and HD.34 in the 1950s and 1960s (Figure 76). Hurel-Dubois planned to develop a turbojet version, the HD.45, but this project got rejected and the HD.45 never produced.

Figure 76 - The Hurel-Dubois HD.31 in flight, source: U.S. Navy Naval Aviation News September 1956

In light of growing decarbonization efforts, the concept of strut/truss-braced wing was given another consideration. In this scope, the study [10] assessed a comparison among four concepts: cantilever (classical high-wing configuration without strut), unique strut-braced wing (SBW), and two truss-braced wing (TBW) concepts, named Jury and 2-Jury (Figure 77).

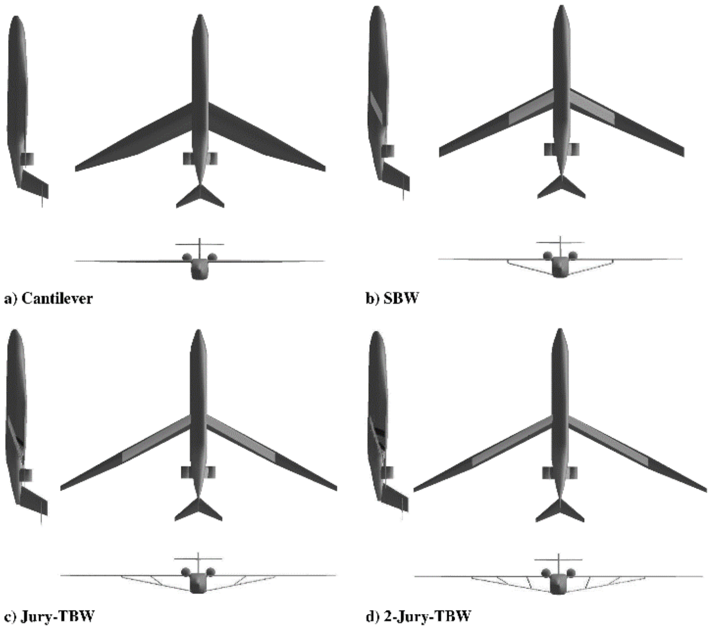


Figure 77 - Baseline optimized minimum-fuel configurations [10]

Those concepts were compared on a same mission distance, altitude, and transonic speed (M0.85). Compared to the cantilever baseline, the SBW and Jury concepts provide some significant fuel savings (see weight of fuel, *Wf*, in Figure 78). But the 2-Jury TBW provides even greater fuel savings, up to 20%.

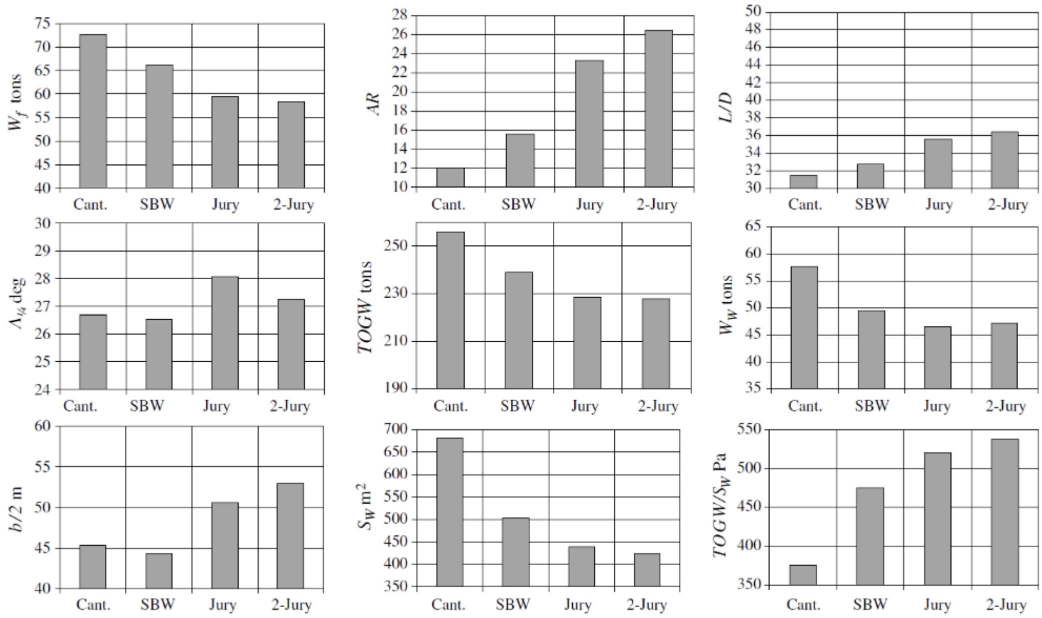


Figure 78 - Comparison of several concepts of strut/truss braced wing [10]

SBW and TBW concepts seem therefore to be promising levers to reduce fuel consumption.
Due to the higher wingspan, these SBW or TBW concepts may not be compatible with airport constraints, so they should possibly be combined with foldable wings to maintain current airport accessibility.

Box wing

Figure 79 - Representation of the PrandtlPlane (PrP) under development within the project "PrandtlPlane ARchitecture for the Sustainable Improvement of Future AirpLanes" (PARSIFAL) [18]

According to Figure 68, the best value for the span efficiency factor is around 1.46 with the box wing concept. This concept of wing was proposed very early in the history of aviation, in 1924, by Ludwig Prandtl. But it was never used as a commercial aircraft.
Actually, the box wing could be considered as a continuation of the winglet concept. The main (low) wing box includes a winglet at its wingtip and this winglet is then connected to a secondary high wing with an inverted sweep angle. This secondary high wing is fixed to the fuselage by vertical tail planes (Figure 79). This reduces drastically the induced drag, because there is not any clear wing tip that could generate any massive vortex. Moreover, the horizontal tail plane is replaced by a high wing, which includes the pitch control actuators. The yaw control could be also improved by adding yaw actuators on both "winglets" that connect the high wing and the low wing.
The study [18] performed a comparison between an existing classical aircraft and a box-wing aircraft in the scope of the PARSIFAL project, and identified almost 20% of the fuel burn reduction.
Although this concept appears promising and remains rather classical (tube-and-wing concept with low and high wings and connecting winglets), the main challenge remains that there is no experience of existing similar commercial aircraft, thus no real reference basis.

Maturity

Classical and blended winglets

As stated above, winglets are a very mature technology, with widely-proven efficiency on many aircraft over the last 40 years. Besides, it can also be installed on existing aircraft with a light Supplemental Type Certification (STC). TRL for winglets is at 9.

Foldable wingtip

Foldable "on-the-ground" wingtips are currently in certification phase on the 777X. The aircraft is planned to enter service by 2025 [03]. So, TRL for "on-the-ground" foldable wingtips is set 7.
However, "in-flight" variable foldable wingtips were only studied in laboratory. So, "in-flight" variable foldable wingtips have a TRL set to 4. Availability for these is not expected before 2030.

Strut/Truss-Braced wing

As mentioned above, strut/truss-braced wings were used early in the development of aviation. But this concept has not been used on commercial aircraft since the mid-20th century. The timeline for entry-into-service is estimated between 2030 and 2040 [05] and its TRL is between 1 and 3 [15]. Considering the past experience of Hurel-Dubois airplanes, some could consider the TRL to be around 3.

Box wing

The concept of box-wing aircraft was suggested very early in the history of aviation. It was revived lately in the scope of a more sustainable aviation. Although it had never been applied for commercial transport yet, it is not new as it is compiling various existing concepts (high wing, low wing, and winglets). However, it can be complex to implement due to the additional interference drag between the two wings, and the additional structural weight penalty required to strengthen both wing roots and their junctions.
Of course, it will require a new program of aircraft, but the innovation gap is not as important as it could seem. In the study [15], this concept’s TRL is assessed between 1 and 3. Timeline is around 2035-40 according to [05].

Environmental Impacts

Classical and blended winglets

There is not any negative environmental impact that was identified about the winglets technology.

Foldable wingtip, Strut/Truss Braced wing, or Box wing

Those technologies are not impacting the environment because they only apply to the aerodynamics.

SUITABILITY

Constraints

Classical and blended winglets

The winglets are efficient on all aircraft impacted by the induced drag. So, most existing aircraft can improve their operating cost with winglets.

Foldable wingtip

Foldable wingtips support some high constraints at the hinge. The hinge robustness needs to be dimensioned against the high load in flight, in particular in gust situation.

Strut/Truss Braced wing

This technology requires a new structural design, so it cannot be implemented on existing aircraft. So, a new aircraft program should be launched. Moreover, the increase of the wingspan could restrict access to some airports if not combined with foldable wingtips.

Box wing

The wing box requires a new structural design and cannot be implemented by retrofit on the existing aircraft.

Certification Aspects

Classical and blended winglets

There are no identified certification obstacles to the implementation of winglets, and this can be done through a retrofit under an STC.

Foldable wingtip

Foldable wingtips are impacting the control of the aircraft. So, a major safety assessment should be undertaken prior to certification.

Strut/truss Braced wing

The strut/truss-braced wing requires a new structure. So, a complete certification process is necessary.

Box wing

Due to the new structural design, the box wing requires a complete certification process.

Aircraft Segments Concerned

Classical and blended winglets

Most existing aircraft types can implement winglets. Of course, the fuel saving portion increases with the aircraft range.

Foldable wingtip

Folding wingtips are effective on high aspect-ratio aircraft. Those aircraft are in the range of widebodies, maybe future single-aisles.

Strut/Truss Braced wing

The SBW or TBW applies for medium- and long-haul aircraft [15].

Box wing

According to [15], the box wing concept is likely to apply for medium-haul aircraft.

APPLICABILITY

Market Acceptance and Barriers

Classical and blended winglets

The winglets do not raise any acceptance obstacle or any barrier. Several companies are proposing the implementation of winglets by retrofit. Some impacts must be studied regarding airport compatibility, especially for down-facing winglets (potential obstacle for airport trucks).

Foldable wingtip

Foldable wingtips are mainly implemented to maintain airport compatibility while increasing in-flight wingspan. There are no identified obstacles to their acceptance, only minor airport adaptations have to be considered.

Strut/Truss Braced wing

The SBW or TBW were used in the past. So, there should not be any major barrier for this concept, except some minor considerations for ground handling.

Box wing

Box wing aircraft require additional studies to determine the structure robustness necessary against the load generated by the airflow and the aircraft weight. Careful consideration must also be given in terms of airport compatibility due to the wingspan increase.

Costs

Classical and blended winglets

Winglets can be installed through light retrofits. The cost of this implementation remains reasonable (a few hundred thousands of dollars) compared to its benefits.

Foldable wingtip

Foldable wingtips require a new derivative program development (such as a new wing), as they are impacting the aircraft structure. So, the implementation of this technology requires major investments, that should be however lower than the cost of a new aircraft program.

Strut/Braced wing

The SBW or TBW concepts require a new aircraft program. Large investments are necessary.

Box wing

The box wing concept requires a new aircraft program. Large investments are expected.

Implications on Aircraft Designs

Classical and blended winglets

The implementation of winglets does not cause any impact on the design of existing aircraft beyond studying necessary reinforcements due to higher load in the wing.

Foldable wingtip

The folding wingtips is impacting the structure of the wing. So, the robustness of the wing needs to be demonstrated when integrating foldable wingtips.

Strut/Truss Braced wing

The geometry of the SBW and TBW implies relocating the engines.

Box wing

The box wing design imposes additional loads on the vertical tail planes, as well as on both wings. Engines can be relocated for structural optimization but it is not necessary. Flight control surfaces are largely modified, and require a complete redesign of the control laws.

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CANARD CONFIGURATIONS

This concept is partially treated in the laminar flow control for forward swept wings. However, the study [01] indicates that fuel efficiency cannot be demonstrated for the canard concept. We found [02], a more optimistic study of the canard configurations that expects a fuel saving of around 4%. Considering the complexity of implementing such a concept, the benefits in terms of fuel efficiency do not seem worth it. This concept has not been detailed further in this document.

Figure 80 - Saab 37 Viggen with a canard configuration

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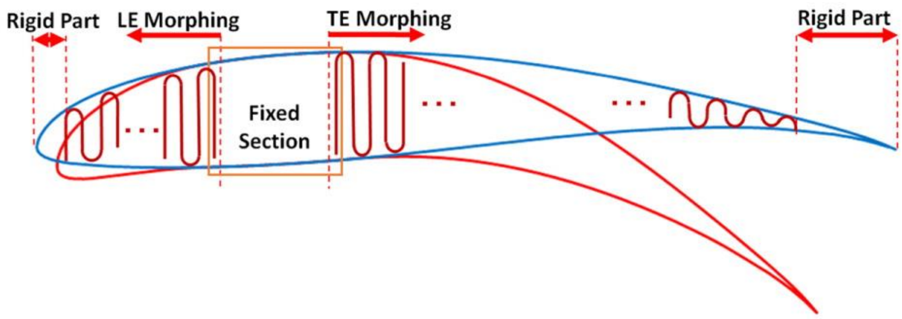
This concept is partially used in commercial aircraft because the slat and flap devices enable to change the airfoil of the wings during the take-off and landing phases. The basic airfoil of existing wings is optimized for cruise phases. So, the variable wing camber concept is not expected to improve drastically fuel efficiency. In fact, the study [01] shows that the implementation of variable camber on the commercial aircraft is expected to reduce fuel consumption by 3% to 6%. Consequently, as this concept requires a drastic change to the wing structure, and given the low maturity of these technologies, this concept has not been detailed further in this document.



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NEW TECHNOLOGIES BASED ON ALTERNATIVE FUELS

This Chapter reviews the emerging technologies based on non-fossil fuels such as the Sustainable Aviation Fuels, hydrogen or electricity.

The overall objective of these disruptive technologies is to use alternative power sources that are either non-CO_2 emitting or carbon neutral over the total life cycle.

SUSTAINABLE AVIATION FUELS (SAF)

Sustainable Aviation Fuel (SAF) is the main term used by the aviation industry to describe a non- conventional (fossil derived) aviation fuel.

Biofuels typically refers to fuels produced from biological resources (plant or animal material). However, current technology allows fuel to be produced from other alternative sources, including non-biological resources; thus, the term is adjusted to highlight the sustainable nature of these fuels. The chemical and physical characteristics of SAF are almost identical to those of conventional jet fuel and they can be safely mixed with the latter to varying degrees, use the same supply infrastructure and do not require the adaptation of aircraft or engines. Fuels with these properties are called "drop-in fuels" (i.e. fuels that can be automatically incorporated into existing airport fueling systems).

Moreover, to validly use the term ''sustainable'' they must meet sustainability criteria such as lifecycle carbon emissions reduction, limited fresh-water requirements, no competition with needed food production (like first generation biofuels) and no deforestation.

Relative to fossil fuels, sustainably-produced jet fuel results in a reduction in carbon dioxide (CO_2) emissions across its life cycle. Carbon dioxide absorbed by plants during the growth of biomass is roughly equivalent to the amount of carbon dioxide produced when the fuel is burned in a combustion engine, which is simply returned to the atmosphere. This would allow the SAF to be approximately carbon neutral over its life cycle. However, there are emissions produced during the production of SAF, from the equipment needed to grow the crop, transport the raw goods, refine the fuel and so on. When these elements are accounted for, the use of sustainable aviation fuel has been shown to provide significant reductions in overall CO_2 lifecycle emissions compared to fossil fuels, up to 80% in some cases. Furthermore, SAF contains fewer impurities (such as sulfur), which enables an even greater reduction in SOx and particulate matter emissions than present technology has achieved.

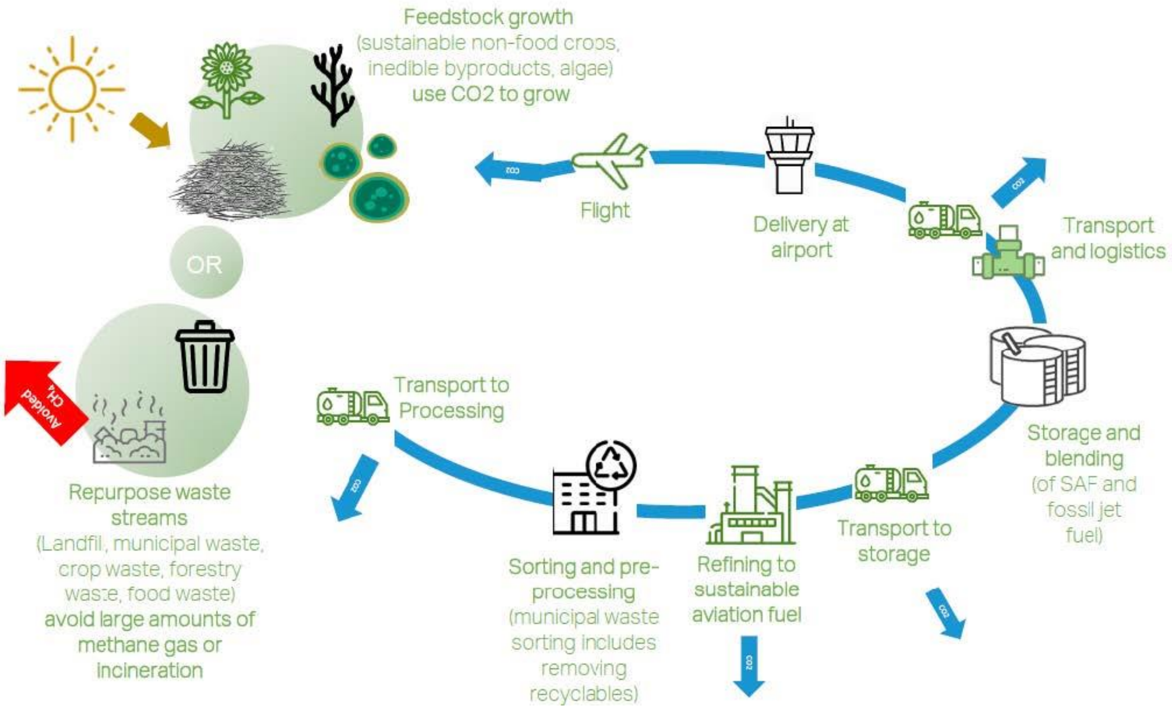

Figure 81 - SAF carbon life cycle diagram (Source: IATA)

Synthetic fuels for aviation (or e-fuels) are produced through a power-to-liquid (PtL) process which, when powered by renewable energy, can result in a carbon-neutral, drop-in fuel for aviation. They capture CO_2 in the manufacturing process. In a first stage, hydrogen is produced from water. Carbon is added to this to produce a liquid fuel. This carbon can be recycled from industrial processes or even captured from the air using filters. Combining CO_2 and H_2 then results in the synthetic fuel, which can be kerosene, gasoline, diesel or even gas.

As drop-in fuels, SAFs do not require any change to the current engine design and architecture, and most engine and aircraft manufacturers are currently certifying their production engines to operate with SAF.

As this technology does not imply changes to the design of aircraft and engines, only some minor modifications, it is not further detailed in this document.

DESCRIPTION

Concept

Fossil fuel combustion is used to produce thrust from the heat of gases. However, alternative methods exist to produce useful thrust from electromagnetic forces. Those forces are generated by electric energy, from a battery, and such energy does not emit any pollutant.

In more details, the main magnetostatic force is the Laplace force: when $\overline{dl}$, an element of wire with a current of intensity I, is submitted to a magnetic field $\overline{B}$, the resulting force is around: $\overline{dF} = I \cdot \overline{dl} \wedge \overline{B}$ [EQ1]

The Laplace force is illustrated in Figure 82 below.

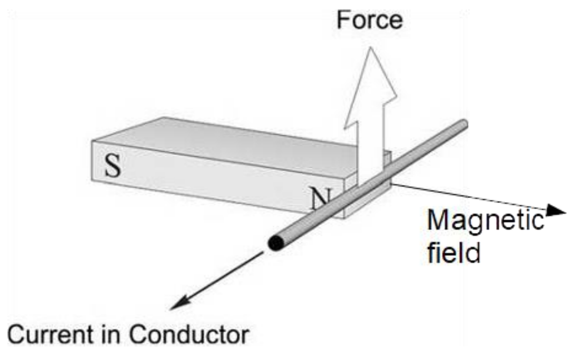

Figure 82 - Mechanical force produced on a current-carrying wire in a magnetic field [08]

In Figure 83, the equation EQ1 is extended from a small wire to a coil. Thus, this coil is submitted to a torque, $\overline{\Gamma}$ with following expression:

$$\overline{\Gamma} = I\,\overline{S} \wedge \overline{B} \qquad \text{[EQ2]}$$

with:

- I, the intensity inside the coil
- $\overline{S}$, the surface vector with surface value, oriented according to the current in the coil
- $\overline{B}$, the magnetic field

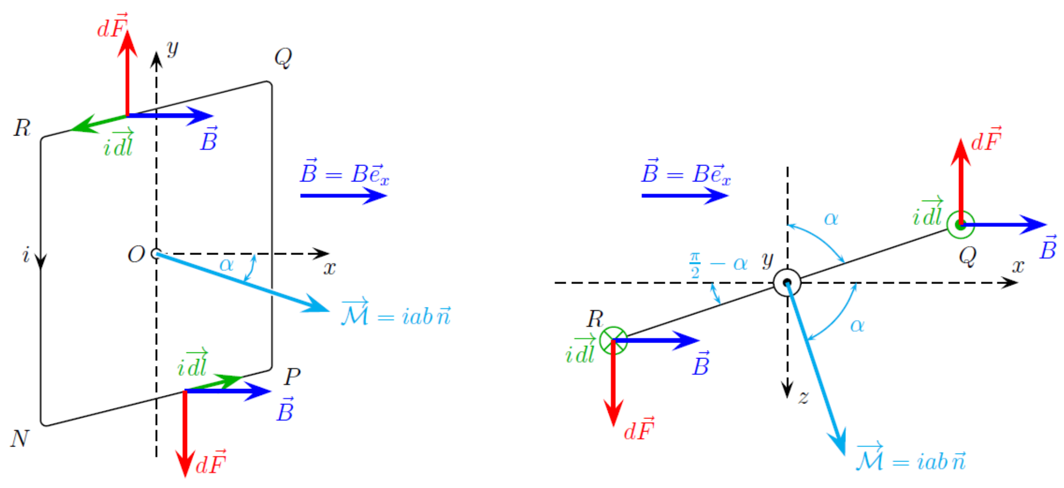

Figure 83 - Torque of a coil due to a magnetic field [06]

This torque is maximum when the coil plane is parallel to the magnetic field and, it is around zero value when this plane is perpendicular to the magnetic field. When this torque is maintained maximum with an appropriate magnetic field or current value, this can produce a rotation movement. In most motors, there are multiple coils grouped in a winding.

Using an appropriate electric supply to the coil enables a mechanical motion from electric energy. Figure 84 shows a basic example of electric motor.

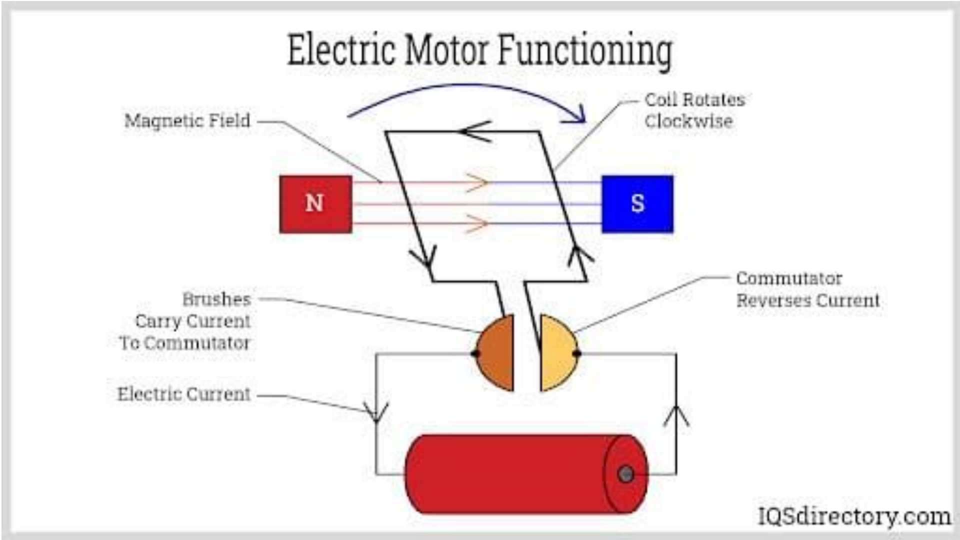

Figure 84 - Basic electric motor with DC supply and brush commutator. Source: IQSdirectory.com

Components of Electric Motor

Electric motors are composed by three main components:

Bearings: Allow the motor axis to rotate by reducing the friction between the static part and the rotating part. This component is not specific to electric motors. It is similar to thermal motors.

Rotor: the rotating part of the motor. It can be a winding, a permanent magnet, a non-magnetic shape, or an induction cage.

Stator or Exciter: The static part around the rotor, providing the magnetic field with permanent magnets or winding.

Types of Electric Motors

Based on study [07], There are four possible aviation electric motor types:

Electrically Excited Synchronous Machine (ESM): This motor type consists of a rotor with electrically-supplied windings, and other windings in the stator part. Although this motor can provide multi-megawatt powers for many industries and does not require any permanent magnet (containing rare earths), it does not represent a proper candidate for aerospace as brushes electrifying the rotor do not allow rotational speeds higher than 15,000 rpm.

Permanent Magnet Synchronous Machine (PMSM): Here the rotor includes a permanent magnet, with a stator made up of windings generating a synchronous rotating magnetic field. See below a few examples of PMSM in Figure 85.

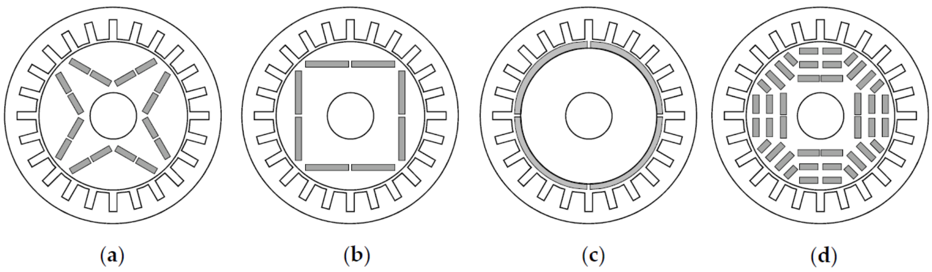

Figure 85 - Different rotor concepts of permanent magnet synchronous machines: (a) V-shaped

The main issue with this concept is the need for permanent magnets (and rare earths) inside the stator. However, this type of motors without brush contact is able to rotate at very high speeds and to generate power over 1 MW. This makes it a good candidate for electric aircraft engine.

Switched Reluctance Machine (SRM): The concept of reluctance machine appeared very early. In 1842, Robert Davidson presented a locomotive with a reluctance machine able to run up to 4 miles per hour (Figure 86). Unfortunately, it was not very successful at the time because it was easier to use coal as energy than electricity. This concept became popular with the interest for sustainable electric engines.

Figure 86 - The exhibition of the R. Davidson electric locomotive [12]

The SRM principle is based on the ability of the magnet to attract ferromagnetic materials such as iron, nickel, or cobalt which have a lower reluctance than void or air. In order to minimize its total energy, a magnetic field uses the minimum reluctance of the material supporting its lines of field. This is the reason why iron filings rearranged and aligned to the magnetic field (Figure 87).

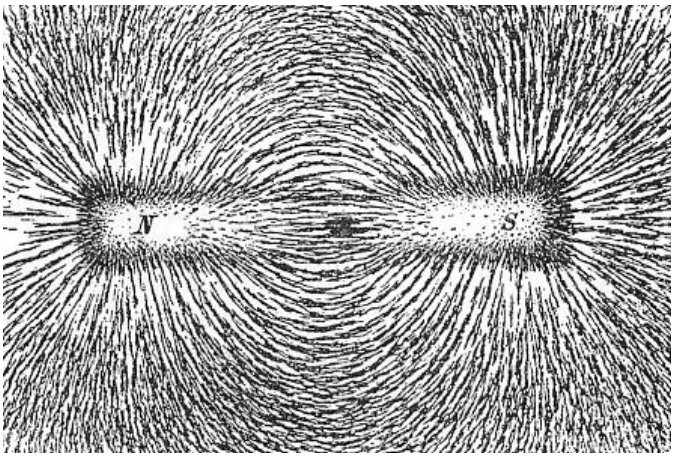

Figure 87 - The iron filings aligned to the magnetic field
Source: Newton Henry Black, Harvey N. Davis (1913) Practical Physics, The MacMillan Co., USA, p. 242, fig. 200

The idea is to build a structure of rotor that minimizes the reluctance when it is aligned with the magnetic field generated by the rotor, and maximizes the reluctance when the rotor is not aligned. The torque supported by the rotor is proportional to this difference of the reluctance when the rotor is not aligned. The magnetic field is activated when the rotor is not aligned, and it is deactivated as soon as it aligns with the field (Figure 88).

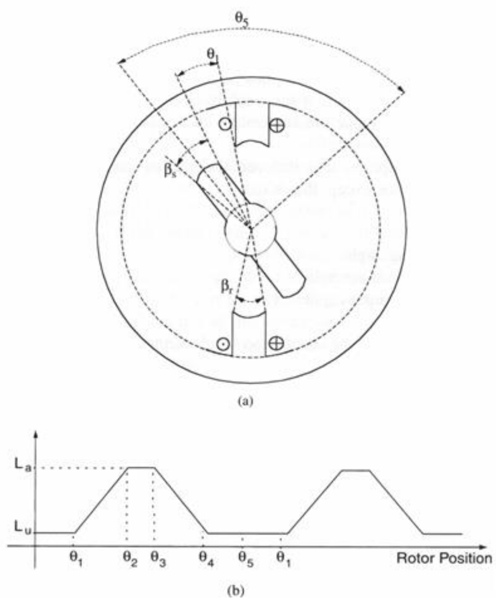

Figure 88 - Example of basic SRM: $\vartheta 1= 12\ (2\pi Pr-(\beta s+\beta r))$; $\vartheta 2= \vartheta 1+ \beta s$; $\vartheta 3= \vartheta 2+(\beta r-\beta s)$; $\vartheta 4= \vartheta 3+ \beta s$; $\vartheta 5= \vartheta 1+ \vartheta 4 = 2\pi Pr$ [14]

To produce an efficient torque on the stator, the magnetic field intensity and orientation depends on the angle of the rotor. The challenge of these motors is the control of the intensity and orientation of the stator magnetic field that needs to be computed from the current value of rotor angle. These SRM remain very good candidates for sustainable aviation motors. Figure 89 details several existing SRM.

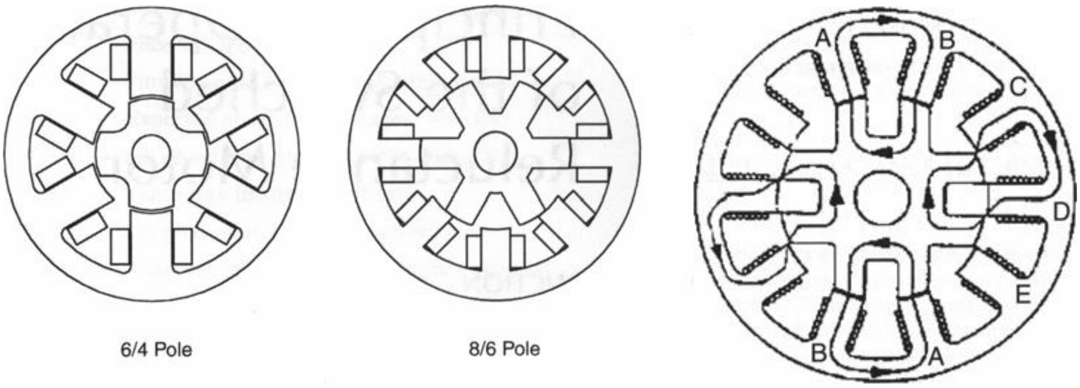

Figure 89 - Examples of industrial SRM engine, with the optimized shape of the rotor close to the magnetic field generated by the stator's windings [14]

The study [14] lists below advantages and disadvantages for these engines:

Advantages:

- Construction of the motor is simple
- Brushes, commutators, permanent magnets are absent
- Starting torque is quite good
- Accurate speed control is possible
- Cost effective and easy maintenance
- Higher efficiency
- More power per unit weight and volume
- Has no windings or slip rings in the rotor
- Can run at very high speed (up to 30,000 rpm) in hazardous atmospheres
- Four-quadrant operation is possible with appropriate drive circuitry

Disadvantages:

- Noisy in operation
- Not well-suited for smooth torque production
- Flux linkage and non-linear function of stator currents as well as rotor position control of the motors is a tough challenge.

Such motors are currently used in several non-aviation applications such as washing machines.

Cage Induction Machine (IM): This machine is based on the principle of induction. This phenomenon is described by the Lenz-Faraday law: $U = -\frac{d\phi}{dt}$ (EQ3)

where:

- U, is the electric difference of potential in the coil (same coil configuration as in Figure 84)
- ϕ, is the flux of B, the magnetic field through the coil
- B, is the magnetic field generated by windings located in the stator and rotating around the motor axis.

The rotor is composed of several coils with an appropriate shape. So, the variation of B generates an inducted current, which then generates another magnetic field from the rotor. The shape of the rotor coils is designed in such a way that the rotor magnetic field is not to be aligned with the stator generated field (Figure 90). This misalignment between the rotor and the stator generates a torque that makes the induction motor rotate.

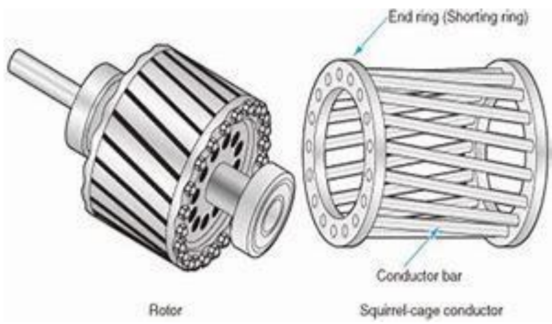

Figure 90 - Examples of in Squirrel Cage Rotor [04]

According to [07], the advantages of induction motors are their robustness, the low cost of production, and the absence of permanent magnets and brushes. Compared to SRM, they offer a better power factor. They can reach very high speeds, in the order of several 10,000 rpm, and a very high power of almost 10 MW.

Synthesis: Those four above types of electric motors were compared in the study [07]. It appears clearly that ESM motors is not adapted for aviation. See below detailed pros and cons for these motor types.

Key Characteristic	ESM	IM	SRM	PMSM
Rotor losses	–	o	o	++
Stator losses	++	o	o	o
Windage Losses	-	o	–	++
Rotor thermal limitations	o	+	++	o
Cooling options	–	o	o	++
Rotor mechanical limitations	–	o	+	++
Torque-to-inertia ratio	o	o	o	++
Compatibility with bearings	-	o	o	++
High-speed capability	–	o	+	++
Short-circuit behaviour	–	++	++	-
Machine complexity	o	+	++	+
Current density	–	+	+	+
Power density	–	+	+	+

Figure 91 - Comparison of key characteristics for different electrical machine concepts.
(– unfavorable; - disadvantageous; o neutral; + beneficial; ++ very beneficial) [07]

The study also collected several scientific performances of these types of motors in terms of rotation speed and power. Results are presented in Figure 92.

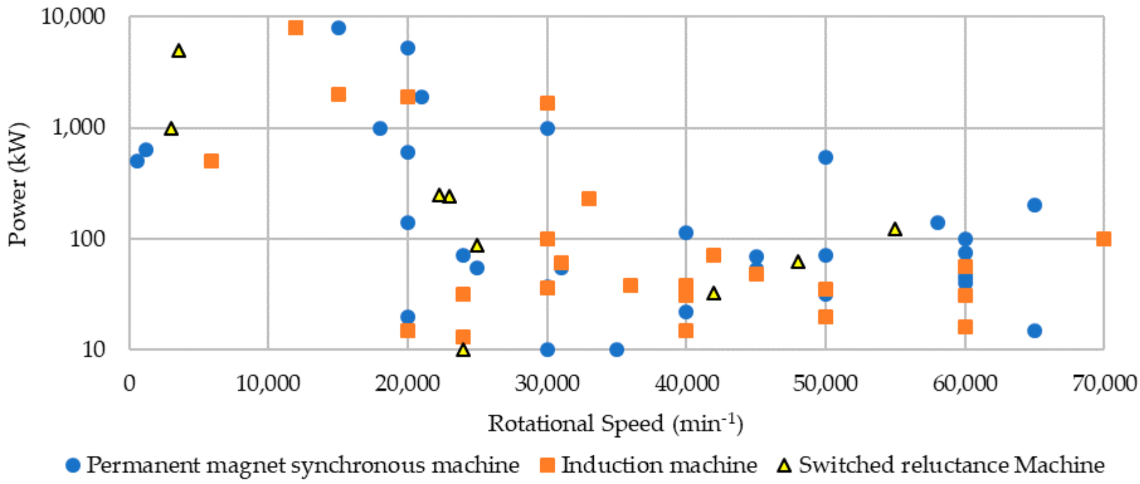

Figure 92 - Overview of electrical machine designs from the literature [07]

However, the promising results presented above were observed in laboratory with controlled conditions. To validate the efficiency of these electric motors for aviation, they should be verified in flight conditions. Several airframers are developing flying demonstrators for this purpose, such as the MEGAWATT project from Airbus [02].

Figure 93 - Concept View of Airbus Megawatt Demonstrator onboard A380 [02]

Distributed Electric Propulsion (DEP): An example of Electric Motors application

In the Aerodynamic section related to laminar flow control, the Boundary Layer (BL) suction appears to be a promising method to get around 10 to 30% drag reduction. The principle of BL is detailed in Figure 46.

The main idea of distributed propulsion is to replace the pumps in Figure 46 with motors inside the wings. The air inlet of the motor is used for BL suction at the leading edge of the wing. The outlet air is in a nozzle located in the trailing edge. Due to the small thickness of an aircraft wing, the distributed propulsion motors are constrained in size [03]. A classic engine is based on a gas chemical reaction between fuel and air oxygen and this reaction requires a lot of volume. However, while some of the above-described electric engines require a large volume (such as SRM), most electric motors can operate with reduced size. This leads to install electric motors following a distributed propulsion.
Study [09] describes the results of an experiment on the DEP in terms of aerodynamic coefficients. Figure 94 shows a photo of the lab and some graphs of aerodynamic results.

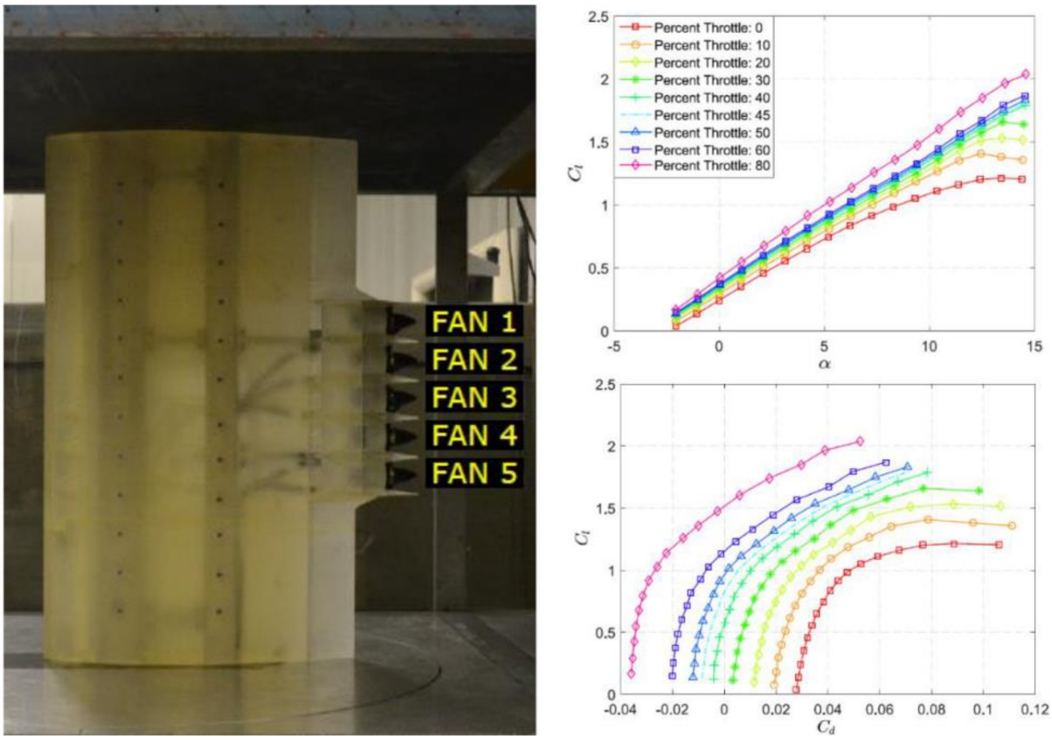

Figure 94 - Aero-propulsive coupling experiment at the University of Illinois: Five-fan test article and resulting lift and drag airfoil performance (University of Illinois at Urbana-Champaign, Urbana, Illinois) [09]

These charts show an obvious increase of the lift coefficient coupled with a reduction of the drag coefficient.

The expected outcomes of the DEP are:

- Zero CO_2 or NOx emission
- Reduction of cruise drag
- Ability to perform STOL or VTOL
- Noise reduction

Of course, the advantage obtained in terms of aerodynamics should be balanced by the penalties of using DEP to assess the overall efficiency. In addition, as explained in the BL suction section, this DEP can also be applied to the fuselage to improve the aerodynamics of the whole aircraft. Therefore, several demonstrators were developed for DEP (Figure 95).

Figure 95 - Joby S2 aircraft (photo: Joby Aviation, Santa Cruz, California), Lilium jet (photo: Lilium, Munich, Germany), and Airbus Vahana VTOL aircraft (photo: Airbus, Leiden, Netherlands) [09]

Based on the analysis on the BL suction, the DEP is expected to only require almost 50% of current existing engine power. For these reasons, the DEP is a very promising technology to completely decarbonize aircraft in the future. Figure 96 shows several aircraft concepts based on DEP.

Figure 96 - NASA N3-X and STARC-ABL, and ESAero's ECO-150 (photo: ESAero, San Luis Obispo, California) aircraft concepts [09]

Hybrid Fossil-Electric Architectures

Today, pure electric propulsion only exists for experimental or general aviation aircraft. These technologies may not be mature for years/decades for larger commercial transport. Moreover, the conversion of existing mass transport aircraft such as single-aisles to pure electric propulsion seems very challenging at the horizon of 2050 due to batteries weight and volume. Therefore, hybrid architectures with a mix of electric and fossil propulsion are studied for large commercial aircraft. Hybrid architectures combine two sources of power, electric batteries and thermal fuel, with several means of propulsion that can be a fan or propeller.
Hybrid-electric propulsion engines can be divided into three main architectures:

- The parallel hybrid
- The series hybrid
- The turbo electric

Terminology varies between the various studies and would need some harmonization among the research community.

Figure 97 - Daher, Safran, and Airbus Make First Hybrid-electric EcoPulse Demonstrator on December 5th, 2023. Source: Safran

Figure 98 below details these hybrid architectures.

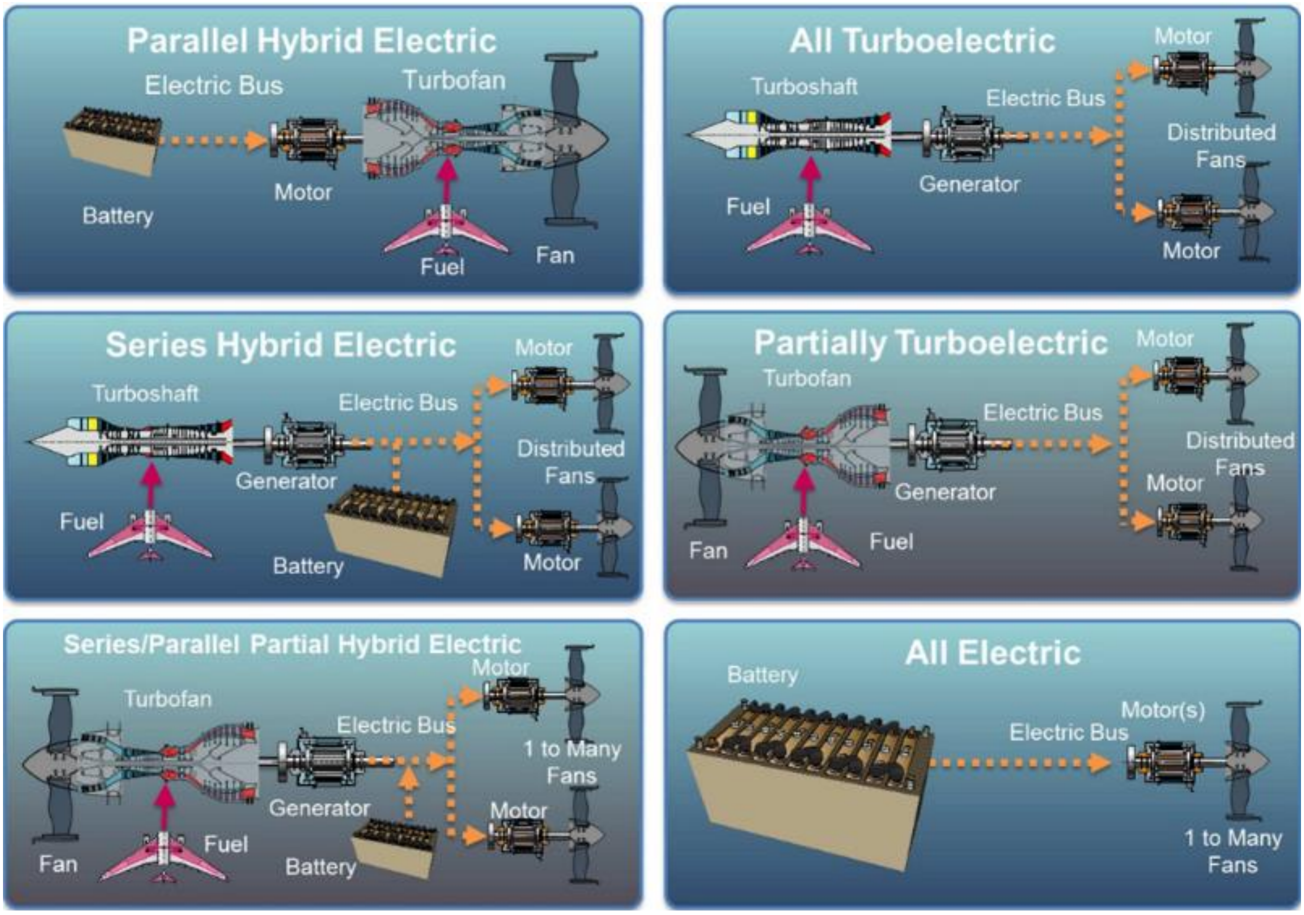

Figure 98 - Felder's classification of power system architectures for aircraft electric propulsion [15]

The main challenge of hybrid technology is to provide an optimal balance between thermal and electric propulsion. On the one hand, hybrid thermal propulsion consumes more fuel than non-hybrid propulsion because the electric engine slows down the thermal engine [15]. On the other hand, maximum electric propulsion complemented with the thermal engine results in a minimum fossil fuel consumption, but the total energy consumed is not optimal and could be reduced. An optimal control device should be added to determine the optimal balance between electric and thermal propulsion. This could be equivalent to the existing cost index (CI) of Flight Management Systems (FMS). It can also be included in the CI management inside the FMS.

The parallel hybrid

The parallel hybrid consists in a classical jet engine with an electric engine connected to either the HP or LP shaft. Generally, the electric engine is connected to the LP shaft to be used to provide some additional power to the fan in parallel to the thermal combustion (we talk about electrically-assisted turbofan). It can be also used as an alternator to load batteries. Below is an example of parallel hybrid architecture (Figure 99). In this case, the electric motor is located after the turbine in the nozzle area.

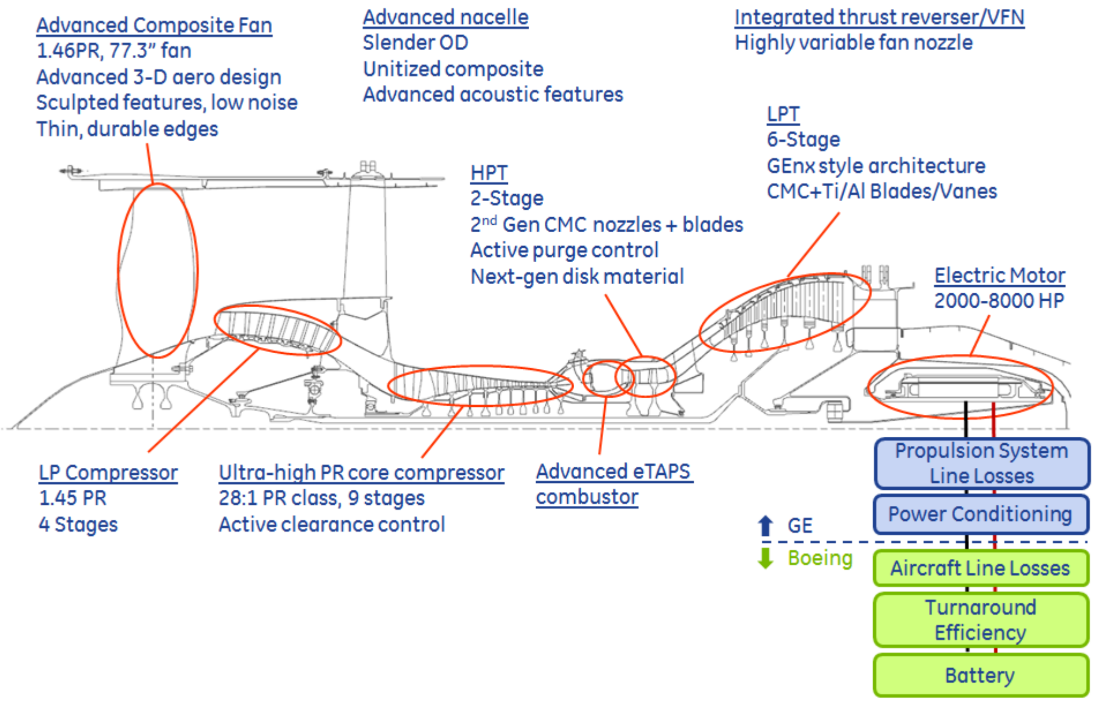

Figure 99 - NASA SUGAR Hybrid Electric hFan+ Architecture [05]

The parallel hybrid can be a short-term decarbonization lever as it is based on a modification of existing thermal engines. It could be also a long-term zero CO_2 project with the use of hydrogen for thermal propulsion.
Several projects of parallel hybrid are currently under study and their expected results are presented in Figure 100.

Study	Category	Technical Specification	Key Findings
NASA Boeing SUGAR Volt [37,38]	150 PAX single-aisle aircraft. Range: 900 nmi	Battery SE: 750 Wh/kg EM SP: 3–5 kW/kg EM efficiency: 93% EM power capacity: 1.3 MW (balanced), 5.3 MW (core shutdown)	Transonic truss-braced wing, 'balanced' version: reduces fuel burn by 60% and energy use by 54%. 'Core shutdown' version: EM for cruise on 100% electric power, reduces fuel burn by 64% and energy use by 46%.
NASA UTRC hGTF [38,39]	150 PAX single-aisle aircraft. Range: 900 nmi	EM power capacity: 2.1 MW Battery SE: 1000 Wh/kg	Optimized geared turbofan engine for cruise, electric power boosting for take-off and climb; 7–9% block fuel burn reduction and 3–5% energy saving.
NASA R-R LibertyWorks EVE [39,40]	150 PAX single-aisle aircraft, exploring mission optimization using battery power for taxiing, idle decent, and take-off power augmentation	EM power capacity: 1 MW-2.6 MW	28% fuel burn reduction for 900 nmi mission, 10% energy saving for 500 nmi mission, 18% reduction in total fleet fuel usage.
Horizon 2020 H3PS *(High-Power High-Scalability Aircraft Hybrid Powertrain)* [40]	4-seat general aviation aircraft developed on the platform of Tecnam P2010	Engine: Rotax 915 (141 hp) EM power capacity: 30 kW (thrust booster motor during take-off and climb, operating as a generator to recharge batteries during cruise)	TECNAM: airframe and system integration, BRP-ROTAX: design and integration of combustion engine and e-motor, ROLLS-ROYCE: e-motor and power storage.
Clean Sky 2 NOVAIR project [41,42]	150 PAX single-aisle large passenger aircraft (retrofitted on A320 NEO). Range: 800 nmi	Technology level: 2040+ Battery efficiency: 95.0% Battery SE: 1 kWh/kg EM efficiency: 98.0% EM SP: 15.0 kW/kg	With downscaled, more efficient turbofan engine core, potential trip fuel reduction is about 14%.

Figure 100 - Applications/studies/conceptual designs of parallel hybrid electric aircraft to date [16]

The series hybrid

Figure 101 - Example of hybrid series architecture, the turbo fan is located at 1 and the electric motors are at 5 [13]

The series hybrid architecture consists of electric motors, with electricity provided from batteries, and kerosene-supplied gas turbines (Figure 101).

This electric propulsion could also be used as a Laminar Flow Control when it includes DEP configuration combined with pure turbofans like in Figure 101. Hence, the fuel consumption reduction results from a double effect of electric propulsion and drag reduction.
Figure 102 details current projects envisaging a hybrid series architecture.

Study	Category	Technical Specification	Key Findings
Zunum Aero [31]	Seat capacity: 12 economy, 9 premium, 6 executives; max payload: 2500 lbs; range: 700 nmi; target YEIS: 2020	Propulsion system: series hybrid with range extender Max power: 1 MW Turbogenerator: 500 kW	Emissions: 0.0 to 0.3 lbs CO_2/ASM Operating cost: 8 cents/seat mile, USD 250 per hour.
XTI TriFan 600 [32]	6-seat fixed-wing aircraft with VTOL. Range: 600 nmi in VTOL, 900 nmi for conventional take-off and landing; YEIS: 2024	Propulsion system: a turboshaft engine driving 3 generators for electrical energy generation, powering motors which are mechanically connected to propellers	Three ducted fans, hybrid energy system (hydrogen fuel cell, sustainable aviation fuel compatible).
Airbus E-Fan X [33]	100-seat regional jet. Payload: 6650 kg; YEIS: 2030	Motor power: 2 MW Generator power: 2.5 MW EM power density: 10 kW/kg Power distribution: 3 kV DC	One of the four jet engines (AE2100) was replaced by a 2 MW electric motor.

Figure 102 - Applications/studies/conceptual design of series hybrid electric aircraft to date [16]

The turbo electric

The turbo electric architecture is similar to the series hybrid as it also consists of a thermal engine and an electric propulsion engine. The main difference is that the thermal engine primarily aims to supply electric power to the electric propulsion through an alternator and batteries (Figure 103). The thermal engine can be supplied by kerosene from the aircraft tanks, hydrogen being more efficiently used in fuel cells than in turbo electric architectures.

Figure 103 - NASA CONCEPT: N3-X Distributed Turboelectric Propulsion System. (Credit: NASA)

In the context of decarbonization, turbo electric engines should only be an intermediate step toward zero emissions. It takes advantage of the DEP based electric propulsion with poor or unavailable high electric power storage devices.

Study [16] presents a list of projects that are currently using the turbo electric architectures (Figure 104).

Study	Category	Technical Specification	Key Findings
NASA N3-X [38,43]	300 PAX hybrid wing body with fully distributed propulsion, 16-aft motor-driven fans. Range: 7500 nmi	Superconducting electric machines and power distribution. Power distribution: 7500 V Fully distributed power: 50 MW	70% fuel burn reduction compared to Boeing 777–200 LR.
Empirical Systems Aerospace ECO-150 R [38,44,45]	150 PAX regional jet, fully distributed propulsion system with a split-wing concept. Maximum payload range: 1500 nmi	Superconducting electrical machines cooled with liquid hydrogen	16-wing motor-driven fans.
NASA STARC-ABL [38,46]	154 PAX single-aisle aircraft with tube and wing airframe. Range: 900 nmi; target YEIS: 2035	EM SP: 8 hp/lb EM efficiency: 96% Inverter SP: 10 hp/lb Inverter efficiency: 98% Power distribution: 1000 V Motor power capacity: 2.6 MW	12% reduction in start of cruise TSFC, 9% reduction in economic mission block fuel, 15% reduction in design mission block fuel.
Boeing SUGAR Freeze [38,47]	154 PAX single-aisle aircraft using a truss-braced wing combined with boundary-layer ingestion. Range: 900 nmi	Solid oxide fuel cell, superconducting motor, cryogenic power management system	56% reduction in fuel burn.

Figure 104 - Applications/studies/conceptual design of turboelectric aircraft to date [16]

Full Electric APU

Auxiliary Power Units (APUs) are generators used to provide electricity in an aircraft when engines are turned off, or as a power backup source in case of engine failure. They are today powered by kerosene.
The concept of full-electric APU is raised as a mean to reduce fuel burn in Study [01]. A full-electric APU commonly refers to an APU only providing electrical power from a gas turbine, such as the APS 5000 onboard the 787. It allows to reduce maintenance costs and fuel consumption of the APU. It also improves reliability compared to kerosene-powered APUs. However, in the context of decarbonization, this enhancement of APU fuel reduction is not sufficient. This concept is not detailed further here.

Maturity

Today, electric propulsion only exists on two-seat general aviation aircraft with restricted autonomy. Therefore, the TRL of pure electric propulsion is around 4 to 6 [10]. The ATAG document [17] assesses the timelines for electric propulsion availability:

- For small aircraft up to 9 seats, some test electric aircraft are already flying
- Electric airplanes with up to 19 seats are planned for the late 2020s
- Regional aircraft fully electric are expected in the 2030s
- There is a project to operate short-hauls flight by 2040.

The parallel hybrid

The parallel hybrid can either be installed on existing thermal engines to reduce kerosene consumption or be part of new hybrid engine architectures.
To improve existing thermal engine, the TRL is assessed at 5 to 6 because experimental prototypes are currently running. The timeline for such improvement of existing engines should occur between 2030 and 2040.
For parallel hybrid engines with hydrogen, the TRL is assessed at 4 as only lab prototypes were evaluated for the moment. The timeline here should be after 2040.

The series hybrid

The series hybrid is only used on new architectures. Its TRL is assessed around 4 to 5. The timeline for the series hybrid is expected to be around 2040-2050.

The turbo electric

The turbo electric architecture mainly consists of prototypes for demonstration of DEP. Its TRL is around 7 because these prototypes exist, and they can fly for experimental purposes. The timeline for turbo electric should be from now to 2040, as more efficient battery technology is expected to become available by 2040.

Environmental Impacts

Electric propulsion does not produce any direct CO_2, vapor or NOx. However, although less noisy than a gas turbine, an electric motor can be source of high noise, especially the SRM types.
In addition, electric propulsion is highly dependent on battery efficiency. Hence, availability of pure electric propulsion is tied up with the challenge of high-storage capability batteries.
It should be added that electric propulsion has an indirect effect on the environment due to the materials used for batteries and motors that could become highly toxic if not appropriately recycled.

The parallel hybrid

The parallel hybrid still produces CO_2 but lower volumes, from around 5% to 30% depending on the adopted design.
It is possible to remove completely the CO_2 emissions if the thermal engine is supplied by hydrogen. However, today, the level of readiness of hydrogen combustion on aircraft is too low to speculate on the applicability of hydrogen in parallel hybrid configurations.

The series hybrid

The series hybrid is also emitting CO_2 as it is using a gas turbine. However, the implementation of electric propulsion allows to add DEP configuration. Hence, there is a major effect in terms of CO_2 reduction. The reduction of fuel consumption for series hybrid is estimated at around 30% to 50%.

The turbo electric

Turboelectric is only expected for experimental aircraft. It enables to demonstrate the feasibility of pure electric aircraft in absence of efficient batteries. This architecture is not foreseen as operational at the moment.

SUITABILITY

Constraints

The main constraints of electric propulsion are related to the weight and to the volume of the electric motors and batteries. Another indirect limitation is the ability to rely on green and cheap electricity to supply aircraft batteries.

The parallel hybrid

The parallel hybrid requires batteries onboard the airplane. The electric engine is also downgrading the performance of the kerosene engine, especially at take-off and climb, or during phases where the electric engines are inactive. However, the architecture is expected to provide a major reduction of the total fuel consumption, despite the weight increase due to batteries and the increased individual consumption of the thermal engine.

The series hybrid

The series hybrid implementation is constrained by the geometry and weight of the aircraft to cope with the installation of electric engines and gas turbines. The weight of batteries and electric engines is increasing the aircraft weight. So, aerodynamics must be completely optimized using the DEP to compensate for the excess weight.

The turbo electric

Constraints of turbo electric observed in an experimental context cannot be extended to real operations. Experimental aircraft using turboelectric technology are aimed at demonstrating the performance of electric propulsion. Kerosene is still used as the source for electricity.

Certification Aspects

Although some specific regulations need to be developed, there is no major certification obstacle identified for electric propulsion, as long as system redundancy is applied in case of an engine loss.
However, electric motors in a DEP configuration will require special efforts to reduce drag, i.e. installation of engines in uncommon loculations for an aircraft. Hence aircraft geometry is expected to be largely impacted. Therefore, a full redesign of the aircraft is expected for pure electric propulsion.

The parallel hybrid

Some light parallel hybrids could be certified very easily as a retrofit, if there is no major impact on existing engine rear design.

The series hybrid

The series hybrid requires a complete redesign of the aircraft. So, a complete certification process is necessary for these architectures.

Aircraft Segments Concerned

As mentioned above, electric propulsion is foreseen at least for regional aircraft. As for single-aisles, the power requirement cannot be supplied with current electric motor technologies. So, for pure electric propulsion to be considered on single-aisles, real breakthroughs would need to take place in battery energy storage efficiency and capability.

The parallel and series hybrid

The main advantage of the hybrid architecture is that it can be used on all aircraft categories, because thermal engines are able to ensure the necessary propulsion requirements regardless of the electric engine limitation.

The turbo electric

No commercial transport is expected for turbo electric.

APPLICABILITY

Market Acceptance and Barriers

Except for the price of electricity, no market barriers are identified. For PMSM, the availability of rare earths is necessary to produce efficient permanent magnets.

Costs

Electric supply requires huge investments in the production of electricity and the capability to store high quantities of energy in batteries.
In addition, electric motors will require the development of new aircraft programs.

The parallel hybrid

In the case of implementation of parallel hybrid on existing aircraft, the cost can be equivalent to a retrofit such as the NEO or MAX programs. In the case of new aircraft, the cost is expected to be slightly higher than a new aircraft program.

The series hybrid

Due to the complete redesign and innovations required by series hybrid, the cost of the program is expected to be significantly increased compared to a new program development.

The turbo electric

The cost of experimental turboelectric aircraft is very light compared to a new program, as these architectures are implemented on very small size aircraft.

Implications on Aircraft Designs

The replacement of thermal engines by electric motor is not very constraining. But the installation of heavy batteries or fuel cells could require some significant modifications to the aircraft structure.

The parallel hybrid

In the parallel hybrid, the electric propulsion takes the place of the thermal engines. However, the supply of electricity and the installation of batteries require some major modifications compared to classical aircraft programs.

The series hybrid

The series hybrid implements electric propulsion in coordination with aerodynamic optimization and DEP implementation. These aircraft are clearly expected to have drastically changed geometry, configuration, and operations.

The turbo electric

No commercial transport is expected for turbo electric.

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DESCRIPTION

Concept

Introduction

The main function of fuel cells is to generate electricity very efficiently through an electrochemical reaction. They differ from batteries since they require a continuous source of fuel and oxygen, whereas in a battery the chemical energy comes from substances which are already present inside the battery.

Fuel cells were originally invented by Sir William Grove in 1838. At this time, he constructed a cell consisting of two separate sealed compartments, each of which was fed by either hydrogen or oxygen gas. He called his invention a “gas voltaic battery.” Unfortunately, it did not produce enough electricity to be of much use. It remained a scientific curiosity until the 20th century, when English engineer Francis Thomas Bacon matured the original idea to develop the world’s very first hydrogen-oxygen fuel cell in 1932.

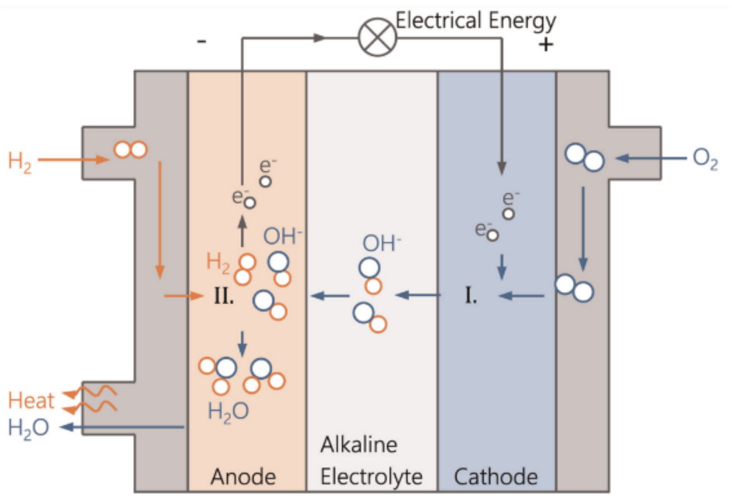
Several applications were found since 1950s: automobiles, submersibles and space programs. Particularly, Bacon’s fuel cell was a key solution to power satellites and rockets for space exploration programs, including Apollo 11 since the 1960s. As the story goes, the then US President, Richard Nixon, would have said: "Without you Tom, we wouldn't have gotten to the moon” [1].

From the mid-2000s, aviation applications have been increasingly studied as such technology has the potential of delivering energy very efficiently compared to other technologies, while reducing greenhouse gases emissions (GHG) and dependence on fossil fuels.

Different technologies of hydrogen fuel cells

Even if different types of FCs exist, they are all based on the same chemistry of oxidation-reduction (redox) reactions. More precisely, they consist of two electrodes, which are separated by an ion-conduction medium called electrolyte. On an electrode called anode[3] an oxidation occurs freeing electrons which are in turn transported to the cathode[4] (the other electrode, where a reduction occurs) via an electrical conductor. It is here that the electric energy can be accessed and distributed [2].

On one side, electrons circulating in a conductor over time produce effectively an electric current, and on the other side, ions must be transported between the two electrodes in the electrolyte to complete the circuit. A schematic of the first historical fuel cell, the Alkaline Fuel Cell, is shown below in Figure 105 [3]:



$$\text{II. } H_2 + 2OH^- \rightarrow 2H_2O + 2e^- \qquad \text{I. } O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

Figure 105 - Alkaline Fuel Cell

[3] Note that the terms anode and cathode describing the reactions occurring on the electrodes are not always used because in electrolysis the chemical reactions on these get reversed. The terms fuel electrode and air electrode are often found in literature.
[4] See note 2

The following diagrams describe other fuel cell variants [3]:

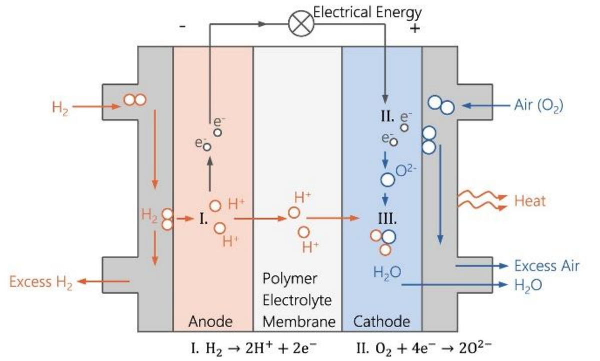


Figure 106 - Proton Exchange Membrane Fuel Cell

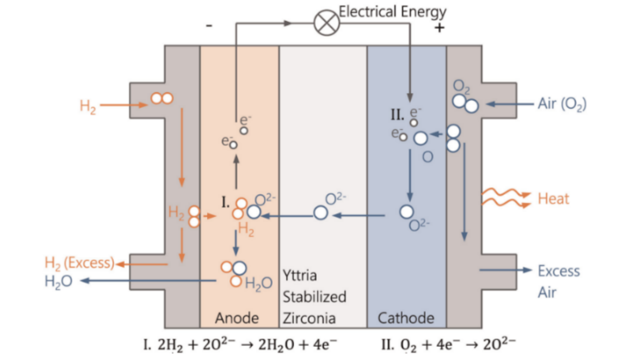


Figure 107 - Solid Oxide Fuel Cell

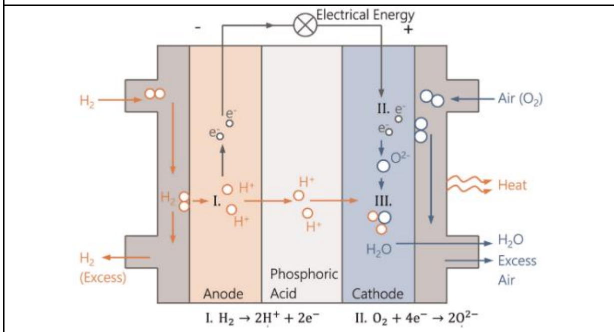


Figure 108 - Phosphoric Acid Fuel Cell

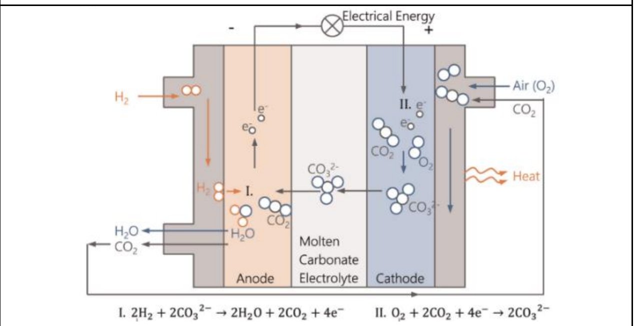


Figure 109 - Molten Carbonate Fuel Cell

They all have the same one-step reaction using hydrogen as a fuel and oxygen as the oxidizer. They furthermore only reject water (the compounds in gaseous form have the subscript g): $2H_{2_{(g)}} + O_{2_{(g)}} \rightarrow 2H_2O_{(g)} + Heat$

The main differences between them are about the ions transported in the electrolyte, the electrolyte and its concentration, the materials for electrodes and the operating conditions (temperature and pressure). Concerning electrodes, in a few words, the choice of their material depends on many factors such that the type of electrolyte (if it is corrosive, highly/low concentrated…) and the operating environment (hot, cold, high/low pressure, humidity…) Electrodes can be made of gold, tantalum, titanium and carbon and only the platinum group metals can be used as catalysts [4].
Materials as catalysts are very important because they improve the chemical kinetics of the cell. For instance, the operating pressure, temperature, and the electrolyte concentration drive the efficiency of the cell and, if they are too low, the catalyst material is essential to compensate for the associated low efficiency of the reaction [2,4].

For aviation applications, the most important measure is power. The following table summarizes the power ranges with other important design characteristics (specific power discussed below):

Fuel cell type	Acronym	Electrolyte	Charge carrier	Operating temperature	Power range	Efficiency	References
Alkaline Fuel Cell	AFC	Immobilized liquid potassium hydroxide	OH^-	50-220°C	1-10kW	45-60%	[2,3,5,6]
Proton Exchange Membrane Fuel Cell	PEMFC	Humidified polymer membrane	H^+	30-100°C	Up to 1MW	40-60%	[2,3,5,6]
Phosphoric Acid Fuel Cell	PAFC	Immobilized liquid phosphoric acid	H^+	150-220°C	10kW-1MW	40-45%	[2,3,5,6]
Molten Carbonate Fuel Cell	MCFC	Molten carbonate	CO_3^{2-}	600-700°C	1MW-100MW	45-55%	[2,3,5,6]
Solid Oxide Fuel Cell	SOFC	Ceramic	O^{2-}	500-1000°C	1kW-100MW	45-65%	[2,3,5,6,8]

Table 6 - Summary of main characteristics of hydrogen fuel cells

Note that the PEMFC described here is the low-temperature PEMFC (LT-PEMFC), another type called high-temperature PEMFC operating between 120-200°C is also studied. Even if much less mature than its predecessor, it offers many advantages for heat management (due to higher thermal gradient between cells and coolant temperatures), humidification of the membrane (not required), purity of air and hydrogen (more tolerant to impurities than LT-PEMFC) [6].

Balance of Plant (BoP), specific power of fuel cells at system-level

To operate, a fuel cell requires several other subsystems named Balance of Plant (BoP). It includes an air/oxygen supply conditioning subsystem, a fuel supply conditioning subsystem, a thermal management subsystem, an electric power management and conditioning subsystem, and a control system [5].

Components such as vessels, pumps, heat exchangers for cooling, humidifiers, de-ionization filters, cell monitoring modules, DC/DC voltage stabilization or conversion circuitry, hydrogen distribution are part of the BoP. It is the Balance of Plant that differentiates how FC-powered aircraft are designed and configured rather than the fuel cell stack itself [2] because all these components add mass and require additional volume.
In addition, to improve the powertrain performance during the transient phase and to provide an efficiency response during power peak, batteries are today installed in parallel to the fuel cell system [5]. They are not included in the BoP, but it is important to note their presence for weight estimation in the aircraft design phase.

A very simplified schematic of the fuel cell electric propulsion is shown below in **Figure 110** (adapted from [34]) illustrating part of the elements mentioned previously:

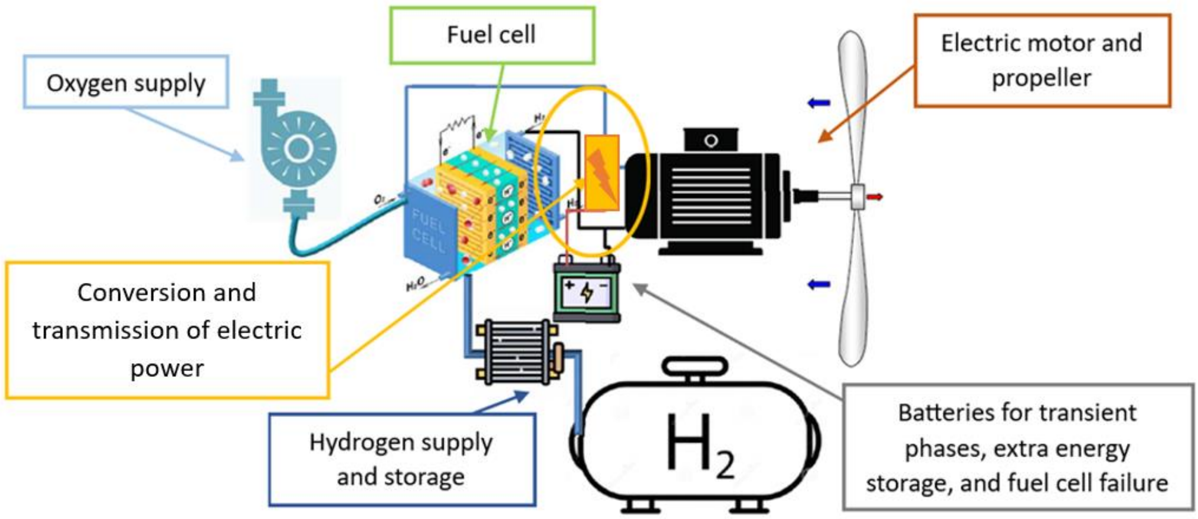


Figure 110 - Simplified schematic of the fuel cell electric propulsion

As an order of magnitude, specific power of fuel cells at system-level, i.e. the ratio between the power delivered and the mass of the system, are in the range of 0.1-0.7kW/kg today [2,6,7]. The efficiency is about 40-60% [2,3,4,5,6,7]. However, state-of-the-art fuel cell systems claim 1kW/kg [5].

It can be noted that, at cell stack level, specific power of prototypes can achieve 1-3kW/kg [2,6,22], but at system level the specific power reduces by 50-80%, depending on the application [2]. In comparison, turboprop have a specific power of about 5-6kW/kg and a gas turbine 10-15kW/kg. This parameter gives an order of magnitude of how heavier the propulsive system will be, to deliver the same power, if the entire kerosene engine was to be replaced.

Maturity

In aerospace applications, the first fuel cells were AFCs and PEMFCs. Even if very mature for many low power applications, improvements are required to reach higher powers.

It has been demonstrated that the LT-PEMFC is the most promising type of fuel cell for aviation purposes and is, therefore, used in most of the projects [8]. In fact, it has a high efficiency (40–60%), the highest specific power (0.5-1KW/kg), quite high-power application range (up to 1MW), fast start-up and shut-down times due to low operating temperature (30–100 °C), cold start and cold storage capability.

Another promising type of cells, which could be used in aviation, is the SOFC. It has the highest efficiency (up to 65% theoretically) and the highest power range. However, it is still today underdeveloped for mobile applications [8] but several studies show how it could be used to replace the actual kerosene APU on today's commercial aircraft [2,3,5,6] allowing greener taxiing.

From previous comments, a special focus will be made on LT-PEMFCs. Several successful prototypes were built and tested in the last 15 years [2]:

- In 2007, the Georgia Institute of Technology built a demonstrator aircraft (of 16.4kg) to test the performance of a hydrogen fuel cell onboard. A total net output power of 448W was available from the 500W rated fuel cell system [28].
- In 2008, DLR's research aircraft ATRA (A320 aircraft) included the test of an emergency system based on a hydrogen fuel cell of 20 kW. The system was integrated and tested up to a flight altitude of 25 000 ft under several acceleration and inclination conditions [25]. It supplied power to the aircraft electric motor pump for the back-up hydraulic circuit ailerons operated during the flight [23].
- In 2008, Boeing built the first hydrogen-manned aircraft to use a fuel cell. The plane could fly for 45 min, but the tests were for only half that amount of time. The aircraft was a two-seat light aircraft DA20 whose internal combustion engine was replaced by a PEMFC with lithium-ion batteries [9,10].
- In 2009, the ENFICA-FC consortium led by the University of Turin flew the Rapid 200-FC, 20 kW PEMFC-powered manned airplane with gaseous hydrogen compressed at 350 bars.
- During the same year, the German Aerospace Center's Antares DLR-H2 became the first manned research airplane with the capability to take off solely using fuel cell power. Based on the power glider Antares 20E, it has been developed to flexibly and cost-efficiently test airborne fuel cell systems. The airplane was able to cover distances in excess of 700 km. The PEMFC fuel cell produced 33 kW with 52% efficiency.
- In 2016, H2FLY, the DLR-led partnership flew HY4, the world's first four-seat hydrogen fuel cell–powered airplane (**Figure 111** [32,33]). The fuel cell produced 45 kW [3]. Their design was further improved in 2020 under the EU project MAHEPA, achieving redundancy of powertrain and fuel system, as well as multi-hour endurance, and higher fuel cell power of 55kW [31]. Adding batteries, they reached more than 100kW of power [31].

Figure 111 - HY4 demonstrator in flight

- In 2020, ZeroAvia flew their fuel cell-powered demonstrator in a six-seat Piper Malibu. Later released details describe the powertrain as being 250 kW battery-hydrogen hybrid with 100 kW from a PowerCell MS-100 hydrogen fuel cell.
- In June 2022, Deutsche Aircraft has begun the early stages of modifying a legacy Dornier 328 twin-turboprop to serve as a flying testbed for a new megawatt-class fuel cell powertrains [11].
- Airbus announced during its December 2022 Summit, a fuel cell of the mega-watt class for its future ZEROe regional aircraft. Tests are scheduled for 2026 and EIS in 2035 [12].
- In January 2023, ZeroAvia flew a Dornier 228 (**Figure 112**) with the fuel cell and electric propulsion systems powering the left wing and today continue to increase the performance envelope. The fuel cell powertrain has a power of 600kW. ZeroAvia intends to power zero-emission commercial aircraft of 9-19 seats by 2025 [13]. A megawatt design is studied today.
- In March 2023, Universal Hydrogen flew their Dash8-300 aircraft with a fuel cell-electric propulsion (**Figure 113**). One of the two turboprops was replaced by a fuel cell from Plug Power. 10 of the 50 seats were removed to carry the liquid-hydrogen tank. The company plans to put into service an ATR 72 regional

Figure 112 - ZeroAvia's Dornier 228 during flight

aircraft converted to run on hydrogen. No fuel cell powertrain power value was announced yet, however during the second circuit over the airport the kerosene turboprop was throttle down to minimum and the horizontal flight could be maintained [14,15].

Figure 113 - Universal Hydrogen's Dash8-300 during flight test (2023)

According to these breakthroughs, fuel-cell powertrains for aviation of megawatt-class power level are expected to reach TRL 6 maturity by 2026–2028, with an entry into service post 2030 [2]. The PEMFC seems the preferred fuel cell type for low power aerospace applications and therefore low power propulsion. No precise data have been found to access where the power frontier between the use of hydrogen fuel cell and hydrogen gas turbine was, because, in fact, it depends on many factors such as the power to be delivered by the system, its weight, volume and complexity… However, a frontier of 2MW can be reasonably considered according to expected fuel cell and electric motor designs for 2030.

Environmental Impacts

Assuming a green hydrogen, i.e. hydrogen produced by electrolysis whose electricity comes from renewable sources such as solar, wind or hydro, the presented hydrogen fuel cells operation are carbon free as hydrogen does not contain carbon atoms. However, it is important to note that SOFCs can emit by-products such as toxic CO, but still much less than observed in combustion engines [2]. Furthermore, for SOFCs, emissions can be injected into the burner of an engine in case of hybrid configuration [5].

Concerning NOx, unlike a classical jet engine combustor where the high temperature flame produces NOx (due to nitrogen present in the injected air), a fuel cell does not produce any type[5] of NOx as by-products [16,17].

In addition to these main improvements, noise is also reduced [20]. In fact, even if compressors and the ventilation systems of the BoP effectively produce noise, we expect them to be easily isolated. Moreover, a fuel cell inside a pod under a wing (the most convenient design tested today) is clearly significantly less noisy than a gas turbine. In fact, there is not any turbomachinery rotating and the exhaust gas produced has a very small velocity compared to jet engine – so, significantly less jet noise. The propeller (or the fan) connected to the electrical motor will therefore produce most of noise.

The main by-product of fuel cells is water vapor. It is estimated that even if they will form more contrails than traditional kerosene engines, these are likely to be optically thinner and less persistent due to the absence of particulate matter in the exhaust [16, 21]. Note finally that most of this water could be used for inboard purposes like toilets and air conditioning, thereby reducing the amount that needs to be loaded on an aircraft before departure [20].

[5] *It exists three types of NOx [18,19]:*
Thermal NOx – combination of the nitrogen from the air ingested in an engine with the O and OH radicals produced by the combustion/flame. At temperatures well below 1300°C, much smaller concentrations of thermal NOx are produced.
Fuel NOx – produced when a fuel containing nitrogen is combusted, resulting from oxidation of the already-ionized nitrogen contained in the fuel.
Prompt NOx - Prompt NOx is formed from molecular nitrogen in the air combining with fuel in fuel-rich conditions which exist, to some extent, in all combustions. This nitrogen then oxidizes along with the fuel and becomes NOx during combustion, just like fuel NOx.

SUITABILITY

Constraints

Several constraints have been identified concerning the applications of LT-PEMFC in aircraft. Note that all hydrogen fuel cells have similar constraints, however the membrane is much less critical for HT-PEMFC and SOFC, as it has a solid electrolyte (which is also not affected by flight manoeuvres).

Thermal Management

Hydrogen fuel cells have an efficiency of approximately 50% at sea level conditions. This means that 50% of the power is wasted into heat that must be evacuated. Most of this heat is transported by the water vapor produced on electrodes and the rest comes from the cathode exhaust or un-reacted hydrogen [2].

To evacuate this heat, three methods exist:

- Air-cooled, so the heat is rejected into the atmosphere without any useful work
- Hot water for food preparation in the galleys (the heat released is then only partially used)
- Cryogenic fuel cooled, i.e. cooled by heat exchange with a fuel at cryogenic temperature.

Depending on the method, different constraints appear. In today's prototypes, an air-cooled configuration is mostly used but, for instance concerning PEMFC, as the temperature difference between the fuel cell and the coolant (i.e. the ambient air) is small (operating temperature of about 80°C), the heat dissipation will be more difficult to achieve. This implies high radiator areas [3,5,26] leading to substantial increase in aircraft weight, drag, so fuel consumption. More precisely, some prototype designs convey the thermal energy by a liquid-cooling system to heat exchangers where it is finally air-cooled.

If this heat is partially used for cooking, radiators are still required as preparation of food is not constant during all the flight. So, the same drag issue as discussed before arises.

Finally, cryogenic cooling is not yet mature, however there are a lot of expectations about this technology for cryogenic tanks storing liquid hydrogen and cryogenic cooling systems.

Operating conditions, water management

To operate efficiently, fuel cells must be monitored in pressure, temperature, humidity (included in the water management herein below), oxygen and hydrogen purity.

Operating pressure

The pressure is the main driver of efficiency and power of the cell. An increase results in a cell voltage gain (so efficiency improvement and power) at the same current density [6,23]. To provide pressurized oxygen, several methods are studied.

The bleeding of air from the main kerosene engines after compressions can be envisaged for hybrid configurations but fuel consumption increase will result. The fact that this overconsumption of kerosene lead to more GHG emissions than the reductions brought by the fuel cell would create a sensitive situation that needs to be studied.

Another way is to use the passenger cabin pressure, but it may not meet the required flow rate for the fuel cells or the cabin safety and control criteria [2].

The power demand for supercharging the fuel cell with outside air might be about the same as the loss in power output of the fuel cell due to low-pressure operation [24]. Further studies will be required.

In summary, it is necessary to maintain an operating pressure at least at about 0.8/1 bar up to 2/3 bar [5,6] for efficiency reasons. However, pressure-induced stresses on cell components might be detrimental for life cycle duration at these higher pressures [24].

Gaseous hydrogen supply

The fuel cell itself requires gaseous hydrogen therefore, a decision must be taken as to where the state transition between liquid and gaseous form hydrogen will occur, in case liquid hydrogen is used.

There are three possibilities for hydrogen to transition from liquid to gaseous form [2]:

- At the exit of the hydrogen tank, with or without active boil-off management
- Just before entering the fuel cell
- In a specific element of the fuel system, which would be dedicated to (at least partially) manage boil-off.

This process is critical to manage for the fuel cell operations and must not pose a risk to the safety of the aircraft. At the same time, simplicity and low-weight designs are required.

Operating temperature

The heat effect is more pronounced for high-temperature fuel cells but high temperatures also improve fuel cell performance [6]. If the temperature is too low, extra system to pre-heat the cells will be required [2] with batteries for example, but then extra-weight is expected. Note that depending on the ambient temperature and the pressure ratio of the compressor, the air coming may also match reasonably the operating temperature of the cell or may have to be cooled.

Water management

Water management for fuel cells is another concern. If water is not evacuated properly from the inside of a cell or if too much water is removed and the membrane becomes too much dehumidified, an inhibition of the electrochemical reaction occurs and damages the fuel cell [8].

A humidification of the membrane of around 30% is required to achieve optimal operating conditions [3], however the ohmic losses of the ion exchange membrane increases with humidity [5]. So, a stringent monitoring is required. High-Temperature PEMFC do not require humidification, however their development and cost are unaddressed [6].

Note finally that, on the other side, this water produced also has an advantage: it could be used for toilets and air conditioning thereby reducing the amount of water that needs to be loaded in the aircraft [20].

Weight

The specific power of a fuel cell system is a complex calculation because it depends on the fuel cell application. However, no expectation higher than 1kW/kg have been found at system level before 2035. This low value compared to turboprops (about 5-6kW/kg) and gas turbine (10-15kW/kg) means that to get the same power, the equivalent fuel cell design would be 5 to 15 times heavier. This creates a major weight constraint, as the fuel cell development remains only a small part of the solution. In fact, the balance of plant represents more than 50% of the total weight of the system, so efforts have also to be made to significantly improve cooling, hydrogen storage and distribution. Only then, efficiency gains of this technology will surpass the weight penalty.

Other constraints have been summarized in the table below:

Purity	Membrane and platinum catalytic layer on electrodes can be poisoned by CO and H_2S, which penalises the electrochemical reaction and leads to reduced power output [8]. Both air and hydrogen must therefore be cleaned for PEMFC. HT-PEMFC are more tolerant to these pollutants [6]. Also, the membrane is sensitive to metal ions that would be introduced by corrosion of the electrodes. Contamination is a major contributor to the degradation of PEMFC performance and lifetime [27].
Power dynamic testing	Batteries will be required to manage transient phases with high-power demand and to avoid damaging the membrane [2,3,23].
Cost, manufacturing, maintenance	Rare materials used for membrane-electrode assembly (e.g., a platinum catalytic layer) represent around 50% of the entire PEMFC cost [8,29,30]. Unknown maintenance cost and life cycle of components with power demand.
Flight	Inclination disturbs the chemical reaction, so performance instabilities can occur for liquid electrolytes [23].

Table 7 - Other fuel cells constraints

In summary, for any FC type to become a viable option for electric aircraft propulsion, the main constraints are the evacuation of excessive heat, the air pressurization, the weight reduction, the manufacturing and maintenance costs, and the reliability and longevity. An appropriate balance of plant implementation has to be determined, and this remains a challenge requiring transversal knowledge of thermo- and aero-dynamics, cryogenics and system safety. Associated ground infrastructure readiness will also need to be developed concurrently to ensure the viability of any entry-into-service [6].

Certification Aspects

Today, there is no clear path to certification for hydrogen-powered heavier-than-air aircraft. However, since last decade working groups from EUROCAE, SAE International, ATSM and aviation authorities are making efforts to provide more precise guidelines, standards and means-of-compliance materials. Further details can be found in the publication [2] in the chapter Fuel Cell-Powered Passenger Aircraft Safety and Certification Challenges (7), and the following publications can be cited:

- AIR6464/ED-219 in 2013, Aircraft Fuel Cell Safety guidelines
- AIR7765/ER-20 in 2019, Considerations for Hydrogen Fuel Cells in Airborne Applications. On hydrogen application and benefits for aircraft, providing insight about why and how to use hydrogen and fuel cells in aviation.
- AS6679 in 2019, Liquid Hydrogen Storage for Aviation. Guidelines for the safe integration, operation and maintenance, and for certification of Liquid Hydrogen Storage Systems (LHSS) in aircraft. This document also defines guidelines for safe refuelling operations of hydrogen aircraft. This document does not address airport infrastructure, nor how the refuelling means is specified, except the provisions required for the safety of the aircraft refuelling operation.
- AIR6464 in 2020, Hydrogen Fuel Cells Aircraft Fuel Cell Safety. Main safety requirements for integrating fuel cells into aircraft.
- AS6858 in 2023, Installation of Fuel Cell Systems in Large Civil Aircraft. Elaborates the requirements for designing, testing, and certifying fuel cells.

At aviation authorities' level, both EASA and FAA are working on how to certify this technology mainly based on the publication of these entities. In a few words, all above-mentioned constraints must be clearly investigated to get the system certified. In fact, a loss of control of the thermal management with overheating will damage the entire system and impact flight safety. If a chemical inhibition occurs, a back-up system will be required. And flight manoeuvres must not disturb the performance of the cells (for liquid electrolyte, e.g. for PEMFC).

Aircraft Segments Concerned

Orders of magnitude of the required power for each aircraft segment are summarized in the table below. These values are indicative:

Aircraft segment	Power required during take-off and climb	Power required in cruise, in % of take-off power
Commuters (less than 19 seats)	$\leq 2\ MW$	$50-80\%$
Regionals (turboprop)	$5-10\ MW$	$50-80\%$
Single-aisle	$20-50\ MW$	$50-90\%$
Twin-aisles, widebodies	$80-100\ MW$	$75-90\%$

Table 8 - Power range requirement for each aircraft segments at take-off and cruise

According to these values, the power range of fuel cells will limit the applicability. Moreover, the balance of plant size and associated weight increase with power requirement. The applicability is still complex to estimate but a 100% fuel cell-based propulsion is not possible for all flight segments for the above-mentioned reasons. Aircraft manufacturers could then design hybrid configurations which would then apply to all aircraft segments.
Considering that megawatt powertrains with fuel cells could reach TRL 6 maturity by 2026-2028, the commuters and regional aircraft segments could both be concerned before 2035. For single-aisles and twin-aisles, fuel cells could be used in hybrid configurations if the additional weight don't exceed the estimated kerosene consumption savings.

APPLICABILITY

Market Acceptance and Barriers

These solutions based on hydrogen require the existence of a global hydrogen economy which aviation could benefit from.

From a general public standpoint, there could be some reluctance to fly in fuel cell-powered aircraft simply because they will be equipped with propellers which can give the impression of old technology (we already observe this in some regions where there is a passenger preference for jets). However, the lower noise levels associated with clear environmental messages could turn such perceptions upside down.

For airlines, operating costs will be the main driver for adoption and it is difficult today to predict where the cost of hydrogen will be as it depends heavily on the existence of a world hydrogen economy beyond aviation. Maintenance costs are also unknown today.

For airports, investments in infrastructure will have to be made to store and distribute hydrogen at the gates. Even if at the beginning, the airport supply in hydrogen can be made by trucks, very quickly more will have to be developed to cater for airline needs.

In a nutshell, hydrogen-based decarbonization solutions will require massive investments for many stakeholders (airports, manufacturers, fuel suppliers…) If hydrogen-based aviation starts, it will be from the regional segment. Although this may not represent the bulk of the decarbonization needs for aviation, it will certainly create a new momentum where it will be again acceptable to fly short-haul. We can expect in that case, a huge momentum, revitalizing regional aviation, and boosting airline short-haul networks.

Costs

As still in a research phase, no estimation of cost could be found. However, the fuel cell costs are mainly driven by the membrane-electrode assembly due to the use of rare materials [8,29,30]. The balance of plant will also represent a major cost item due to its complexity. Life-cycle and maintenance remain also to be evaluated.

Implications on Aircraft Designs

Many implications on aircraft design can be identified with fuel cell-based propulsion:

- Due to low gravimetric index of hydrogen (even in liquid form) than kerosene, much heavier designs requiring much more volume are expected;
- The hydrogen fuel supply and the balance of plant within a given restricted volume inside the aircraft will also be a challenge and will lead to significant design modifications;
- The distribution of hydrogen in the wings, submitted to torsion and bending moments, will certainly also impact the aircraft design.

Therefore, either less cabin will be available so less payload and revenue for airlines, or different and new aircraft designs will be envisaged. Disruptive technologies and designs will be necessary to solve this challenge.

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DESCRIPTION

Concept

Hydrogen was the first element to appear in the early universe and its mass is estimated to represent approximately 75% of the global observable universe mass. Although hydrogen is the main content of outer space, on earth, gaseous hydrogen is very rare, and it is mainly present in the form of water. Hydrogen is also the main source of energy for stars as a fuel for nuclear fusion under high conditions of temperature and pressure inside stellar cores. Production of electricity from nuclear fusion is not foreseen before 2050 in labs [04]. However, hydrogen can be a source of chemical energy when it is combined with oxygen to synthesize water as described in the equation:

$$2H_2 + O_2 \rightarrow 2H_2O + Energy \qquad \text{(EQ1)}$$

As shown in EQ1, the reaction of hydrogen (H_2) with oxygen (O2) generates only water (H_2O) and energy. So, this reaction is an appropriate lever for decarbonization of aviation. There are two methods to use the energy of hydrogen:

- Combustion of hydrogen inside a thermal reactor to produce thrust;
- Production of electricity inside fuel cells.

The current section addresses only the combustion method. Compared to fuel cells, hydrogen combustion is less efficient in terms of energy conversion. Fuel cells provide thrust with electric propulsion. As stated in study [15], electric motors are currently not able to supply propulsion for aircraft size larger than single-aisles, at best (Figure 114).

Aviation Sector	EM Power Capacity	EM Specific Power	Battery Specific Energy
General aviation	Motor: <1 MW	Motor: >6.5 kW/kg	>400 Wh/kg
Regional/single-aisle	Motor: 1–11 MW	Motor: >6.5 kW/kg	>1800 Wh/kg
Twin-aisle	Not feasible	Not feasible	Not feasible

Figure 114 - Electrical system component performance requirements for all-electric propulsion systems [15]

Hydrogen combustion could be an alternative candidate to supply thrust to single-aisles and twin-aisles.

Hydrogen production

Although hydrogen production is not covered here, we decided to briefly list some of the main methods of gaseous hydrogen generation in Figure 115.

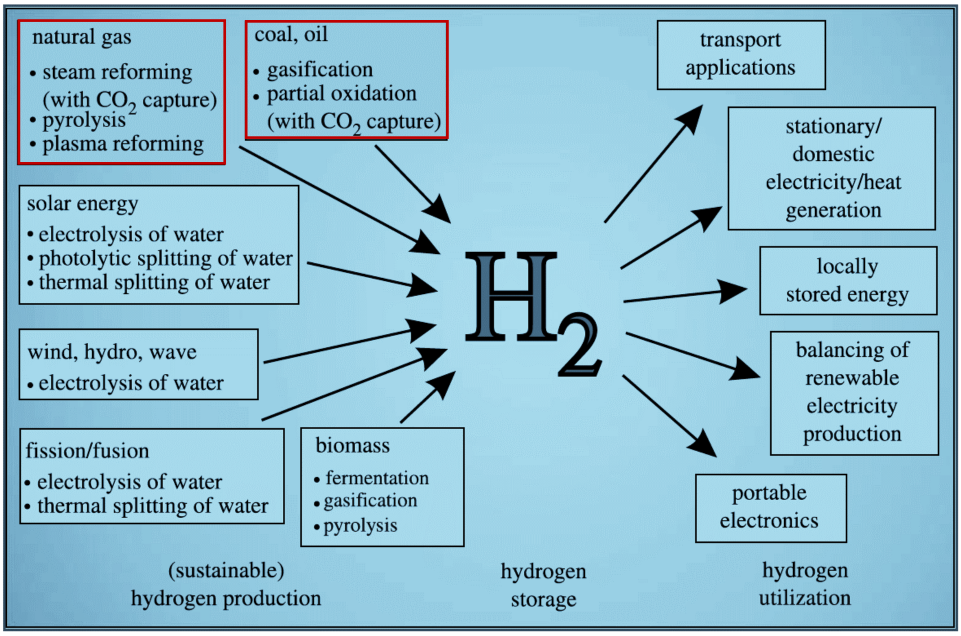


Figure 115 - Hydrogen as an energy carrier linking multiple hydrogen production methods, through storage to various end-users. Highlighted production routes (in red) can involve substantial CO_2 generation [03]

In addition to the above list of hydrogen sources, early 2023, researchers discovered another potential source of gaseous hydrogen at a depth of 1100m in Lorraine (France) [06]. This source of hydrogen could be one of the biggest in the world. This hydrogen could have been generated by the oxidation of materials with water infiltration in the Earth mantle. This gas is trapped at high depths (deeper than 1000m), and it is theoretically possible to find it everywhere on Earth.

Hydrogen Onboard Storage

As presented in study [11], the energy density of hydrogen compared to fossil fuel can be advantageous or penalizing, whether it is the gravimetric or volumetric energy density. This is due to the gaseous nature of hydrogen. The gravimetric energy density of hydrogen is assessed between 121 MJ/kg (lower heating value) and 140 MJ/kg (higher heating value). For real applications, the lower heating value is more adapted, hence hydrogen has an energy content by mass three times higher than the fossil fuel. However, its volumetric energy density is less than 3 MJ/L, largely lower than fossil fuels at around 32 MJ/L. Figure 116 synthetizes this comparison between fossil fuel and hydrogen.

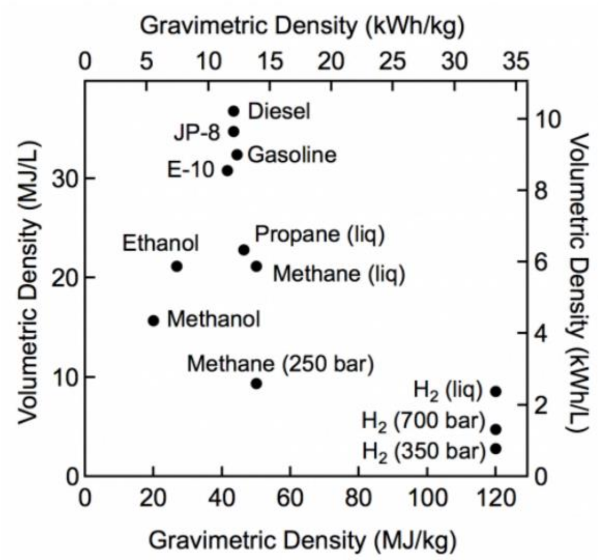


Figure 116 - Comparison of specific energy (gravimetric density) and energy density (volumetric density) for several fuels based on LHV. Courtesy of the U.S. Department of Energy [11]

This poor volumetric energy density of hydrogen is making the storage onboard an aircraft a huge challenge. Currently, three means of storage are considered for hydrogen:

- Compressed gaseous hydrogen at 350 bar or 700 bar
- Liquid hydrogen at –253°C
- Solid-State Hydrogen which consists in trapping hydrogen in hybrid species. Figure 117 presents the performance of several solid-state means. This study topic is still under progress. But there have not been enough mature results of its efficiency, though it could become a promising way to store efficiently hydrogen.

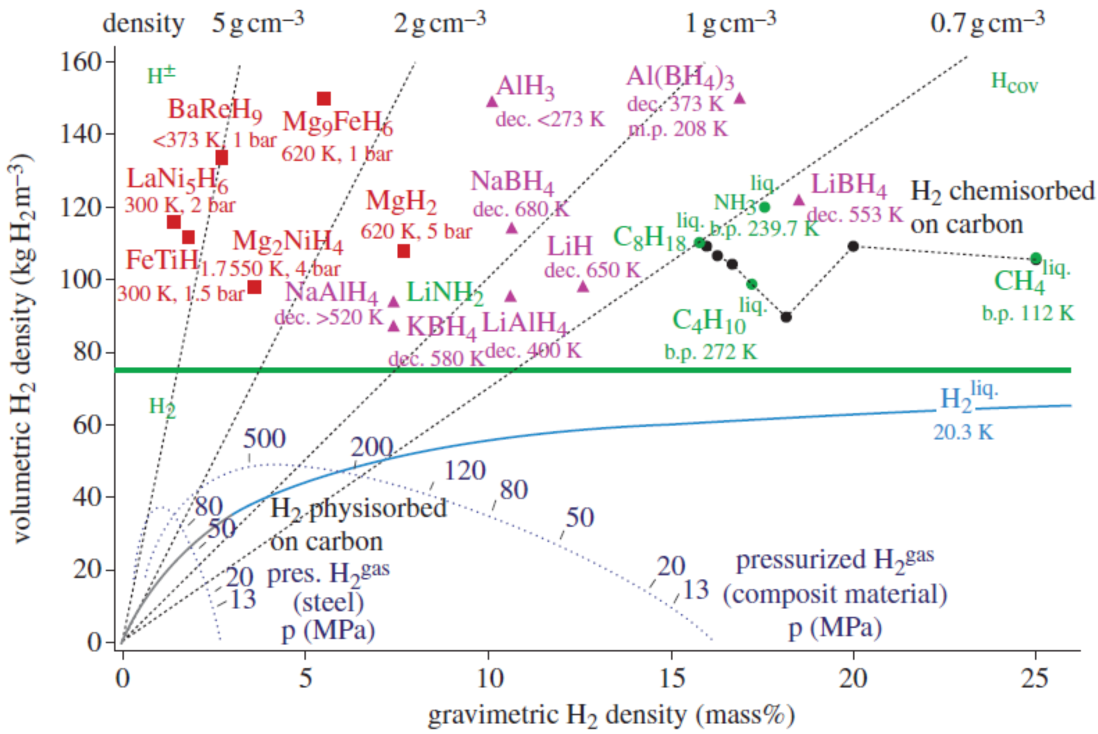


Figure 117 - Volumetric and gravimetric hydrogen density of some selected hydrides [16]

These storages also require significant amounts of energy (between 13% to 40%) to maintain their condition (temperature, pressure) [11].

According to [01], tanks with compressed hydrogen can be applied up to regional aircraft size, such as ATR aircraft. But it cannot be used for larger aircraft. Therefore, liquefied hydrogen for turbofan engines has become the preferred solution to date. Liquefied hydrogen (LH_2) tanks are largely used in the space industry and this experience can be leveraged for aircraft (Figure 118).

Figure 118 - The LH_2 external tank of the space shuttle covered in a layer of sprayon foam insulation (the orange material) that was 1-2 inches thick [01]

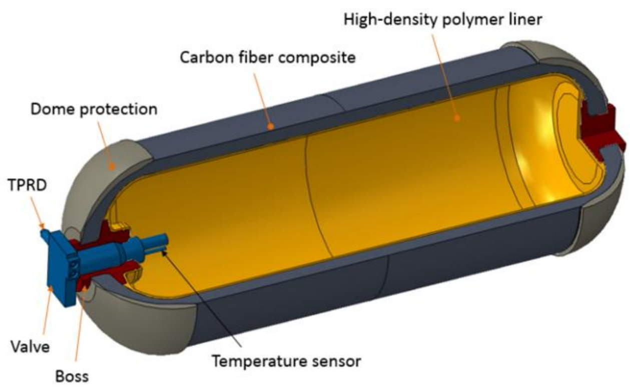


Figure 119 - Tank components for storing hydrogen [14]

LH_2 is taking advantage of the higher density of hydrogen in its liquid phase (2.37 kWh/dm3) [03], requiring to set and maintain the temperature under -253°C (boiling point). It is therefore necessary to add an insulation and cryogenic system to use LH_2 onboard. Although this system has been already used in space transportation for decades, an aircraft LH_2 tank is required to maintain its temperature whenever it contains hydrogen, including during ground phases, and to support around 20,000 take-offs and landings during the aircraft life cycle [14]. These requirements represent major constraints which are also increasing the cost of LH_2. An example of an LH_2 tank is detailed in Figure 119.

Moreover, the LH_2 volumetric density is four times lower than kerosene. So, the volume of LH_2 tanks is proportionally larger than for kerosene [10]. The location of LH_2 tanks become a real challenge as they cannot be installed in traditional wings and should avoid encroaching into payload spaces (cabin) to protect revenues for airlines. Figure 120 shows several proposals of LH_2 tank location onboard tube-and-wing aircraft.

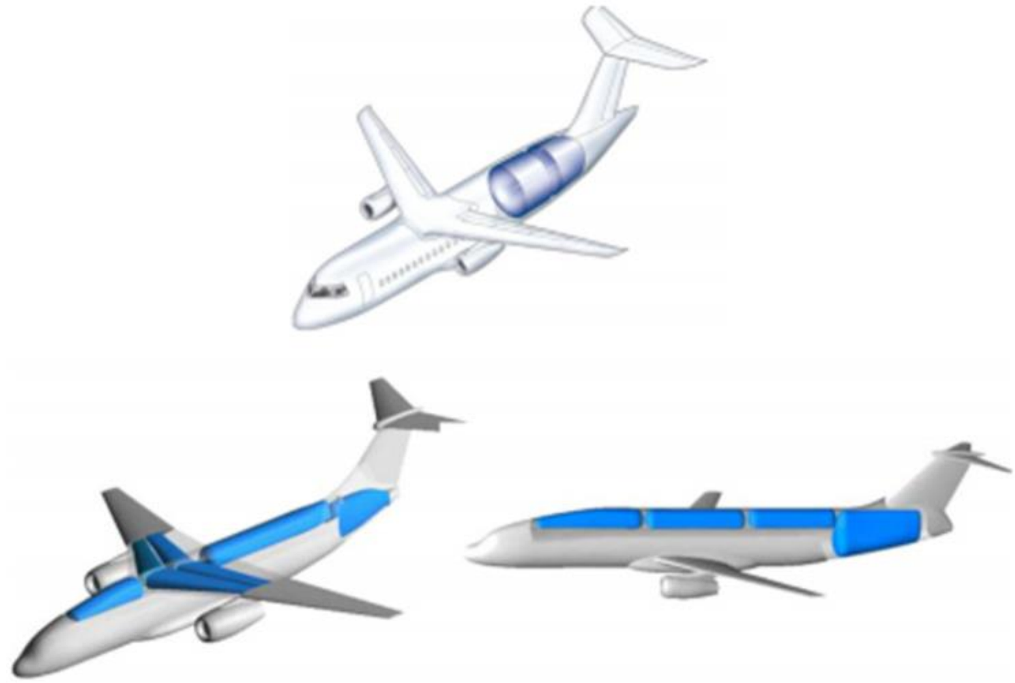


Figure 120 - Liquefied hydrogen aircraft with different tank configurations [10]

New aircraft geometry, such as Blended Wing Body (BWB) aircraft, could offer more possibilities to locate large LH_2 tanks with limited impact on payload (Figure 121).

Figure 121 - Two potential arrangements for hydrogen tanks in a BWB configuration. The darker area shows the passenger cabin [01]

Other types of storage are also under study for alternative storage means such as solid-state. These may have less constraining storage requirement than above detailed tank storages, but, today, they are still at experimental stage [01].

Finally, the issue of hydrogen embrittlement (introduction and diffusion of hydrogen into a material) is a major concern for all operation phases where hydrogen is in contact with metallic structures. The contact between hydrogen and metallic structure should be avoided as much as possible. Some solutions are under study to avoid the loss of metal structural strength due to hydrogen contact.

Hydrogen combustion

As mentioned previously, although the use of hydrogen in electric fuel cells is more efficient, the electric propulsion power is too limited for most of the world fleet. So, hydrogen combustion is currently preferred for aircraft larger than regionals (Figure 122).

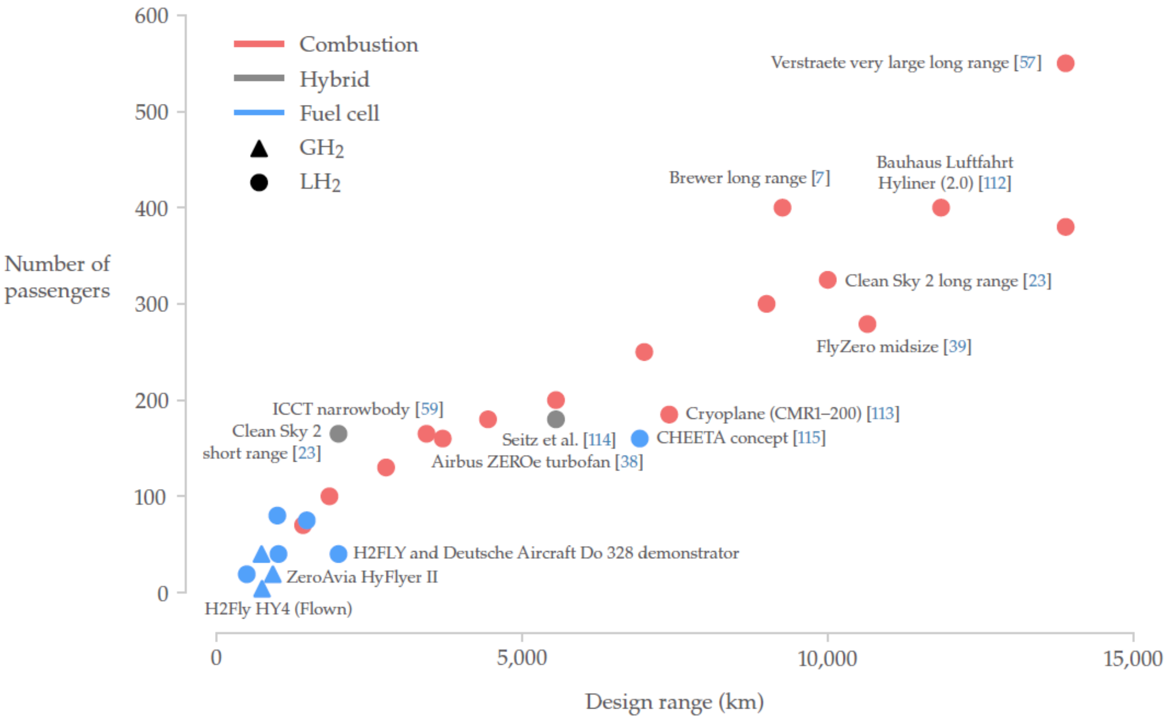


Figure 122 - Passenger vs Range Diagram of Most Recent Hydrogen Use in Aircraft Concepts [01]

Burning hydrogen is not a new idea. Since the 1950s, hydrogen combustion has been tested with pure hydrogen or blended with other fuels [12].

Blending hydrogen with conventional jet fuel

The hydrogen injection combined with kerosene is a first step toward decarbonization and this concept was checked on several experimental aircraft for decades.
There are two approaches of hydrogen blending:

- The pre-mixing
- The injection inside the combustor

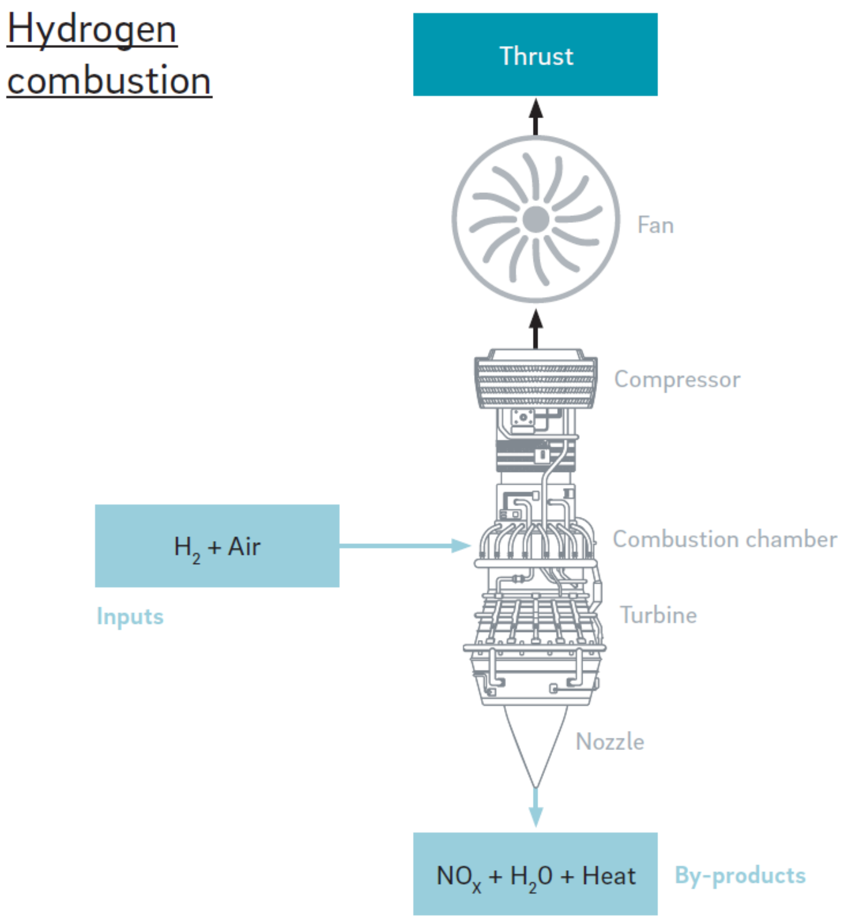
The pre-mixing method consists in mixing gaseous hydrogen with kerosene droplets before the combustor and using the mix in the combustor. Another concern is to keep the mixture homogenous as the big difference of densities could cause hydrogen and kerosene to separate during transfer to combustor.

The injection method consists of directly injecting gaseous hydrogen into the chamber of combustion. The difference of calorific power between kerosene and hydrogen is causing inhomogeneity of temperatures in the chamber. The chamber design and the locations of hydrogen and kerosene injection points must therefore be carefully chosen to optimize the combustion.

Experimentations on existing aircraft have shown a slight reduction of kerosene consumption with smaller quantities of hydrogen blending. However, this implies significant updates in the storage (tanks and distribution system), and in the design of engines, without eliminating CO_2 emissions [12]. This concept is not foreseen as a valid lever for decarbonization, and it is not detailed further below.

Hydrogen Turbofan Engines

This section addresses the concept of turbofan engines supplied with hydrogen instead of kerosene. This concept mainly consists in reusing as much as possible the existing turbofan engine structure while replacing kerosene by hydrogen. Figure 123 describes a turbofan engine structure.



Source: Roland Berger

Figure 123 - Description of hydrogen-based turbofan engine [13]

The main differences between hydrogen and kerosene regarding the combustion are:

- Hydrogen has a higher flammability than kerosene and the stochiometric fuel-to-air ratio is around 1:34 for hydrogen versus 1:15 for kerosene [01]. This means that hydrogen needs more air than kerosene to completely react, or for the same air quantity, less hydrogen is required than kerosene;
- Hydrogen has a higher Lower Heat Value (LHV) of 121 MJ/kg compared to 43 MJ/kg for kerosene [07]. Thus, the same mass of hydrogen provides almost three times more heat than kerosene.

To use hydrogen, the architecture of existing turbofans can be easily adapted when it comes to the air input, compressor, turbine, and nozzle [01]. However, due to the above major differences of combustion conditions, the combustion chamber requires some major modifications to properly burn hydrogen. The diagram in Figure 124 highlights the compared ranges of combustion between hydrogen and kerosene in terms of temperature and fuel-air mixture.

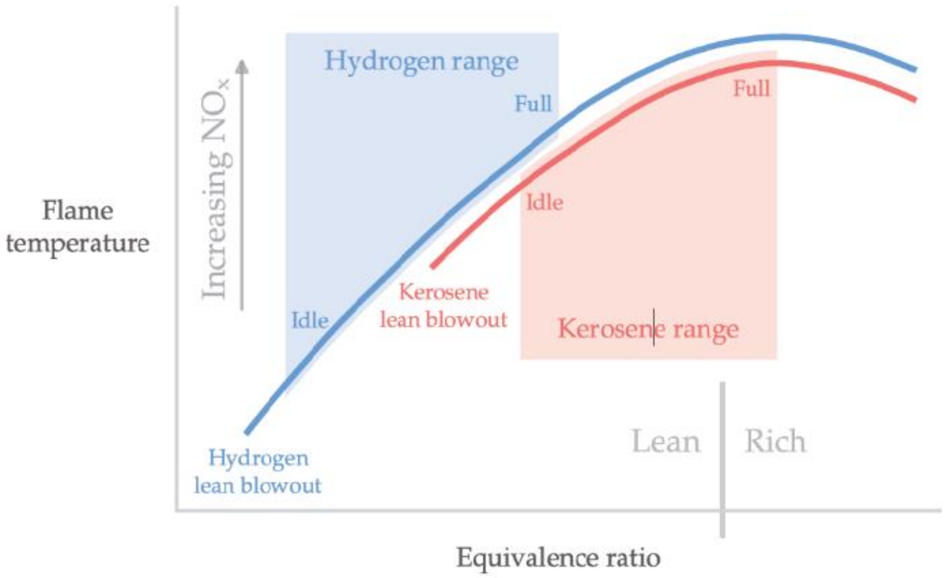


Figure 124 - Hydrogen has wider flammability limits than kerosene, which means that it can be burnt leaner [01]

The main role of the combustion chamber is to ensure the right mixing of fuel and air and a complete combustion reaction without any unburned residual within the combustion zone [08] (Figure 125).

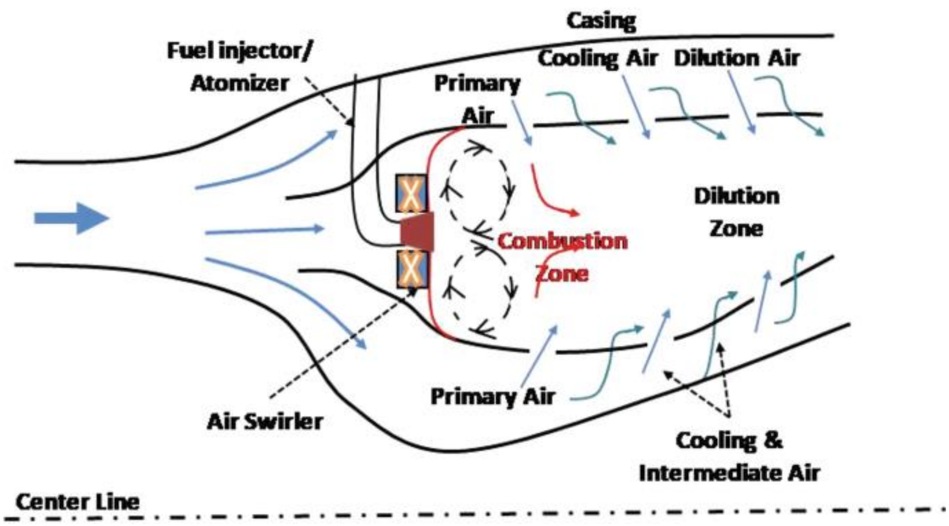


Figure 125 - Chamber of Combustion for Existing Turbofan, annular type [08]

Unfortunately, due to its higher flammability range, the flame of hydrogen combustion expands in a larger area than for kerosene. This phenomenon of flames located outside dedicated areas is called flashback, and it can seriously damage the exposed parts of an engine [07] (Figure 126).

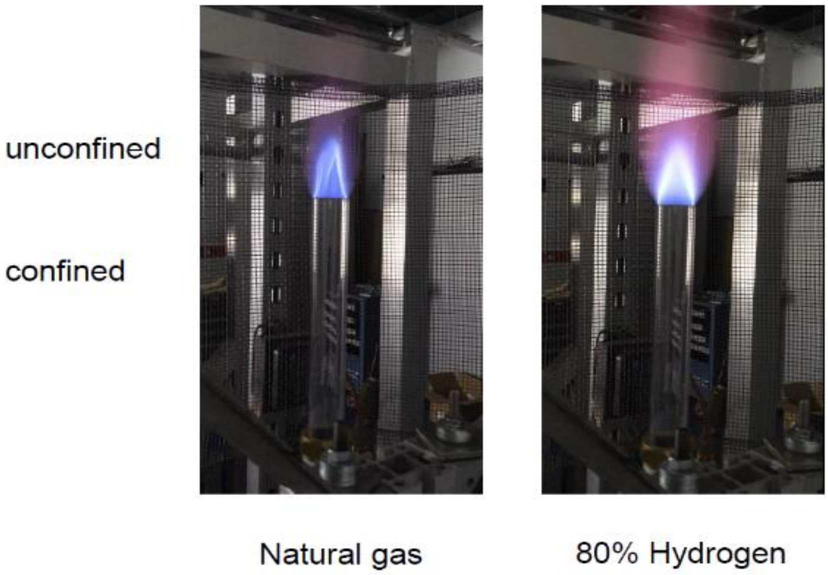


Figure 126 - Comparison of flames between hydrogen and natural gas (hydrocarbon) [07]

The flashback is reduced by adapting the hydrogen share in the mixture with air. There are two possibilities:

- Increase the proportion of air (oxygen): This requires major changes in the whole design of the engine. This is the solution retained for rocket engines (detailed in the below dedicated section).
- Decrease the proportion of hydrogen: This allows to keep the major design of the turbofan engine but a drastic change of the combustion chamber must be made to better mix the hydrogen with air.

The design of the injector and chamber with appropriate poor mixture of air and hydrogen is very complex. However, several concepts are currently under development and seem promising. Figure 127 presents several examples of hydrogen combustor concepts.

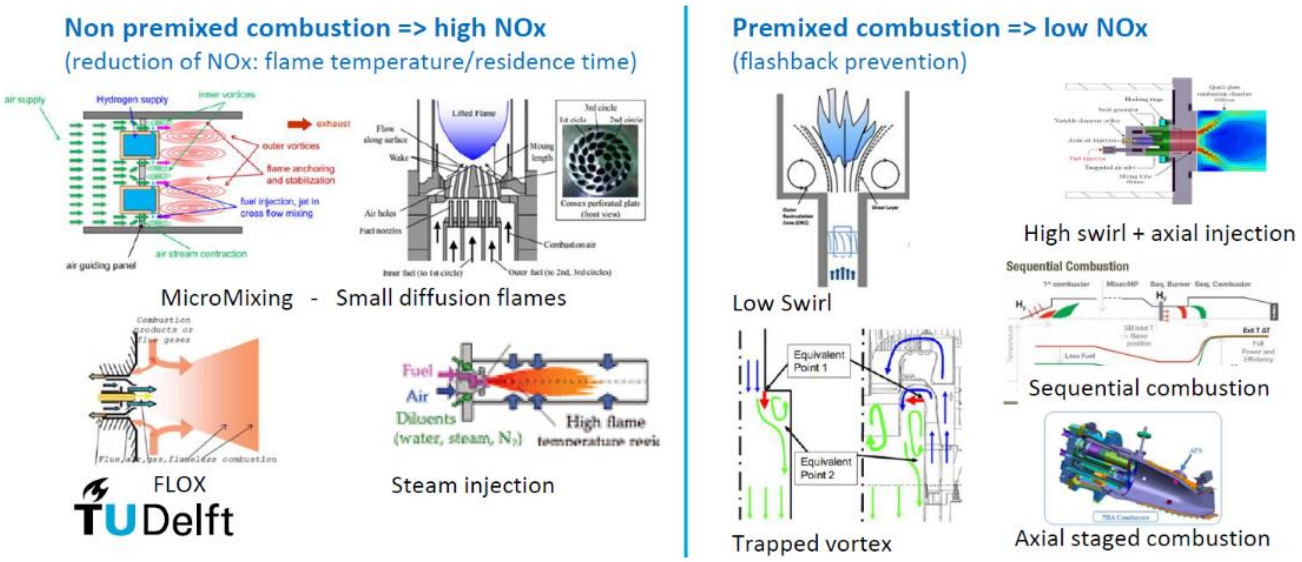


Figure 127 - Combustor designs under development for high hydrogen gas turbines [07]

Moreover, an engine with hydrogen combustion is suitable to produce high thrust but the energy conversion is less efficient than an electric motor engine. So, a hybrid engine concept could be imagined using combustion for take-off and climb, and electric motors for the other flight phases. Figure 128 shows an example of such a hybrid architecture.

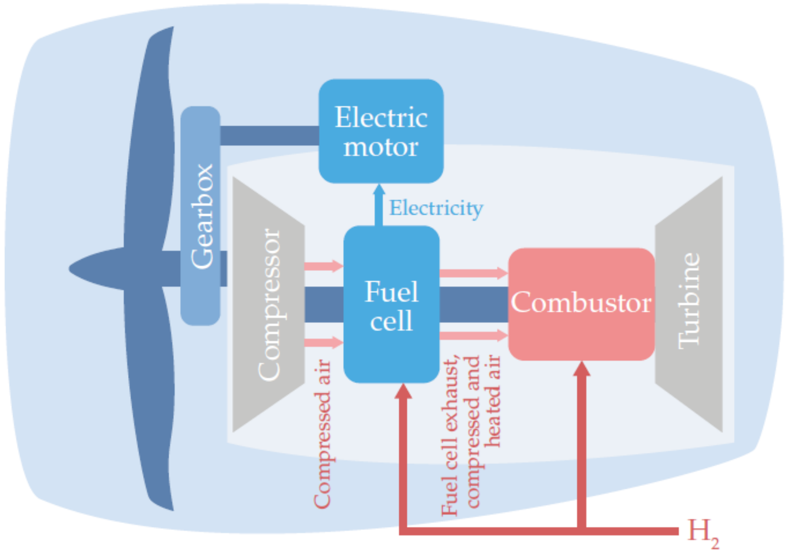


Figure 128 - A highly-integrated fuel cell and combustion hybrid propulsion architecture [01]

Air-Breathing Rocket Engines

For decades, the space industry has accumulated experience on hydrogen-based propulsion with the rocket engines. However, those rocket engines are not adapted for aircraft that require longer autonomy than space launchers. The space rocket embeds hydrogen and oxygen in its tanks because the higher atmosphere is not able to supply enough oxygen. For aircraft, oxygen can be extracted from the atmosphere. As detailed in the turbofan section above, the atmosphere does not include enough oxygen at normal pressure to assure complete combustion of hydrogen. So, air-breathing rocket systems were investigated to increase the oxygen quantity from the air with a high rate of input air compression. This concept, also known as air-breathing rocket engines, has been under study since 1958 to mainly develop horizontal reusable launchers [09].
The current major application of Air-Breathing Rocket Engine is the Synergetic Air-Breathing Rocket Engine (SABRE) under study by UK's Reaction Engines Ltd (Figure 129).

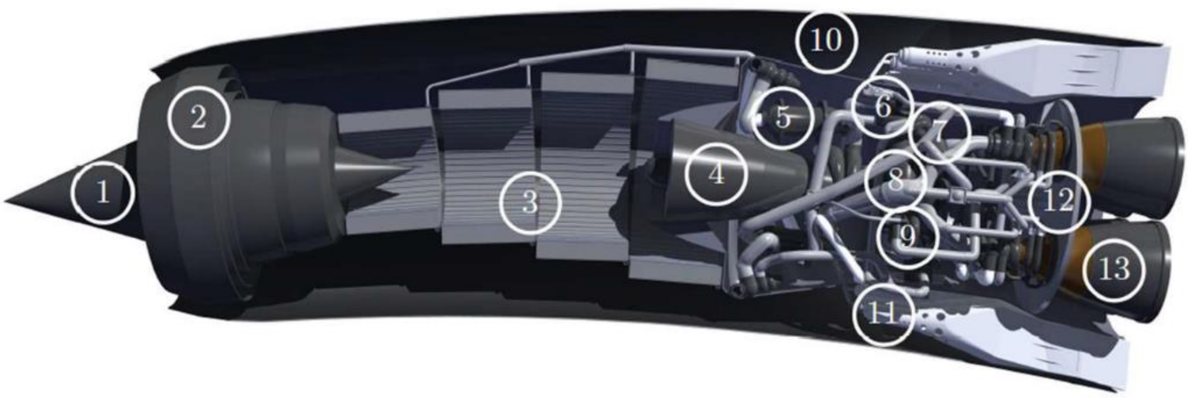


Figure 129 - SABRE section: 1) movable spike 2) intake 3) precooler 4) air compressor 5) preburner and reheater (HX3) 6) helium circulator 7) H_2 pump 8) He turbine and regenerator (HX4) 9) LOx pump 10) spill duct 11) ramjet burn [05]

This engine briefly consists of air intake, precooler, air compressor, and burner in nozzle. In air-breathing mode, the atmospheric air is first cooled, then compressed, and finally burned in the nozzle. SABRE can also switch to a pure rocket engine with the closure of air intakes and the provision of oxygen from onboard tanks. The diagram of Figure 130 details this SABRE concept cycle.

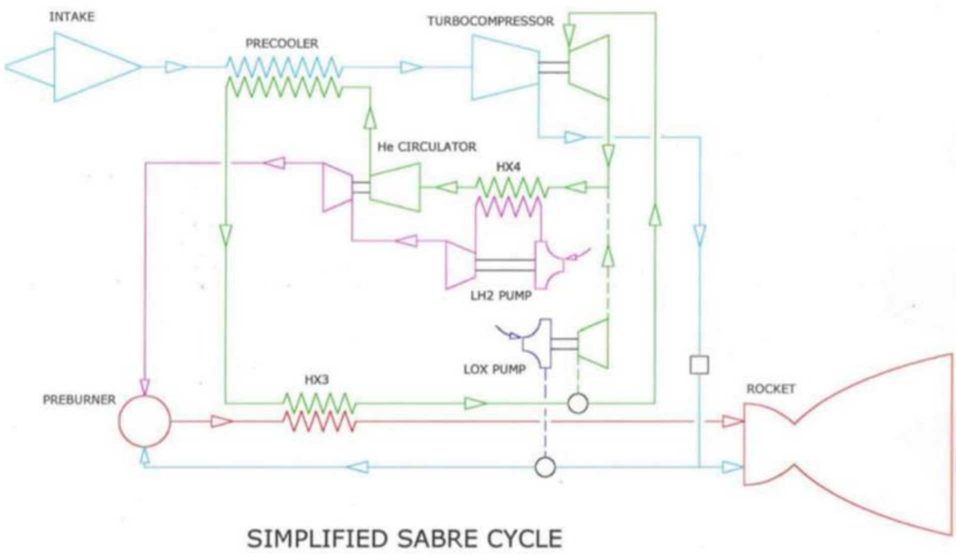


Figure 130 - SABRE cycle in both air breathing and rocket modes [05]

SABRE was studied as the engine for the SKYLON space plane concept by NASA [05]. This airplane could take off and land from a runway and could also be used as a single stage space launcher (Figure 131).

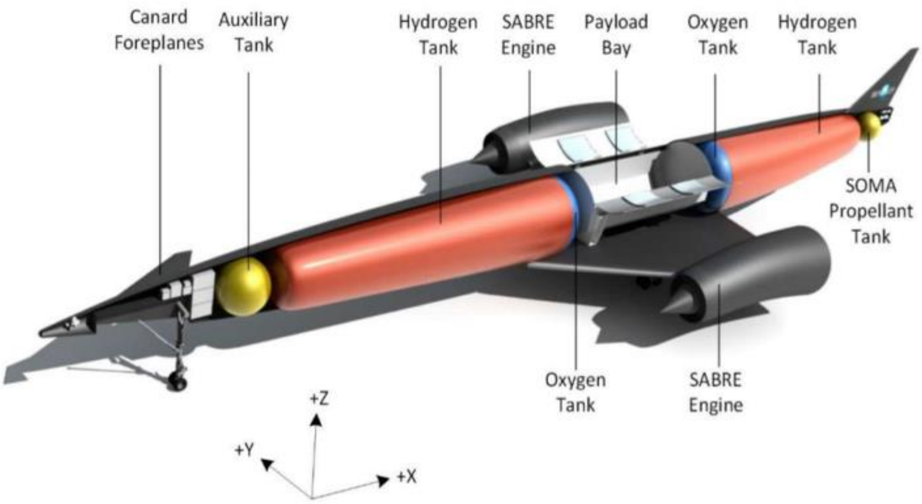


Figure 131 - Skylon layout [05]

Although the Skylon concept and SABRE do not target commercial aircraft, this technology can actually be applied for passenger transportation. This propulsion could provide a thrust of 15,000daN to 20,000daN in the subsonic or transonic Mach areas [05]. This concept could be promising for future sustainable solutions of supersonic, hypersonic or space airplanes. The research and development cost could also be shared with the space industry as it could also be used as a reusable space launcher.

Maturity

Hydrogen Onboard Storage

Onboard liquefied hydrogen tanks raise several concerns regarding the ability to maintain temperature and pressure, or the reduction of hydrogen embrittlement that can damage the metal of the tank.
The LH_2 tank technology is expected to be available by 2030-2035, and its related TRL is assessed at 6 today [02].

Hydrogen combustion

Hydrogen Turbofan Engines

The hydrogen turbofan technology is driven by the ability to generate a homogeneous stochiometric mix of uncompressed air with small quantities of hydrogen. Several theorical studies are currently ongoing in laboratories. The timeline for this technology to mature is assessed to be around 2035-2040 and its TRL should be around 3-4.

Air-Breathing Rocket Engines

The air breathing rocket engine has currently been studied for decades for space vehicles. It needs to demonstrate its adaptation for commercial aircraft. Its endurance and reliability should also be demonstrated airplanes with a 30-year lifetime. An entry-into-service is roughly estimated for around 2040 and its TRL is around 3-4.

Environmental Impacts

Hydrogen Onboard Storage

No environmental impact is foreseen from the storage of liquefied hydrogen.

Hydrogen combustion

All hydrogen combustion propulsions do not produce any CO_2 emissions, but they emit water vapor. Moreover, the high temperature of hydrogen combustion generates NOx. These NOx emissions could be reduced with appropriate steam injections in the combustor.
These emissions are expected to have slighter impacts on the environment than the current CO_2 emissions.

SUITABILITY

Constraints

The hydrogen operating cost for aircraft would raise up to 50% compared to similar kerosene-based aircraft [01] if no global hydrogen economy is developed. In addition, the main challenges are also the protection against embrittlement and the capability to maintain the temperature and pressure of liquefied hydrogen.

The first concern with hydrogen is to maintain appropriate conditions of storage and distribution due to its high flammability compared to kerosene.

Hydrogen Onboard Storage

The onboard storage of liquefied hydrogen increases mass and energy consumption. These penalties could be balanced by improving the shape and aerodynamics of the aircraft. According to the section dedicated to aerodynamics, this could reach up to 60% reduction of the fuel consumption.

Hydrogen combustion for turbofan and rocket engines

By determining the overall efficiency of the propulsor, jet engine using hydrogen combustion is less efficient than electrical motors using electricity coming from hydrogen fuel cells, details can be found in Figure 132 with other economics consideration. However, fuel cells are limited in power (hence thrust), high power application and/or critical flight phases (Take off, Climb) will therefore require jet engines.

In addition, the protection against the high temperatures of combustion and the flashback effect are still under study.

	Reciprocating engine: diesel	Turbine generator	Photovoltaic	Wind turbine	Fuel cells
Capacity range	500 kW–50 MW	500 kW–5 MW	1 kW–1 MW	10 kW–1 MW	200 kW–2 MW
Efficiency	35%	29–42%	6–19%	25%	40–85%
Capital cost ($/kW)	200–350	450–870	6600	1000	1500–3000
O & M cost ($/kW)	0.005–0.015	0.005–0.0065	0.001–0.004	0.01	0.0019–0.0153

Figure 132 - Comparison of fuel cell with other power generating systems [17]

Certification Aspects

Hydrogen Onboard Storage

The leakage of hydrogen is the main challenge in terms of safety and certification. It is necessary to introduce a new certification standard to certify hydrogen aircraft in the future.

Hydrogen combustion

Hydrogen combustion has led to several major accidents in the space industry. These experiences must be leveraged for future aircraft using hydrogen combustion. This combustion is similar to current kerosene combustion. So, the existing certification framework should be easily adapted to encompass hydrogen combustion.

Aircraft Segments Concerned

All sizes of aircraft are eligible to use hydrogen combustion. However, this technology will likely be more attractive for aircraft categories that cannot be decarbonized by other means (widebodies for instance). The additional weight of the hydrogen systems and the required volume for tanks also favor implementing hydrogen combustion into larger aircraft.

Air-breathing rocket engines could provide new solutions for air transport with supersonic, hypersonic or low-orbit flights.

APPLICABILITY

Market Acceptance and Barriers

There is no identified market barrier for these technologies.

Costs

This initial investment for these programs is expected to be several times higher than past aircraft developments because the technologies involved are still largely immature and a lot more research and development must take place before they can be considered as valid candidates for aircraft decarbonization.
For rocket engines, the initial investment is expected to be drastically higher, in line with those for new space programs.

Implications on Aircraft Designs

Hydrogen Onboard Storage

Onboard storage of hydrogen requires a much higher volume and onboard locations different from what exist today (with kerosene stored in the wings). In the case of tube-and-wing aircraft, we can anticipate aircraft with longer fuselages (with related impacts on take-off rotation clearance and airport gates) and with dry wings where the absence of fuel stored would imply specific reinforcements.
New shapes of aircraft, such as blended-wing bodies, should be considered to optimize hydrogen storage and payload.

Hydrogen combustion

Hydrogen turbofan engines should not change the existing design of aircraft beyond those required by hydrogen storage. Only the engine combustion chamber will require drastic changes.

For rocket engines, the whole aircraft is expected to change to fit the constraints of these engines. Moreover, with such an engine design, usual bleed around the high-pressure compressor and mechanical extraction on shafts of turbofan will not be any more possible, hence an auxiliary source of energy will be required to power specific aircraft systems such as air conditioning, de-icing, pumps, etc.
In addition, supersonic, hypersonic or orbital planes would require radically new designs coping with the specificities of their typical missions.

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DESCRIPTION

Concept

Introduction

The use of ammonia (NH_3) as fuel goes back to 1822 with a proposal from Sir Goldsworthy Gurney (in England) for an engine to drive a small locomotive. This breakthrough allowed during 19th century to power some locomotives in the country, and tramways in New Orleans (USA) [41]. However, it was not until 1905 that the first small scale motor was developed by Ammonia Casale Ltd., registering patents in Italy in 1935 and 1936 [3].

During World War II the scarcity of fossil fuels in some regions led to the search for alternative fuels. For instance, the lack of diesel in Belgium in 1942 led to the development, one year later in April 1943 by Emeric Kroch, of a compressed coal gas / ammonia motor to keep public transportation in operation (Figure 133 [40]). This motor-bus fleet logged tens of thousands of miles (and there's anecdotal evidence that some individuals used the ammonia pumps built for the bus fleet to fuel their personal cars during this period!) [39,40].

Figure 133 - NH_3 Fuel Bus, Belgium

In the 1950s in the USA, a military hypersonic research aircraft, the X-15 (Figure 134 [38]) was powered by a rocket-engine using anhydrous ammonia and liquid oxygen as fuel. The gas mixing behavior in the combustion chamber was nearly the same as for kerosene [10]. This rocket settled speed and altitude records.

Figure 134 - X-15 rocket

Forty years later, in 2007, the University of Michigan (USA) ran a gasoline-powered car on 30% ammonia for 3,800 km. Other experiments were carried out around the world (Korea, Japan...) to power cars with ammonia. A concise summary concerning the history of the use of ammonia for transportation is shown in Figure 135 [42].

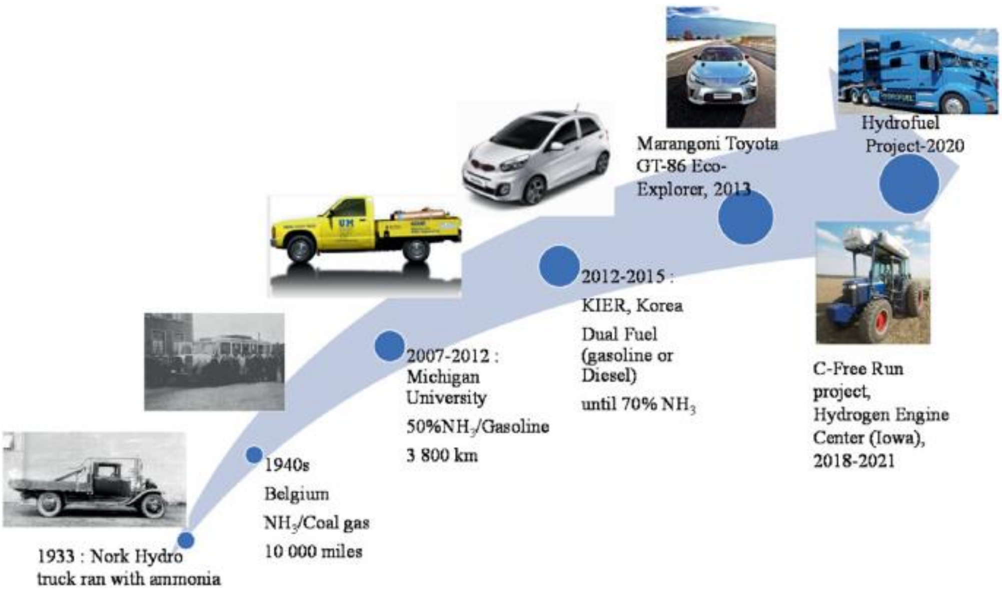

Figure 135 - Ammonia as Fuel for Transportation to Mitigate Zero Carbon Impact

Finally, there were also attempts as soon as in 2017 in Japan, to use ammonia in land-based gas turbines [19]. The company Chugoku Electric Completes partially added ammonia with methane, kerosene, or hydrogen, to decarbonize the energy production of the country [43, 44].

More recently, ammonia has come back into the spotlight as a means of decarbonizing a number of specific sectors, most notably the shipping industry, as a replacement for certain heavy fuels known for their greenhouse gas emissions. It is today considered as an economically viable fuel for this shipping industry.
Concerning aviation, a lot of articles can be found, nevertheless the feasibility and the environmental impact must be well assessed. Recent worldwide breakthroughs on ammonia can be found on the Ammonia Energy Association website (https://www.ammoniaenergy.org/articles/).

Ammonia properties

Ammonia as a zero-carbon emission fuel is further explored because easier to use and to store than hydrogen. Moreover, it can be either a fuel, or an intermediate leading to hydrogen because 17.6% of its mass is hydrogen[6]. Its main chemical and storage properties compared with kerosene and liquid hydrogen (LH_2) are summarized in the following Table 9 and Table 10.

Compared to hydrogen, ammonia is less volatile due to a higher molar weight and has a higher autoignition temperature[7]. Moreover, due to its narrow flammability range[8], it is generally considered as a low reactivity substance reducing accidental combustions or explosions when transported [10]. At the same time, its flame is visible compared with hydrogen, and, as lighter than air, it rapidly dilutes in a spill [3]. From an aircraft storage viewpoint, it has a lower melting point than kerosene preventing freezing of the fuel during flights at high altitudes.

	Kerosene (JET A1)	LH_2	LNH_3
Energy content (MJ/kg) - $\boldsymbol{e}$	43	121	18.6
Molar weight (g/mol) - $\boldsymbol{M}$	Depend on the selected average alkane	2	17
Melting point (°C)	-47	-260	-77.7
Autoignition temperature (°C)	210	560	630
Flammability range (mole %)	0.7-5	4-77	18-28
References	[10, 45]	[3, 10]	[3, 10]

Table 9 - Energy content, state and combustion properties of Kerosene, LH_2 and LNH_3

Concerning more precisely the storage, we define for a tank a gravimetric and volumetric index: how much mass or volume of a given fuel respectively can fit into a tank. In other word, how heavy and large a tank must be to store a given type of fuel. The volumetric index is not discussed here because it is still today in development phase with very few data available. It is based on adsorption processes by the surfaces of solids or absorption processes within the solid which composes the tank [29,30].
The gravimetric index I_g is defined in two different ways described below:

$$I_g = \frac{mass_{fuel}}{mass_{tank} + mass_{fuel}}$$

$$I_{g2} = \frac{mass_{fuel}}{mass_{tank}} = \frac{1}{\frac{1}{I_g} - 1}$$

For kerosene, as it is stored inside the aircraft wings, spars and ribs already present for the structure are used to create a tank with metal plates and joints so the tank is very light compared to the weight of kerosene it can store. I_g is therefore very close to 1 but still inferior, and $I_{g\,2}$ is very high.

[6] By calculation of molar weight $\frac{M(H)_{in\,NH_3}}{M(NH_3)} * 100 = \frac{3*1}{14+3*1} * 100 \approx 17.6\%$
[7] Describes the temperature at which the fuel will self-ignite in the presence of an oxidizer without an external ignition source [10].
[8] The lower and upper limits describe the minimum and maximum of fuel concentration in air at which the mixture can burn. Dilution systems can be needed to avoid this range when hot surfaces or combustion devices are in use nearby [3,10].

	Kerosene (JET A1)	LH_2	LNH_3
Boiling point[9] (°C)	176	-253	-33
Pressure of storage (bar)	/	1	1
Temperature of storage (°C)	-250	-253	-33
Gravimetric index - $\boldsymbol{I_g}$	≈1	0.08 – 0.12	*0.8**
Gravimetric index 2 - $\boldsymbol{I_{g_2}}$	Very high	0.09-0.136	*4**
Volumetric density (kg/m3)	800 (average)	71	600 (25°C / 11 bar) 683 (-33°C / 1 bar)
References	[13,14]	[13,46]	[1,7,10] * values calculated below

Table 10 - Today's storage and tank properties for kerosene, LH_2 and LNH_3

According to Table 10, LNH_3 has a lower boiling point than LH_2 which eases its storage because the temperature required to keep it in liquid form is easier to maintain. For example, this liquid form can be stored at minimum 8.6-bar vapor pressure[10] at room temperature (often 18-bar is chosen [8]) or, at a temperature inferior or equal to boiling point and at 1 bar [8,10,11]. Probably a higher pressure will be required for the cooled storage to protect against air liquefaction in case of a leakage which would pose a safety hazard.

NH_3 is known to have a higher gravimetric index than LH_2 because the storage temperature and the latent heat of vaporization are higher. This implies that the insulation weight for such a tank will not be as significant compared to LH_2 [1,12,15,34]. More precisely, it may be possible to store ammonia within the aircraft wings which will significantly increase the tank gravimetric efficiency, marginally less than that of kerosene given the addition of insulation and greater storage volume [1]. For this reason, the value of I_g has been assumed at a very high value of 0.8*, and $\boldsymbol{I_{g_2}}$ calculated to be of 4* with the previous equation, because the volumetric density of LNH3 is about 20% lower than kerosene.

This property of gravimetric index for a tank has a central influence on the aircraft design. For instance, a LH_2 tank faces today this mass issue: to store 1kg of LH_2, 7-9kg of insulated tanks are necessary (using gravimetric index from Table 10). This means that hydrogen aircraft compared to kerosene aircraft, for the same mission requirements, have much heavier tanks. In addition, during all the flight duration, the weight of the tank is a penalty, which implies that more energy is required onboard for the mission, so less payload available for the same maximum take-off weight (MTOW) (supposing we design an aircraft constrained by this MTOW for airport purposes).

As an order of magnitude, to assess how efficient the storage of ammonia is compared to hydrogen, we can calculate how heavier an LH_2 tank is today compared to LNH_3 for the same energy of mission $Energy_{mission}$:

$$mass_{LH2\ tank\ design} = mass_{LH2\ tank} + mass_{LH2\ required\ for\ the\ mission}$$

$$= \frac{mass_{LH2}}{I_{g2_{LH2\ tank}}} + mass_{LH2} = \frac{Energy_{mission}}{e_{LH2}}\left(1 + \frac{1}{I_{g2_{LH2}}}\right).$$

With $\quad mass_{LH2\ required\ for\ the\ mission} = \frac{Energy_{mission}}{e_{LH2}}$

With the same method:

$$mass_{LNH3\ tank\ design} = \frac{Energy_{mission}}{e_{LNH3}}\left(1 + \frac{1}{I_{g2_{LNH3}}}\right)$$

Doing the ratio, we obtain:

$$\frac{mass_{LH2\ tank\ design}}{mass_{LNH3\ tank\ design}}\Big|_{Average,today} \approx 1.3 - 1.4$$

This result means that, today, the hydrogen tank design is heavier than with ammonia by about 30-40% and so, with ammonia, the payload available will be higher for a given mission and maximum take-off weight.
For these reasons, ammonia could seem to be a nice alternative to hydrogen as both transportation and storage are easier, and so a faster implementation could be envisaged.

[9] Temperature at which the phase transformation between liquid and vapor form occurs, at a standardized pressure of 1 atmosphere.
[10] The vapor pressure describes the pressure of vapor above the liquid phase. If the vapor pressure of a given chemical entities is too high, the change from liquid phase to gas phase can occur. This leads in our case to an interruption of the fuel supply in the fuel line, also called vapor lock. The boiling point is related to the vapor pressure [10].

Ammonia jet engine

The combustion of ammonia faces many difficulties. In fact, it has the downside of a limited ignition range and suffers from limited flame stability: it has the lowest laminar flame speed and extension stain rate compared to other fuels used [3, 10, 11, 44].

More precisely, this means that ammonia is very sensitive to the risk of flame extinction, so it requires low flow velocities in the combustion chamber to get sufficient residence time for the reaction to progress. This implies a diminished Reynolds number effects leading to reduced turbulence and hence less effective mixing which, in turn, decreases combustion efficiency [3]. To solve this issue, many mixtures of ammonia with other fuels like methane, hydrogen and kerosene are studied [3].

Hydrogen has the highest extinction strain rate of all fuels (included kerosene), whereas ammonia has the lowest, therefore a mixture of ammonia with hydrogen could potentially lead to a reasonable flame stability [10].
Studies showed that the flame stability can be improved by adjusting the ratio between hydrogen and ammonia during the operation of the engine. For example, a boost function during take-off could be implemented by a high concentration of hydrogen in the fuel, whereas during cruise, mainly ammonia could be burned [10].

Relatively few publications are available about ammonia jet engines for commercial aviation, nevertheless we know that a 100% ammoniac combustion cannot be possible for the previous flame stability reasons. This is why ammonia crackers (Figure 136 [16], Figure 137 [18]) are designed to produce the right amount of hydrogen and nitrogen to mix with ammonia to improve the combustion characteristics [16,17,18,21,34].

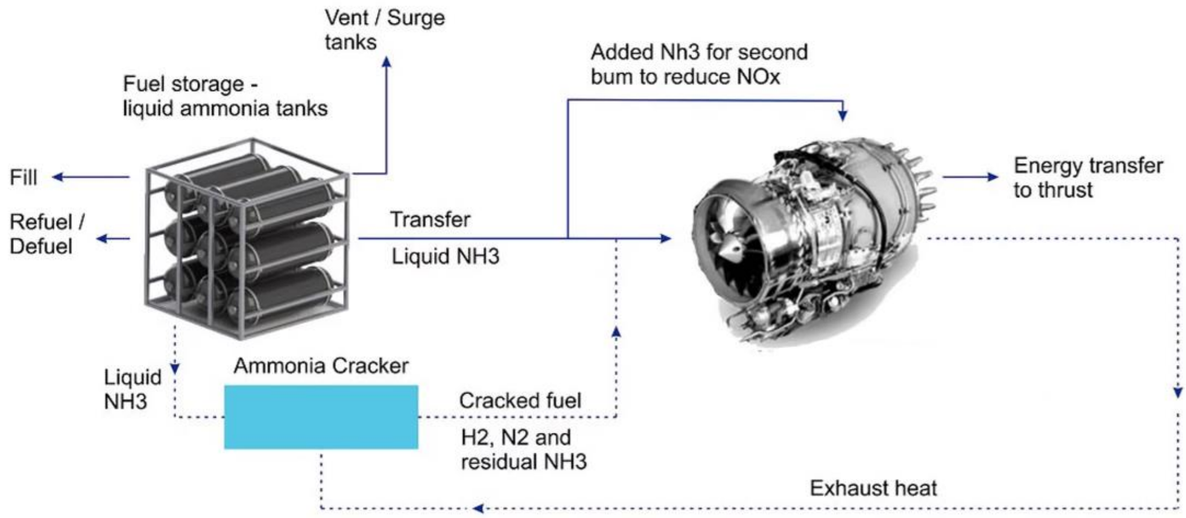

Figure 136 - Design considered to obtain the mixing of ammonia, hydrogen and nitrogen for combustion jet engine

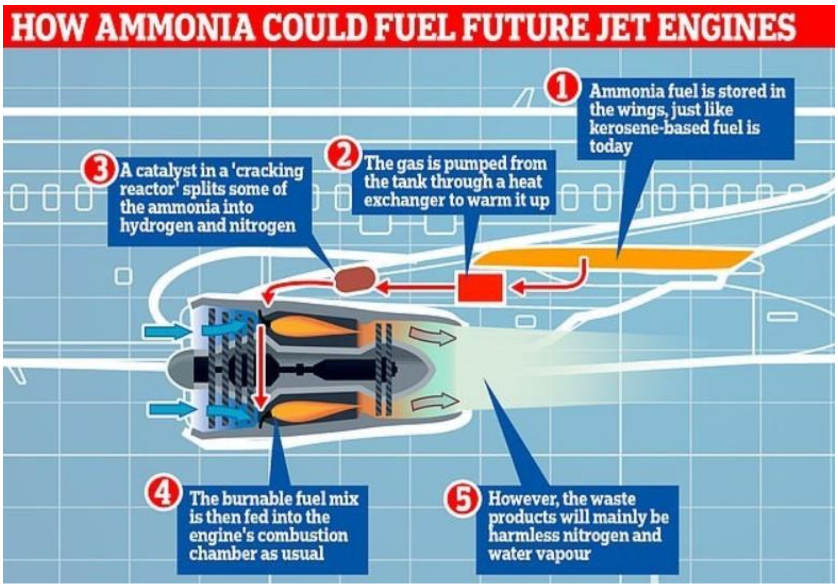

Figure 137 - Simplified view of ammonia combustion jet engine

Ammonia fuel cell

Please refer to the Hydrogen Fuel Cells and Balance of Plant sections in this document for more details on fuel cell composition and components.

Different types of ammonia fuel cells exist, with the main ones being [24]:

- Oxygen anion conducting electrolyte-based solid oxide fuel cells (SOFC-O)
- Proton conducting electrolyte-based solid oxide fuel cells (SOFC-H)
- Alkaline ammonia fuel cells (AAFCs) (including molten alkaline ammonia fuel cells)
- Alkaline membrane-based fuel cells (AMFCs)
- Microbial ammonia fuel cells

Also, when the chemical process requires to decompose the ammonia into hydrogen to make it react with oxygen in a redox reaction (as a classical hydrogen fuel cell), the fuel cell can be named either direct or indirect, depending on where this breakdown occurs [24]:

- Indirect when it is outside the fuel cell
- Direct when it is inside the fuel cell

For example, an ammonia Solid Oxide Fuel Cell (SOFC) can be designed as either direct or indirect. Direct ammonia eliminates therefore the necessity of on-board hydrogen storage and bypasses the decomposition step. This leads to savings in facility and operating costs, improving the overall efficiency.

For the purpose of this document, as the best ammonia fuel cells up to date is the ammonia SOFC [24,27], the focus will be on this type and the others will only be briefly introduced.

Solid oxide fuel cells (SOFC)

SOFCs can be sorted into two categories according to the type of electrolytes used:

- The oxygen anion conducting electrolyte-based SOFCs (SOFC-O), based on the transportation of oxygen anions across the electrolyte;
- The proton conducting electrolyte-based SOFCs (SOFC-H), based on the transportation of hydrogen proton across the electrolyte.

In both cases, the global chemical reaction is the same and is presented below for a complete reaction:

$$2NH_{3(g)} + O_2 \rightarrow N_{2(g)} + H_{2(g)} + 2H_2O_{(g)}$$

1. SOFC-O

The working principle behind SOFC-Os is based on the transportation of oxygen anions across the electrolyte. The initial step is the cracking of ammonia and the hydrogen produced is then electrochemically oxidized. Oxygen or air gas is introduced into the cathode chamber and reduced to oxygen anions at the cathode–electrolyte interface. These oxygen ions travel across the electrolyte where they react with hydrogen at the anode to produce water. This process is illustrated in Figure 138 [24].

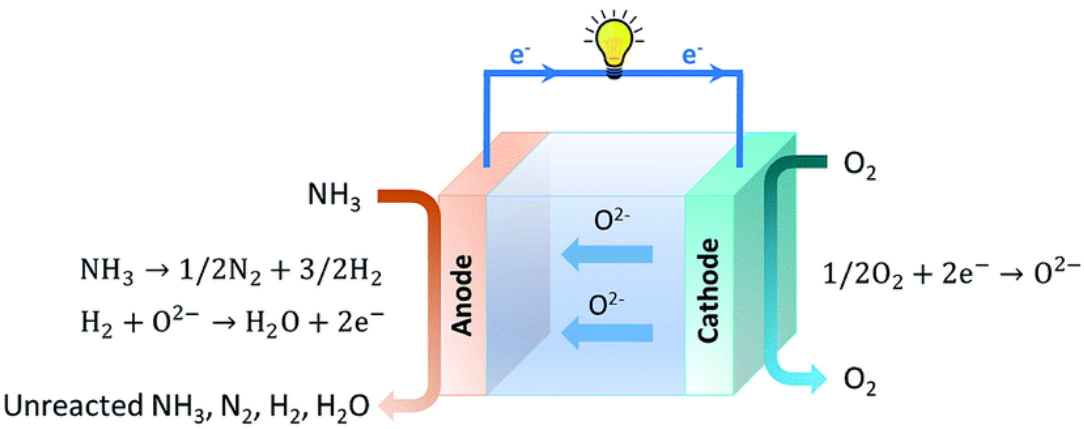

Figure 138 - Simplified view of SOFC-O

This technology needs to operate at high temperatures since there is a direct correlation between the operating temperature and performance:

- The temperature is directly related to the ionic conductivity of the electrolyte as stated in the Arrhenius equation;
- The increase of current density due to the greater conversion of ammonia into hydrogen.

For instance, at an operating temperature of 625°C, the conversion efficiency of ammonia to hydrogen is approximately 88 % and above 800°C it reaches nearly 100%. Moreover, at elevated temperatures, the polarization resistances for both the anode and cathode site decrease, thus improving the fuel cell performance [24].

Therefore, to compensate for the lower performance of ammonia SOFC caused by the diluting effect of nitrogen as another ammonia breakdown product, the operating temperature must be increased. It is desired to obtain as much hydrogen as possible leading to the behavior and the performance of the hydrogen SOFC presented in the Hydrogen Fuel Cells section.

2. *SOFC-H*

The working principle behind SOFC-Hs is similar to that of SOFC-Os. However, the charge carriers in the electrolyte are protons. Ammonia is fed into the cell at the anodic side where it decomposes into hydrogen and nitrogen. The latter acts as an inert species and the formed hydrogen is oxidized to protons which are then transported across the electrolyte where they react with oxygen to produce water. The process is presented in Figure 139 [24].

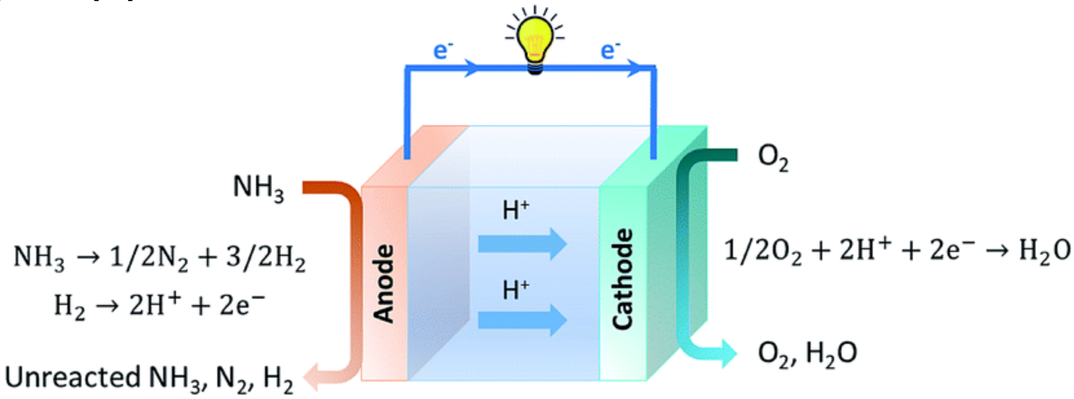

Figure 139 - Simplified view of SOFC-H

They are encouraging candidates since they maintain good ionic conductivity at lower temperatures compared to SOFC-Os. As efficient proton conductivity can be achieved at lower temperatures, the choice of materials that can be used is expanded since the catalyst sintering and thermal expansion mismatch of SOFC components are minimized. Water/steam is formed at the cathode side, and will not dilute the ammonia fuel at the anode. Moreover, efficiency increases with the surrounding pressure, more than 80% can be reached in laboratory [27]. For industrial concepts, efficiencies of 60%-65% have been reached [34].
However, lower operating temperatures in systems employing oxygen ion-conducting ceramic electrolytes would result in lower ionic conductivity, which subsequently would result in high ohmic losses [24].

Alkaline, molten alkaline and alkaline membrane-based ammonia fuel cells (AFC and AMFC)

Since the early stages of fuel cell progression, alkaline fuel cells have been studied and employed in practical systems such as space applications, vehicles and energy storage.

Alkaline membrane-based fuel cells work under similar principles as alkaline fuel cells as they also operate by transfer of OH- ions through the electrolyte and run at a low temperature range of approximately 50-120°C. Oxygen is introduced at the cathodic component where a reaction with water occurs to generate OH- ions. The OH- ions are then transported across an alkaline-based membrane to the anodic side, where they react with ammonia to produce nitrogen and water. The process is presented in Figure 140 [24].

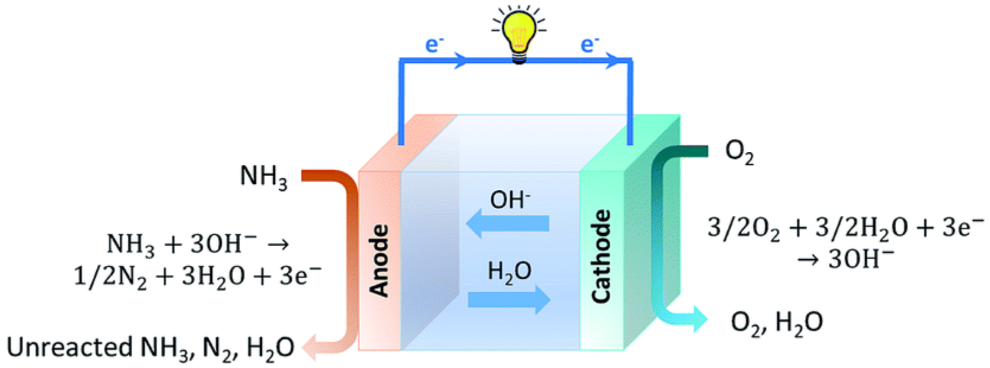

Figure 140 - Simplified view AMFC

Unlike SOFCs, where the ammonia is initially decomposed, AMFCs use ammonia as a fuel. This mitigates the need for high temperatures. AMFCs are still in development phase.

Microbial ammonia fuel cells (MFC)

Microbial fuel cells are an alternative technology which have gathered attention for their ability to treat wastewater whilst simultaneously generating electricity. MFCs use microorganisms and convert chemical energy from biodegradable material into electrical energy.
It is still in development phase.

Maturity

Several concepts of integrated ammonia cracker and fuel cell have been studied for cars (Figure 135) or even farm tractors [35] with encouraging results. Moreover, the shift toward ammonia engines for shipping has already started and more is expected in the next few years [8,25,32,33,36].
Nevertheless, few studies present jet engines burning ammonia and ammonia fuel cells for aviation. It is still in development phase with a low TRL that can be estimated at around 3-4.

Environmental Impacts

Toxicity and way of production

Ammonia is a toxic substance. Any leakage or unburnt residue can be toxic to humans and aquatic organisms over a certain threshold[11]. While in the atmosphere ammonia will highly react and be decomposed, if the leakage occurs inside an aircraft or on the ground, it becomes a safety issue.
Although out of the scope of this document, ammonia production is today mainly fossil-fuel based that raises major sustainability issues [3,5,6]. The most utilized ammonia production method is the Haber-Bosch process which converts hydrogen and nitrogen into ammonia with an efficiency of 42% to 48% [26]. It has the disadvantages of producing high amounts of greenhouse gases emissions and requiring high amounts of energy, mainly due to its high operating pressure (150-250 bar) and temperature (400-600°C) [31]. It is estimated that the world production of ammonia requires 1.8% to 3.0% of the global energy [3].

Such a process is highly stationary with low tolerance to variations, so a direct combination with a fluctuating energy supply (inherent to wind power and photovoltaics) is impossible. This means that the required hydrogen needs to be stored in excess to be available at a constant rate.
Globally, in 2020, more than 90% of ammonia came from fossil fuels through this method [5]. Mainly because the hydrogen itself is fossil-fuel based: in previous years, 72% of this hydrogen was produced by Steam Methane Reforming process which in turn generate 9-10 tons of carbon dioxide equivalent (CO_2eq) for each ton of hydrogen produced. The remaining 26% of hydrogen were obtained from coal [6].

[11] *Function of concentrations and exposure time, exposure guidance can be found in [3].*

The various ways to produce hydrogen required to synthesize ammonia are summarized in Figure 141 below [5]. The renewable routes are indicated in Figure 142 [5]. Currently, ammonia production from electrolyzed hydrogen accounts for approximately 0.5% of global ammonia production [3].

Main energy inputs	Technologies	Brief description	State of commercialization
Electrical	Water electrolysis	Direct current is applied in order to split water into hydrogen and oxygen.	Large
	CH_4 assisted-Solid Oxide Fuel Electrolysis Cell (SOFEC)/ Natural Gas Assisted Steam Electrolysis (NGASE)[a]	The entire process of an CH_4 assisted -SOFEC is based on substituting high value electricity with cheaper methane. In the CH_4 assisted-SOFEC, methane is added to the anode side of the electrolyzer, the decomposition potential (voltage) of water is decreased, and this results in a lower energy usage and higher conversion ratio of electricity for hydrogen production.	Medium/small
	Plasma arc decomposition	Purified natural gas (without H_2S, CO_2, H_2O, etc.) is passed throughout the plasma arc in order to produce hydrogen and carbon soot.	Large
Electrical and thermal	High Temperature Electrolysis (HTE)	Both electrical and thermal energy are utilized in order to initiate, water splitting for hydrogen production.	Large
	Hybrid thermochemical cycles	Both electrical and thermal energy are utilized in cyclical reactions.	Medium
Thermochemical	Coal Gasification	Conversion of coal through, thermochemical process into syngas.	Large
	Fossil fuel reforming	Fossil fuels are converted into hydrogen and carbon dioxide.	Large
	Thermolysis	Thermal decomposition of steam at temperatures higher than 2,226.85°C.	Large
	Thermochemical processes	-Cyclic reactions (net reaction: water splitting into hydrogen) -Thermo-catalytic conversion -Biomass conversion into hydrogen	Large
Photonic	Photo-electrochemical cells (PEC)[a]	A hybrid cell which generates voltage and current through absorption of light simultaneously.	Small
	Artificial photosynthesis	Mimicking photosynthesis process for hydrogen production.	Small
	Photo-catalysis	Direct water splitting via photo-catalyst.	Small
Photonic and Biochemical	Bio-photolysis[a]	Biological processes (microbes/bacteria, etc.) through which water dissociates into hydrogen and oxygen in the presence of light.	Small
Biochemical	Dark fermentation[a]	Biological processes are utilized for hydrogen production in the absence of light.	Small
	Photo-fermentation[a]	Fermentation process initiates through exposure to light.	Small

Figure 141 - Main ways to produce the hydrogen necessary for ammonia synthesis

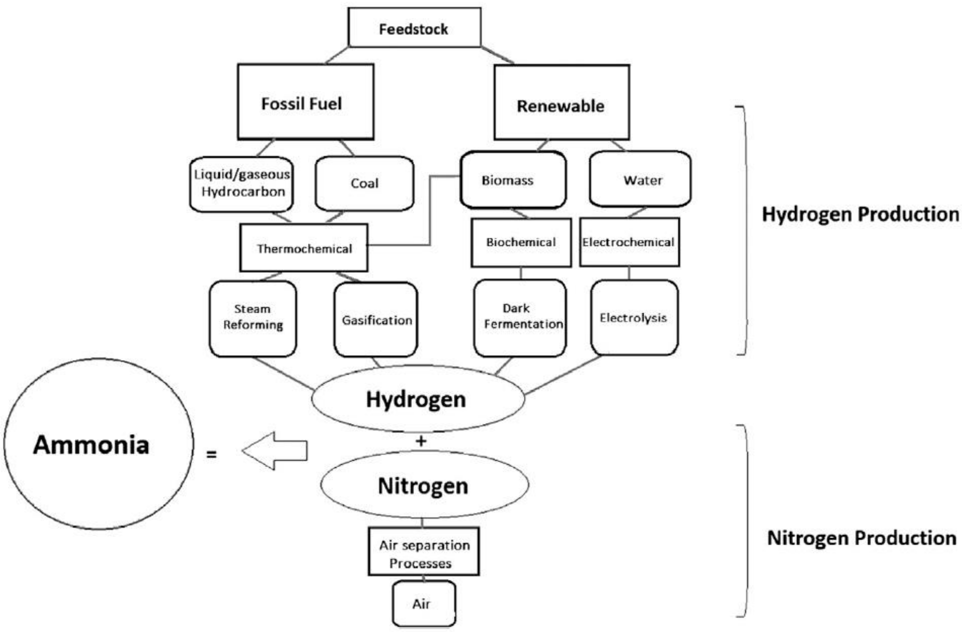

Figure 142 - Main ammonia synthesis routes: renewable or fossil fuel based

The main challenge for ammonia production is finding an economically viable, energy efficient, and more sustainable pathway to produce hydrogen[12]. Today, the ammonia production represents ~290Mt of CO_2, approximately 1% of global carbon dioxide emissions [2,3].

[12] *Compared to hydrogen production, the separation of air to get nitrogen may be assessed to release negligible greenhouse gases. In fact, the only emissions resulting are the air compounds itself that return to the air. Moreover, a small amount of natural gas or electricity is used for the process [22].*

Jet engine

Ammonia is a carbon-free and a sulfuric-free molecule which means that no CO_2/CO, SOx and soot will be emitted by the combustion whose complete reaction is: $2NH_3 + \frac{3}{2}O_2 \rightarrow N_2 + 3H_2O$
Nevertheless, there are other environmental impacts, non-CO_2 related, that must be considered. The main impacts are identified in Table 11.

Impacts	Comment	References
Contrails, water vapour	Approximately 12% higher water vapour emissions for pure ammonia compared to hydrogen combustion, less if blended with hydrogen.	[1]
NO_X	On the one hand, significantly more fuel NOx compared to hydrogen combustion as there is nitrogen in ammonia, in addition to the nitrogen from the air. On the other hand, ammonia shows the lowest adiabatic flame temperature of all the fuels today which means that it has, as the same time, the potential to reduce thermal NOx emissions. The final balance is nevertheless difficult to evaluate because of these different type of NOx[13].	[1,10,31]

Table 11 - Identified basic environmental impacts of ammonia for jet engine

Finally, concerning noise, no study describes the impact of ammonia when used in a gas turbine. However, for hydrogen gas turbines [20], and ammonia compression ignition [21], the noise is higher. Therefore, as ammonia will require to be blended with hydrogen to be efficiently burnt, engine exhaust noise will likely increase.

Fuel cell

For ammonia fuel cells, the main impacts are identified in Table 12:

Impacts	Comment	References
Contrails, water vapour	Expected to be similar to the pure hydrogen fuel cell.	See Hydrogen Fuel Cells section
NO_X	SOFC-O: possibility of NO_x because water is present at the anode along with ammonia. The quantity is difficult to evaluate but could be managed toward a very low level. SOFC-H: Free of NOx	[27] [24]

Table 12 - Identified basic environmental impacts of ammonia fuel cells

SUITABILITY

Constraints

Both technologies of jet engines and fuel cell using ammonia face constraints of storage, corrosivity and toxicity.
According to [1], it may be possible to store ammonia within the aircraft wings, but it will require additional insulation and cooling systems to maintain it below its boiling point conditions. This additional weight is expected to be reasonable as the storage conditions are already known for decades.
When selecting a new fuel for power, impact on materials must be considered. In the case of ammonia, the benefits of greater versatility than hydrogen gets slightly offset by the fact that it is incompatible with various industrial materials. For example, ammonia is corrosive to copper, brass and zinc alloys, forming a greenish/blue color corrosion. Moreover, it should not be mixed with bromine, chlorine, iodine and hypochlorites as ammonia is an alkaline-reducing agent and reacts with acids, halogens, and oxidizing agents [3]. Table 13 [23] lists some compatibility results between ammonia and various industrial materials.

[13] *See note 5*

Copyright © Cole-Parmer. A: excellent; B: good- minor effect, slight corrosion or discoloration; C: fair- moderate effect, not recommended for continuous use, with softening or loss of strength, swelling may occur; D: severe- not recommended; N/A: information not available. Courtesy of © Cole-Parmer.

ABS plastic	D	CPVC	A	Polycarbonate	D
Acetal (Delrin ®)	D	EPDM	A	PEEK	A
Aluminium	A	Epoxy	A	Polypropylene	A
Brass	D	Fluorocarbon (FKM)	D	Polyurethane	D
Bronze	D	Hastelloy-C ®	B	PPS (Ryton ®)	A
Buna N (Nitrile)	B	Hypalon ®	D	PTFE	A
Carbon graphite	A	Hytrel ®	D	PVC	A
Carbon Steel	B	Kalrez	A	PVDF (Kynar ®)	A
Carpenter 20	A	Kel-F ®	A	Silicone	C
Cast iron	A	LDPE	B	Stainless Steel 304	A
Ceramic Al2O3	N/A	Natural Rubber	D	Stainless Steel 316	A
Ceramic magnet	N/A	Neoprene	A	Titanium	C
ChemRaz (FFKM)	B	NORYL ®	B	Tygon ®	A
Copper	D	Nylon	A	Viton ®	D

Table 13 - Compatibility results between ammonia and various industrial materials

Therefore, all components made of brass or copper must be removed from the system to avoid operability issues. Joint compounds will be affected too [25]. To ensure a safe fuel system all these compatibilities will have to be particularly analyzed.

Concerning the toxicity, as shortly described above, any leakage or unburnt ammonia can be fatal over a certain threshold. Ammonia detectors and automatic systems to insulate the cabin will be required. Moreover, maintenance and ground handling will need special consideration.

Jet engine

Combustion stability must be assessed for jet engine. To get a combustion stability, a mixture between ammonia and another fuel is required. For instance, hydrogen is studied as the full combustion will not release carbon and sulfuric molecules.

Nevertheless, this mixing implies the presence of hydrogen and ammonia inside the aircraft. We do consider, for this supply, either the use of a cracker inside the aircraft to convert a part of the ammonia from the tanks into hydrogen and nitrogen, or the use of a cryogenic hydrogen tank used as necessary to keep a constant rate for the combustion.

In any case, this will add a significant number of systems and weight that may be prejudicial to the aircraft performance and payload.

Fuel cell

Contrary to the jet engine, a fuel cell does not face the combustion stability issue, but the power and cooling challenges evoked in the Hydrogen Fuel Cell section.

Concerning the power, it is assumed here that a direct ammonia SOFC has the same performance than a hydrogen SOFC. In fact, for high operating temperatures, the breakdown of ammonia into hydrogen is nearly total. Therefore, performances would be as follows:

Specific power	Operating temperature	Power range	Efficiency	References
0.1-0.2KW/kg	500-1000°C	1kW-100MW	45-65%	37, Hydrogen Fuel Cells and balance of Plant sheet

Table 14 - Ammonia direct SOFC main performances assumed to be equal to hydrogen SOFC performances

As for any fuel cell, for a given propulsive requirement, the cells and the balance of plant associated will bring weight penalties to the aircraft performance. Further studies are required to assess such weight penalties.

Finally, the thermal management will be here more critical than for a hydrogen SOFC since the cracking of ammonia needs high temperature to have a better kinetics and so to reach high efficiency. Therefore, inside the aircraft, this will require special cooling systems to maintain a certain maximum temperature[14] without penalizing the kinetics. This may bring once again additional weight and maintenance complexity.

[14] The redox reaction in the fuel cell is exothermic, so releases heat that could be used for the cracking as the reaction is endothermic. Still, a temperature management system may be required.

Certification Aspects

Ammonia as a fuel faces several environmental and technical issues. All of these must be assessed and solved to get the whole concept certified.

Particularly, the toxicity and corrosion issue previously mentioned are important to consider:

- All components made of brass or copper must be removed from the system to avoid operability issues and joint compounds will be affected too.
- Any leakage or unburnt ammonia can be fatal over a certain threshold.

To answer these points, special maintenance consideration and new leakage management systems may have to be certified. Risks must also be assessed in case of crash or ground collision.

Aircraft Segments Concerned

For fuel cells, according to the constraints of power and weight, this technology is more adapted for commuters and possibly regional aircraft. There are also constraints[15] on electrical motors which, today, do not have enough power to equip single-aisles and widebodies.

Potentially, jet engines using ammonia blended with hydrogen could be applicable all aircraft categories.

APPLICABILITY

Market Acceptance and Barriers

Ammonia production and distribution infrastructure have already been existing for decades. It is the world's second most widely used chemical (after the sulfuric acid) with an annual global production of approximately 180 million tons [8], universally used in fertilizers, pharmaceuticals, beauty products, water purification and much more. This means that it is already a commercially attractive product. Even if ammonia has many constraints compared to kerosene, as we already know how to manage it, the airport infrastructure shift may be easier and with a more reasonable cost.

Nevertheless, most of its production is already used for fertilizer production (80% [8]) therefore global food, and is highly fossil-fuel based. A first shift, likely expensive, toward sustainable production, will be required in priority. Then, its price will determine profitability for airlines.

For aircraft manufacturers, ammonia as a fuel is a new concept and many research and development programs on ammonia storage and cracking unit will be required. Even if the storage conditions are more achievable today than for hydrogen, many other constraints like corrosion and toxicity will create major hurdles.

Costs

As it is a new technology still in development phase, no cost estimate could be found.

Implications on Aircraft Designs

In a nutshell, the actual wing tank design could probably be maintained, keeping in mind the insulation, cooling and corrosivity requirements described above. Nevertheless, the additional systems to crack ammonia into hydrogen and to transport these fuels to the engines will bring complexity and weight for jet engine concepts. Concerning ammonia fuel cells, thermal management will require special designs and integration into the airframe.

[15] To have a high-power electrical motor, a high number of cobber spirals, a very high voltage, and large wires diameter are required. These main criteria lead to very heavy engines.

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SOLAR TECHNOLOGIES

DESCRIPTION

In 2016, the aircraft Solar Impulse 2 (SI2), completed a trip of 43 041 km in 23 days, only using solar energy to power its flight thanks to embedded Photovoltaic (PV) cells [01]. This event raised great interest in solar aircraft as a lever to decarbonize air transport.

Figure 143 - Solar Impulse 2
https://solarimpulse.com/accueil#

According to study [02], the maximum solar irradiance is around 1000W/m². The typical surface available for solar PV cells on current commercial aircraft is around 100 to 500m². This results in a maximum available solar power of 100kW to 500kW in the case of an ideal 100% energetic efficiency. Current commercial aircraft need around 1MW to 10MW of power at take-off which is ten-fold higher than what solar power can supply. Moreover, current state-of-the-art technology for PV cells, batteries and aircraft mechanical transfer elements provides some 11% energetic efficiency (Figure 144).

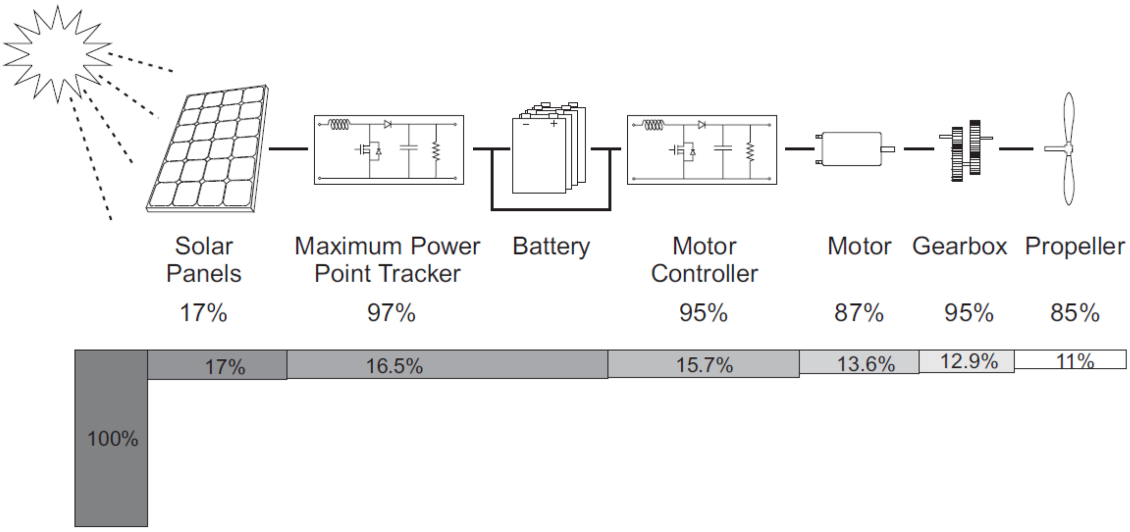

Figure 144 - Energy train on the Sky-Sailor solar airplane with the cumulated efficiencies, [02]

Several groups are actively working on the efficiency of solar air transport. With the above-mentioned challenges, there are no robust elements to foresee any commercial air transport based on pure solar energy by 2050, except in case of unexpected progresses on PV cells and batteries. This technology is not further detailed here.

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DESCRIPTION

In the context of decarbonizing aviation, many new technologies focus on the replacement of chemical fuels by electricity. And today, nuclear powerplants represent the vast majority of decarbonized sources of electricity. For instance, in 2015, nuclear powerplants were generating almost 80% of the electric power in France (Figure 145).

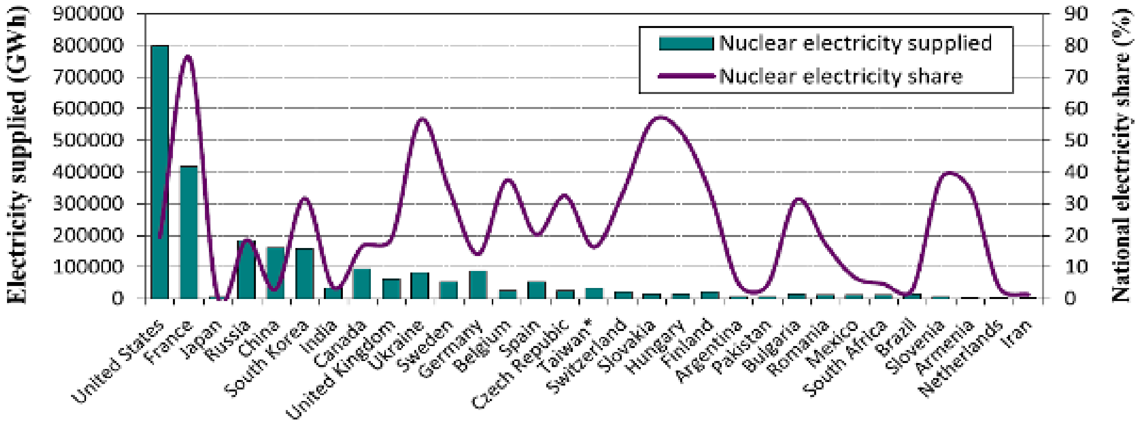


Figure 145 - Production of nuclear energy and the corresponding share of the total national power production in 2015 [01]

Consequently, despite the multiple persisting obstacles, nuclear power remains a major short-term technical option in the decarbonization process [01].

Given this context, the validity of nuclear-powered aircraft should be looked at.

Concept

Nuclear energy is the result of the structural change of an atom nucleus. This change can be either a fission which results in a split of the initial nucleus into other atoms, or a fusion of several atoms nuclei into a new atom nucleus.

Fission reactor

Nowadays, several military submarines and aircraft carriers are powered with embedded nuclear fission reactors. This source of energy has two main benefits. First, its autonomy is drastically long from several days up to years. Second, it can provide very high levels of power, from 1MW to 100MW [02]. In addition, nuclear energy provides the most efficient volumetric and gravimetric density over all other sources of energy (Figure 146).

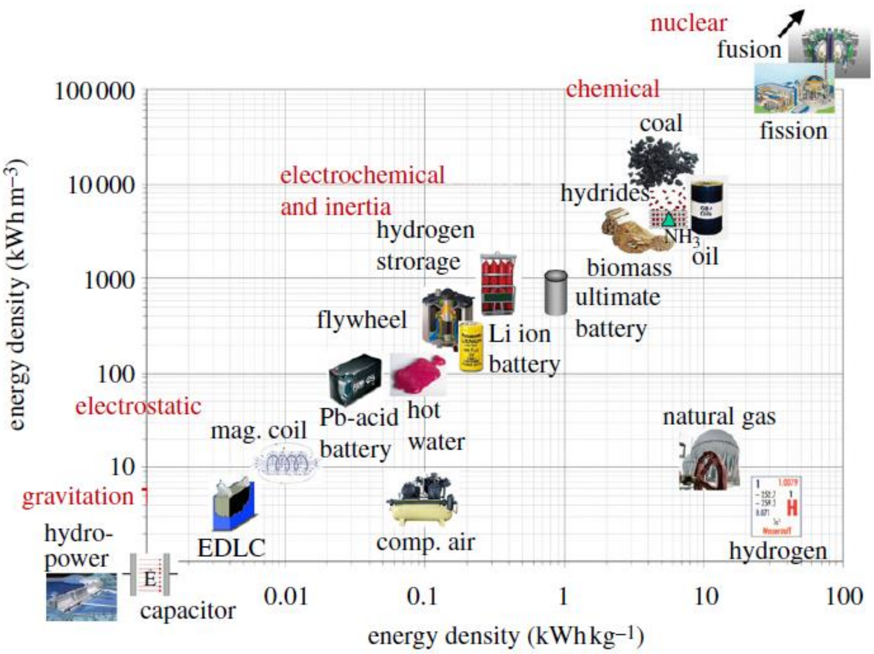


Figure 146 - Volumetric vs. gravimetric energy density of the most important energy carriers [04]

NUCLEAR TECHNOLOGIES

Nuclear energy is based on the chain reaction of uranium atom fission. Among the various uranium isotopes, only the U-235 is fissile by a neutron. The results of this reaction are smaller atom nucleus – that are often still radioactive –, and several neutrons that can collide with other U-235 atoms in a chain reaction (Figure 147).

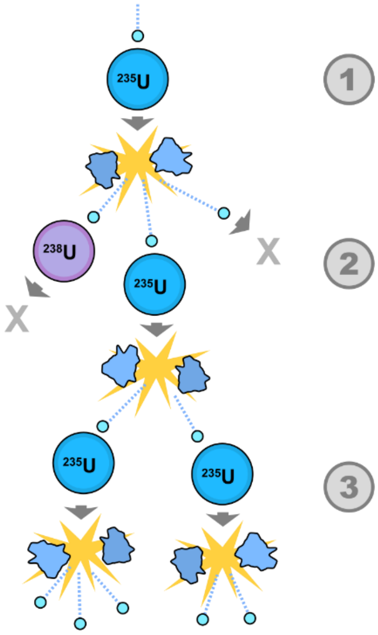


Figure 147 - Schematic diagram of a fission chain reaction. Based roughly on the illustration in the Smyth Report (1945). Caption A uranium-235 atom absorbs a neutron, and fissions into two new atoms (fission fragments), releasing three new neutrons and some binding energy. Both of those neutrons collide with uranium-235 atoms, each of which fission and release between one and three neutrons, and so on. Source: Wikimedia Commons

Chain reaction is only possible with a certain minimum density of U-235 inside the U-238. The natural uranium source includes less than 0.72% of U-235 which does not allow to keep a chain reaction. So, it is necessary to enrich the natural uranium with devices such as centrifugation. This allows to obtain reactor-grade uranium containing more than 20% of U-235. This density of U-235 can propagate the nuclear chain reaction. It can be initiated by a natural radioactive element such as Americium that can provide the first neutrons. The chain reaction can be stopped with bars of lead that absorb the neutrons. For nuclear weapons, a faster chain reaction can be obtained with weapon-grade uranium containing more than 85% of U-235 (Figure 148).

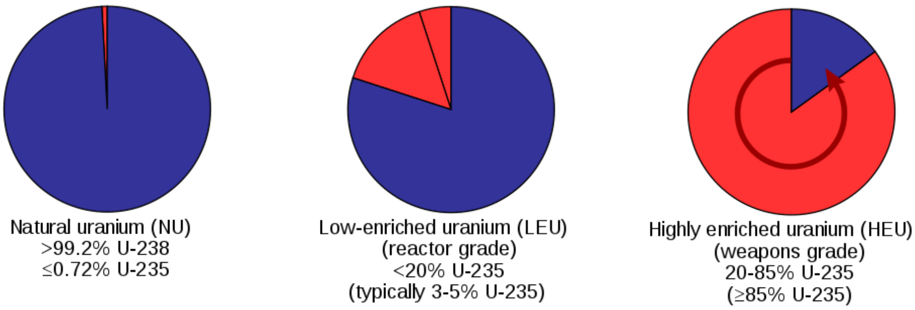


Figure 148 - Proportions of uranium-238 (blue) and uranium-235 (red) found naturally versus enriched grades. Source: Wikimedia Commons

The chain reaction produces directly heat, gamma rays, neutron and radioactive waste. Thus, the nuclear reactor includes also shields to protect the environment from gamma rays, neutrons and radioactive waste diffusion.

NUCLEAR TECHNOLOGIES

Nuclear-powered airplane programs started very early in 1946. A flight testbed named NB-36H flew to demonstrate the ability to carry a nuclear fission reactor, but NB-36H never used the nuclear reactor to produce thrust (Figure 149). These programs ended in the 1960s due to the lack of results. [03]

Figure 149 - NB-36H testbed. Note the "radiation" symbol on the tail of the aircraft [03]

The principle of a fission reactor consists of a core containing nuclear fuel, uranium. The reaction of fission produces heat. This heat is absorbed by a coolant. Depending on the option, either the coolant can exchange heat in the aircraft jet engine to produce thrust (Figure 150), or, the coolant can be refreshed in a turbine to produce the electricity used in the electric motors [02].

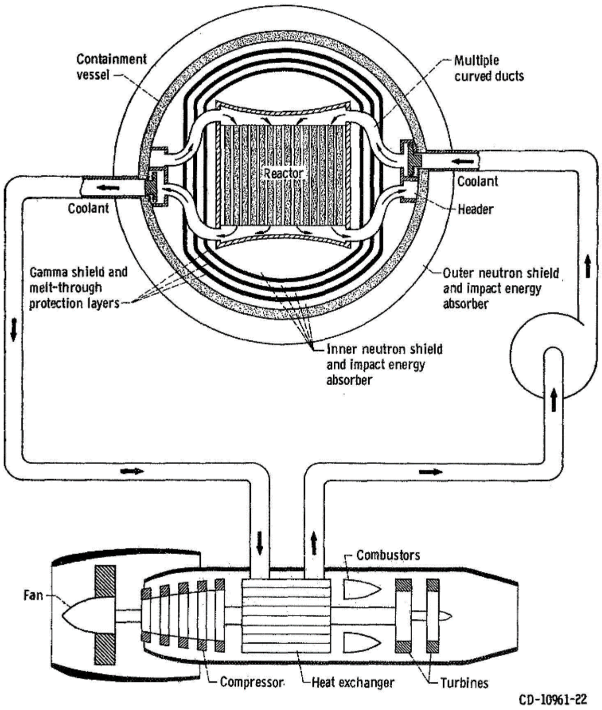


Figure 150 - Schematic drawing of a nuclear aircraft powerplant [02]

The main inconvenience of the current nuclear reactor is its huge mass. The typical weight of a nuclear fission reactor is around several hundred up to thousand tons which is almost twice the maximum weight of the heaviest aircraft. This is mainly due to the shield protecting the environment from the nuclear reaction during flight and in case of crash (Figure 151).

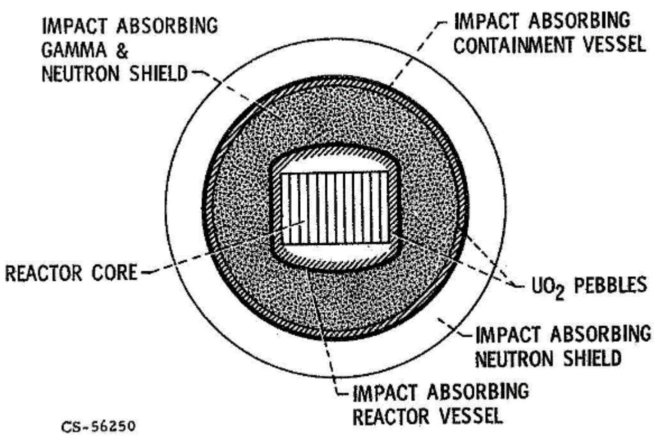


Figure 151 - Mobile reactor containment system concept [02]

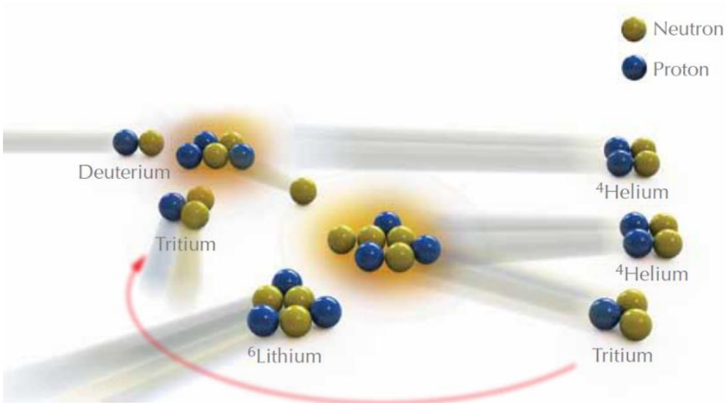
According to [02], the weight of competitive nuclear aircraft is assessed to be 10,000 tons. This aircraft would be able to transport around 5,000 to 10,000 passengers everywhere on the planet without refueling for months. However, the 1968 Nuclear Non-Proliferation Treaty forbids this kind of civil use. The military use of this juggernaut is not even proven to have any added value compared to nuclear submarines that are more stealth.

For the moment no valid use for nuclear aircraft is foreseen except if there is any unexpected scientific discovery on nuclear power which would allow huge weight reductions.

Fusion reactor

Fusion nuclear reaction is the energy source for stars. Unfortunately, the conditions of those reactions are extreme. To achieve the hydrogen reaction inside the sun or in a H bomb, more than 10 million degrees Kelvin are necessary. Those conditions can be permanent only at the center of stars. Until now, only very brief artificial reactions of fusion are achieved in H bombs.

The ITER project aims at building a fusion reactor based on the reaction between Deuterium and Tritium. This reaction should use only Deuterium and Lithium as primary resources (Figure 152) [04].



Fusion of light nuclei is the energy source that powers the sun. A fusion power plant utilizes the fusion reaction between tritium and deuterium. The process yields a helium nucleus and a neutron, whose energy is harvested for electricity production. Deuterium is widely available, but tritium exists only in tiny quantities. The fusion reactor has to produce it via a reaction between the neutron and lithium. Lithium, again, is abundant in the Earth's crust and in sea water. The global deuterium and lithium resources can satisfy the world's energy demand for millions of years. [04]

Figure 152 - Fusion: a virtually unlimited energy source

The resources of Deuterium and Lithium are quite easy to find on Earth, and it is largely enough to satisfy the world demand of energy. This reaction requires more than ten times the conditions inside the Sun. So, the ITER project decided to use a huge magnetic field in Tokamak to confine the fusion reaction in a Toric shape. Unfortunately, for the moment, this device consumes more energy than it produces. According to [04], ITER expects to produce electricity from nuclear fusion by 2040-50. The device should be the size of a multiple-floor building. From this assumption, we can consider that nuclear fusion will not be available for aircraft before next century at best.

Some other investigations are ongoing in the fusion reactor field such as the Princeton Field-Reversed Configuration (PFRC) nuclear fusion reactor concept [05].

However, unless there is any unexpected scientific discovery, none of those studies is foreseen to provide adequate power sources for aircraft before 2050. The subject of nuclear aircraft is therefore not further developed in this document.

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