# ULTRA LOW EMISSION TECHNOLOGY INNOVATIONS FOR MID-CENTURY AIRCRAFT TURBINE ENGINES

ULTIMATE
core engine technologies


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# The ULTIMATE project - talk in short

- Irreversibility
  - Categorizing losses: ”the big three”
- Project objectives and approach
- ULTIMATE technologies
- Impact

# The ULTIMATE project consortium

ULTIMATE

ARISTOTLE UNIVERSITY OF THESSALONIKI

AVANCEZ 1829

Cranfield UNIVERSITY

isae
Institut Supérieur de l'Aéronautique et de l'Espace
SUPAERO

Bauhaus Luftfahrt
Neue Wege.

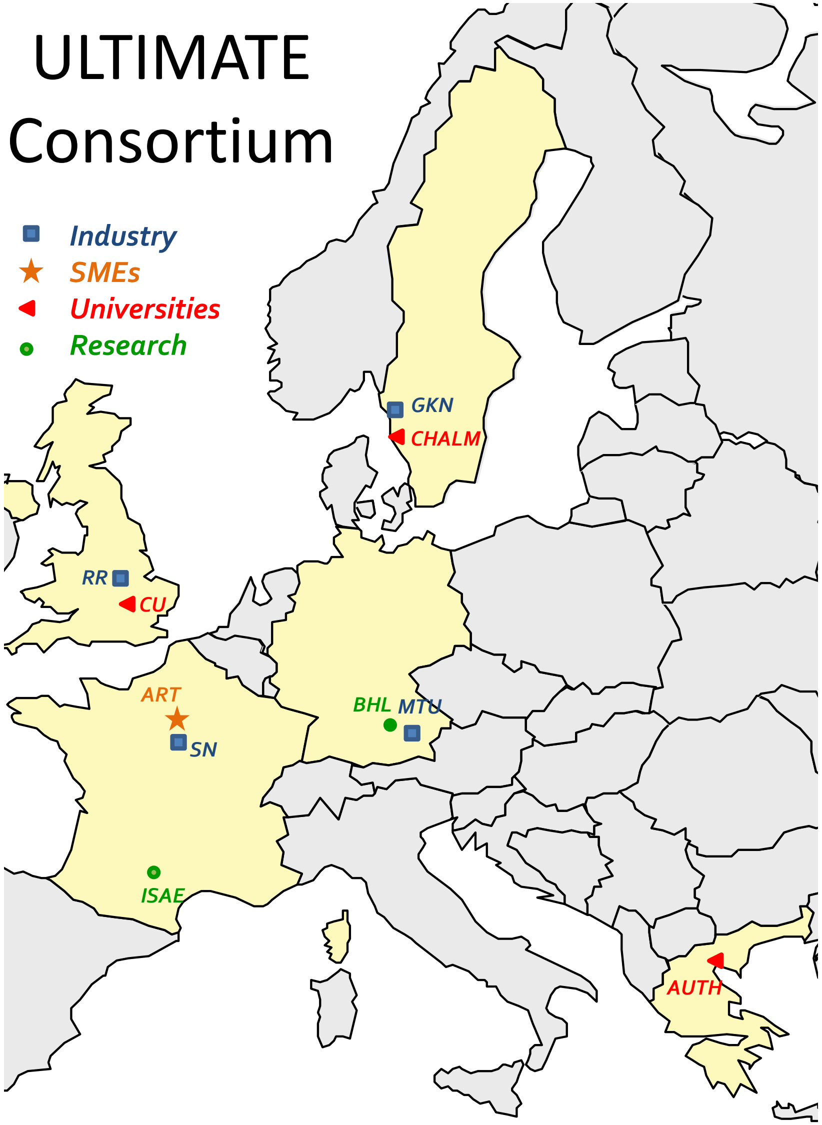
ARTTIC
INTERNATIONAL MANAGEMENT SERVICES

GKN AEROSPACE

MTU Aero Engines

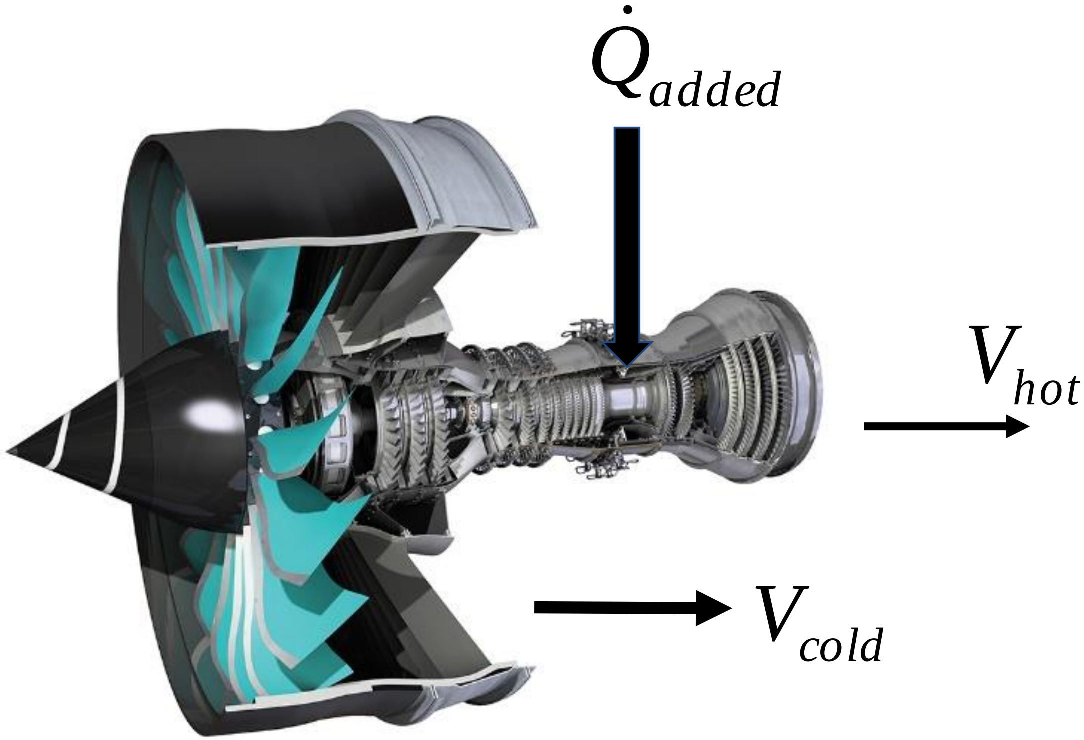
SAFRAN
Snecma

ROLLS ROYCE
Rolls-Royce



# The jet engine

$$\eta_o = \frac{\text{Propulsive power}}{\dot{Q}_{added}}$$

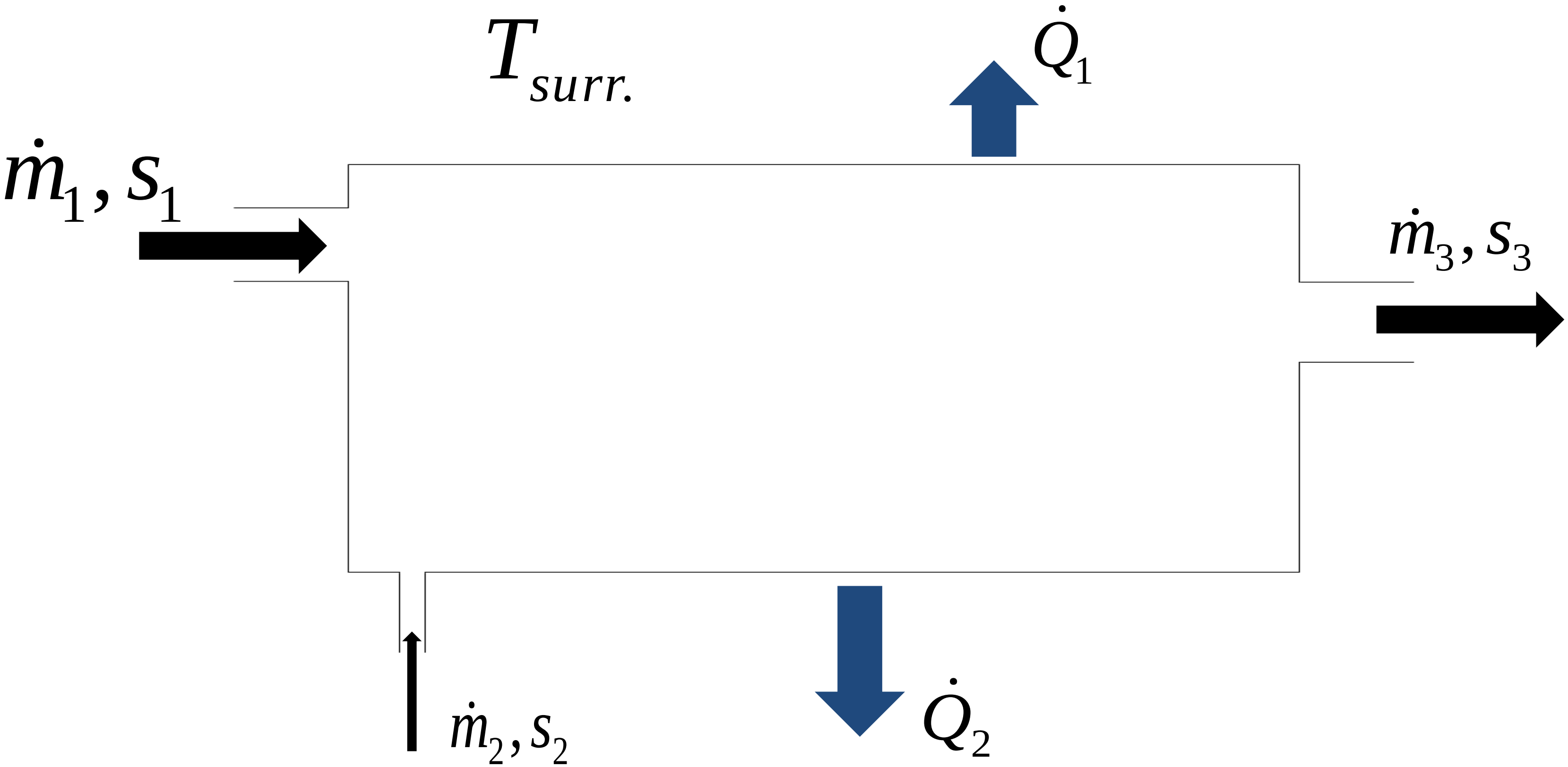



$$\dot{Q} - \dot{W} = \dot{m}_{exit} h_{T,exit} - \dot{m}_{inlet} h_{T,inlet}$$

$$h_T = h + \frac{V^2}{2} + gz$$

First law (open system, stationary, single inflow single outflow)

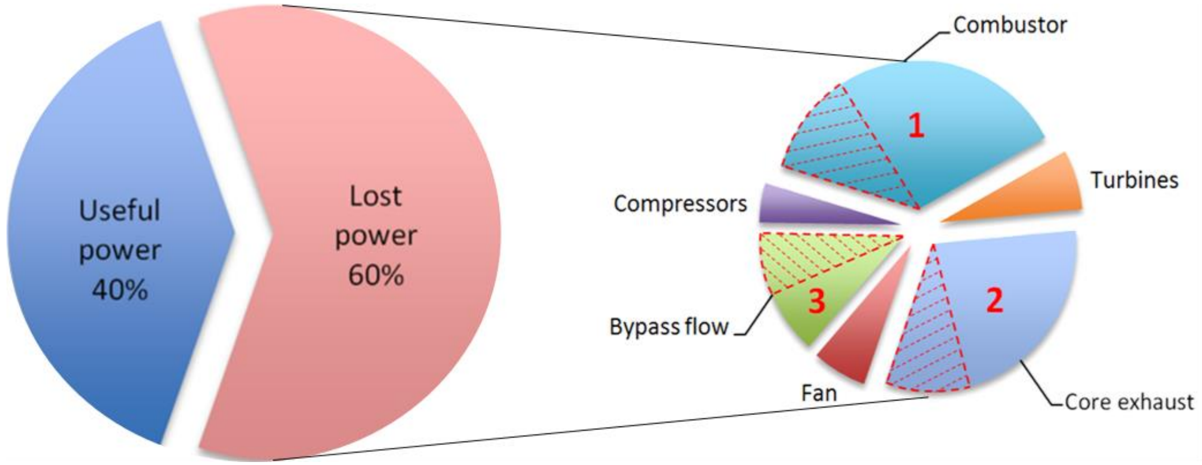
# Second law




$$\text{Entropy generation} = \dot{\Pi} = \sum_{OUT} s_e \dot{m}_e - \sum_{IN} s_i \dot{m}_i - \sum_r \frac{Q_r}{T_r} \geq 0$$

$$\text{Lost power} = T_{surr.} \dot{\Pi} = L$$

# Losses in a 2015 state-of-the-art turbofan




**One needs to attack the "the Big Three"**

- Combustor irreversibilities (1)
- Core exhaust heat losses (2)
- Excess of kinetic energy in the bypass flow (3)

*Exergy, denoted ε, of a steady stream of matter is equal to the* ***maximum amount of work*** *obtainable when the stream is brought from its initial state to a state of* ***thermal and mechanical*** *equilibrium with its environment.*

The red cross-hatched areas may be captured – HOW ???

Grönstedt, T., Irannezhad, M., Lei, X., Thulin, O., Lundbladh, A., "First and second law analysis of future aircraft engines". *Journal of Engineering for Gas Turbines and Power"*, *136* (3), 2014

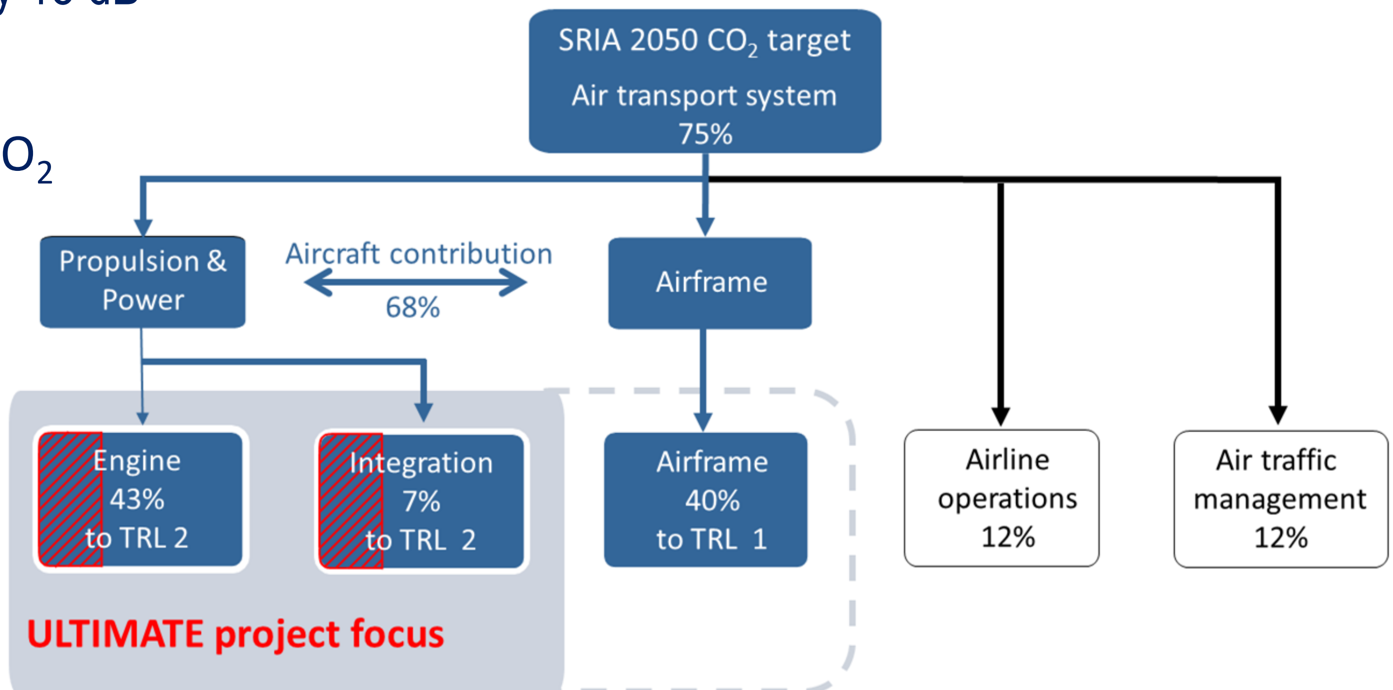
## Major challenge (all relative to the year 2000)

- 75% reduction in $CO_2$
- 90% reduction in $NO_x$ during cruise
- Reduction of noise by 15 dB

## ULTIMATE Alone

- 18% reduction in $CO_2$
- 20% reduction in $NO_x$ during cruise
- 3 dB reduction in Noise

***Develop propulsion "systems concepts" with the potential to fulfil the SRIA 2050 key challenges***




*Initial ULTIMATE SRIA 2050 $CO_2$ target breakdown*

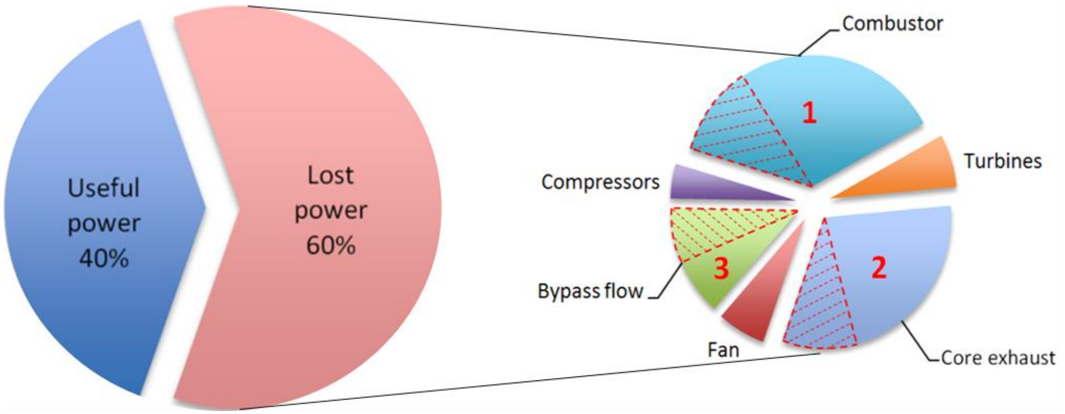
# Propulsion systems with a SRIA 2050 target potential

| 1: Meeting societal and market needs | 2: Maintaining and extending industrial leadership | 3: Protecting the environment and the energy supply | 4: Ensuring safety and security | 5: Prioritising research, testing capabilities and education |
|---|---|---|---|---|
| • European citizens …informed mobility choices.<br>• 90% of travellers within Europe … door-to-door within 4 hours.<br>• A coherent ground infrastructure is developed.<br>• Flights land within 1 minute of the planned arrival time.<br>• An air traffic management system is in place… at least 25 million flights… | • The whole European aviation industry is strongly competitive, delivers the best products and services worldwide and has a share of more than 40% of its global market.<br>• Europe has retained leading edge design, manufacturing and system integration capability and jobs … flagship projects … cover the whole innovation process …<br>• Streamlined systems of engineering, design, manufacturing, certification… …50% reduction in the cost of certification...new…standards… | • $CO_2$ emissions per passenger kilometer have been reduced by 75%, NOx .. by 90% and perceived noise by 65%, all relative to the year 2000.<br>• Aircraft movements are emission-free when taxiing.<br>• Air vehicles are …. to be recyclable.<br>• Europe … centre of excellence... sustainable alternative fuels….<br>• Europe is at the forefront of atmospheric research … | • ..European Air Transport System has less than one accident per ten million…<br>• Weather and other environmental hazards … evaluated…mitigated…<br>• Air Transport … manned and unmanned … safely operate in the same airspace.<br>• …boarding and security measures…. through security controls without intrusion.<br>• Air vehicles are resilient by design to current and predicted …security threat…<br>• The Air Transport System has a fully secured … data network… | • European research and innovation strategies are jointly defined by all Stakeholders… involves the complete innovation chain…<br>• A network of multi-disciplinary technology clusters…collaboration between industry, universities and research institutes.<br>• Strategic European aerospace test, simulation and development facilities are identified, maintained and further developed… |
| **ULTIMATE measurable objectives** | | | | |
| • Short & long range missions<br>• Flexible missions, 30000-45000 ft alt.<br>• Gate-to-gate better than state of the art | • Propulsion system, technology and top-level module requirements to TRL 2<br>• Advanced whole engine analysis, Ph.D's & senior researchers with deep knowledge of multi-disciplinary<br>• Exploiting working process | • $CO_2$: 18% reduction<br>• $NO_x$: 20% reduction<br>• 3 dB reduction from ULTIMATE propulsion technologies alone<br>• Breakdown of goals – airframe/propulsion system | • Show that propulsion systems are judged tolerant of inclement weather (ice, hail, rain, inlet temperature)<br>• have sufficient system redundancy | • Develop the European academic network of Centres of Excellence in conceptual engine design<br>• Multi-objective, multidisciplinary analysis for radical propulsion systems |
| **Explore variability by new concepts…** | **Industry collaboration, tools and roadmaps…** | **Optimizing powerplants…** | **Assess tolerance to inclement weather and safety redundancy…** | **Develop methods and ways to collaborate…** |

# Concept and approach

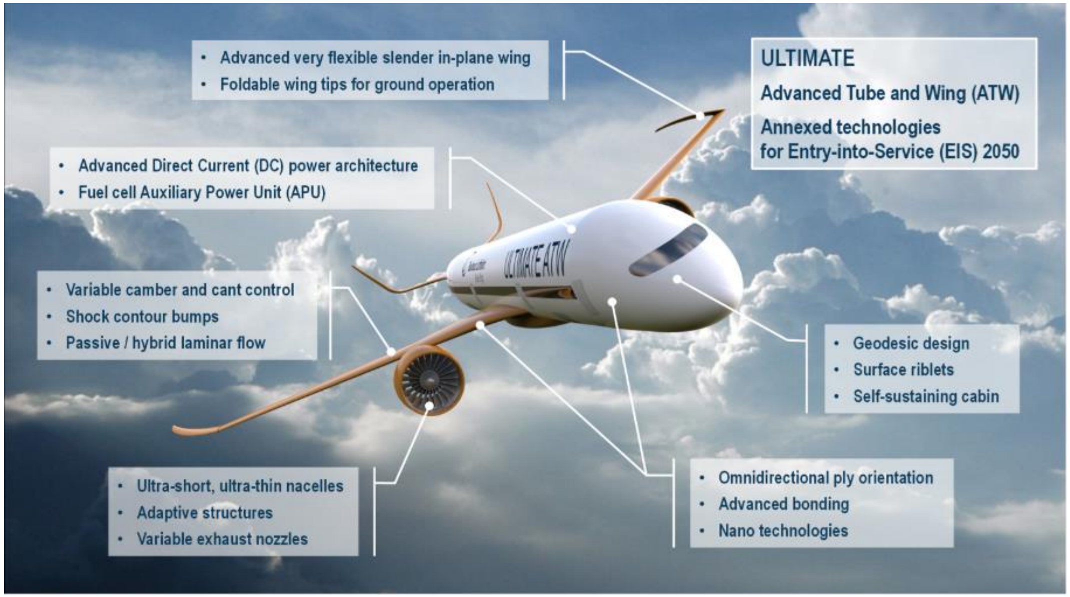
## Exploit synergies between radical engine configurations

- Constant volume type combustion.
- Bottoming cycles
- Intercooling & recuperation
- Advanced low pressure system technology



# Concept and approach

## … together with an advanced tube and wing configuration




Year 2050 Advanced Tube and Wing (ATW) aircraft

- High aspect ratio wings
- Foldable wing tips
- Laminar flow
- Advanced materials

Recent large improvements shown for configurations with less radical powerplants:

- *Boeing estimated a 54% reduction with a truss-braced high AR wing concept "SUGAR High"*
- *MIT's "double bubble", close to 71% reduction (use of boundary layer ingestion)*

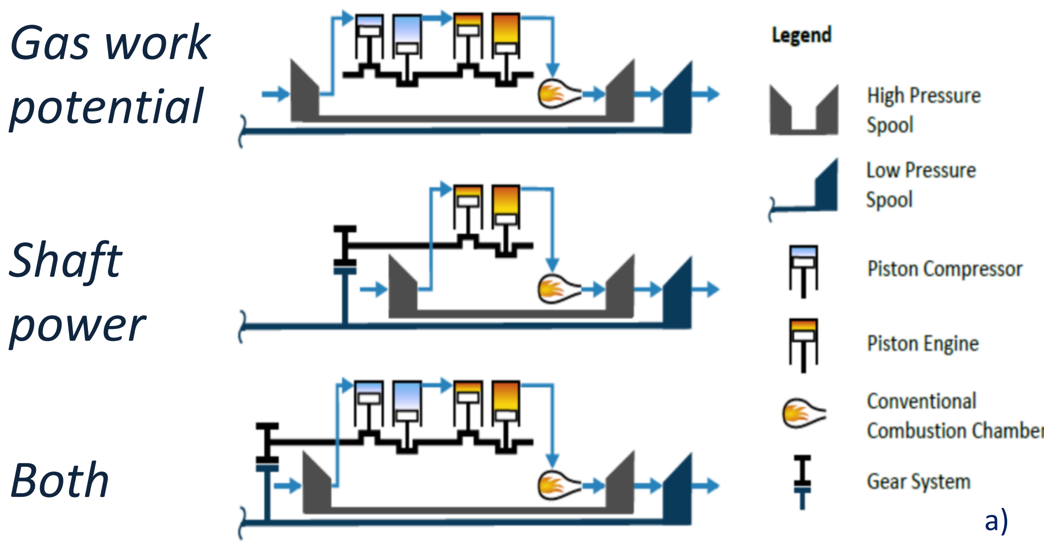
Development of radical concepts applicable in a range of scenarios:

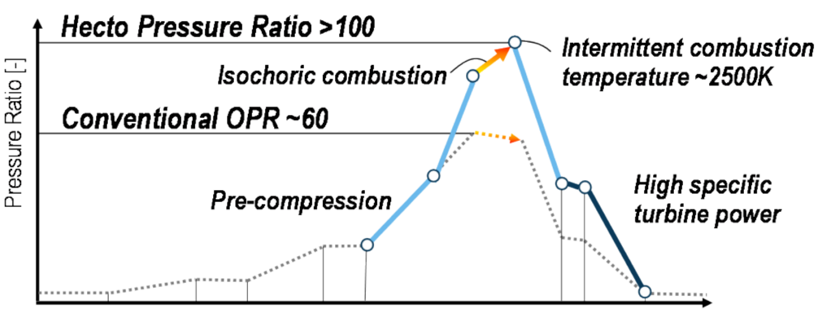
- *Blended wing body*
- *Horizontal double bubble*
- *Prandtl joined wing*
- *Turbo-electric and hybrid propulsion*
- *Hydrogen, methane and biofuel propelled concepts*

# Loss source 1 - combustor irreversibility

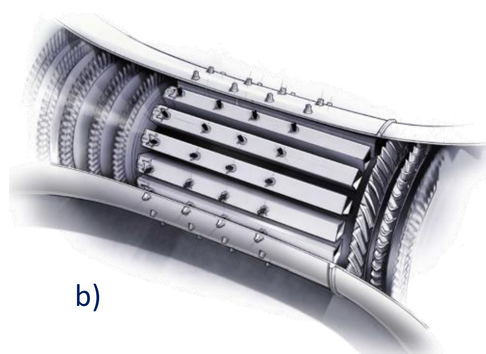
## Attacking loss source #1

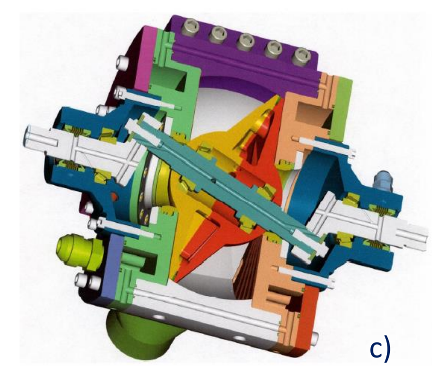
- Piston based composite cycles
- Nutating disc
- Pulse detonation combustion




**A Composite Cycle Engine Concept with Hecto-Pressure Ratio,**
AIAA 2015-4028, Kaiser, Seitz, Donnerhack, Lundbladh

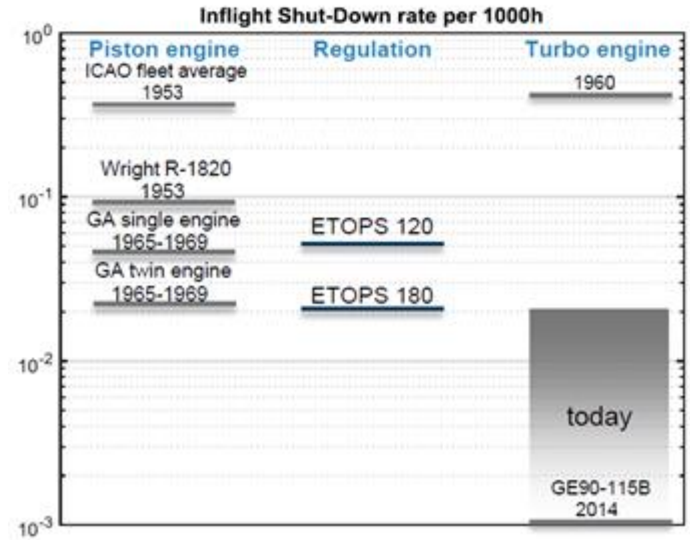

b)

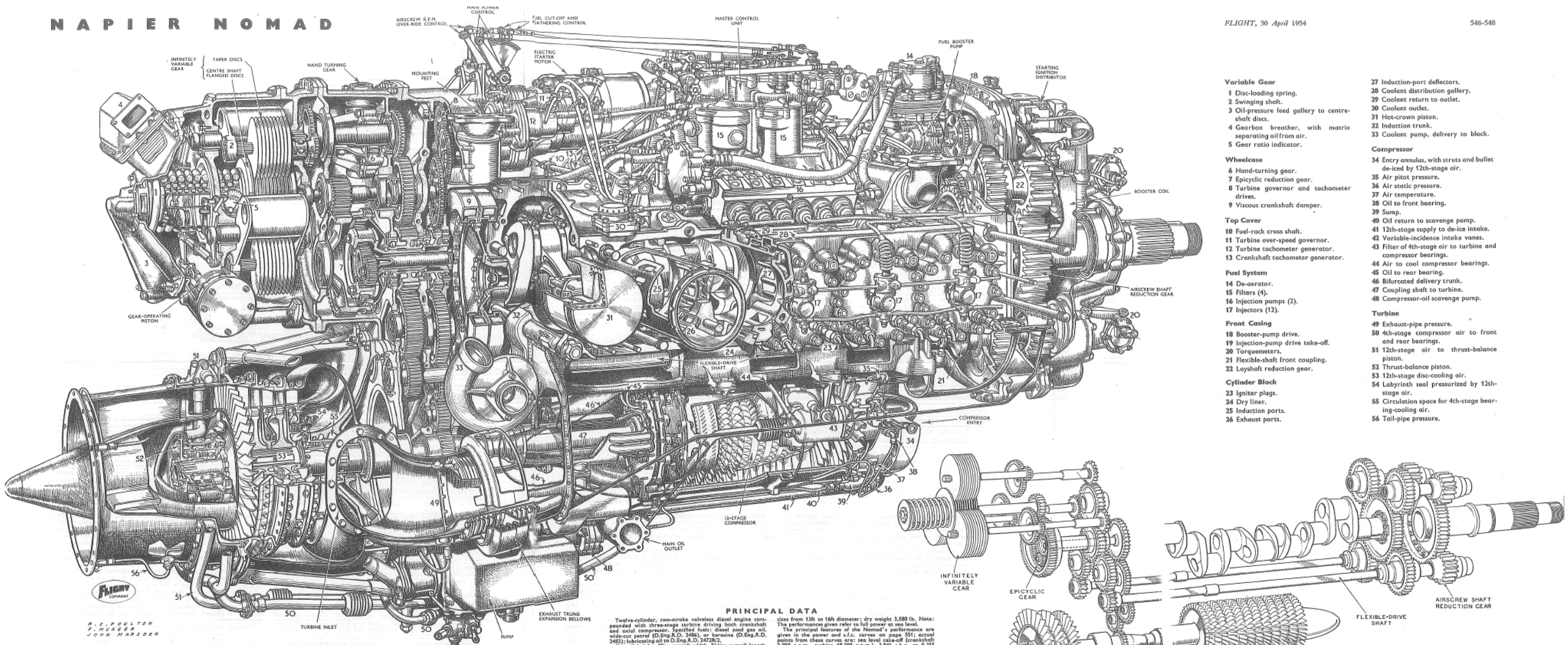

c)

a) Piston based "composite cycle"
b) Pulse detonation core c) Nutating disc

# Source 1 – historical achievements

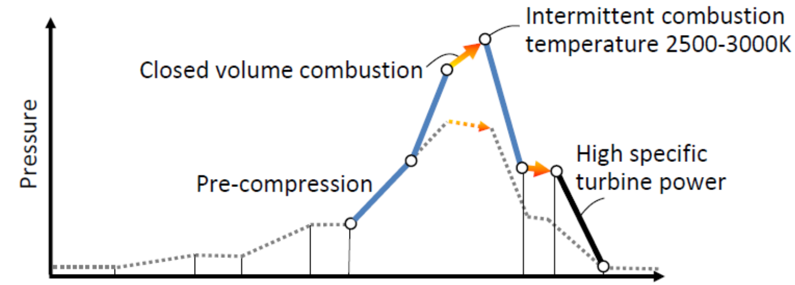
| Compound Engines | BSFC @TO SL (lb/shp-hr) | Power-to-Weight ratio (kW/kg) |
|---|---|---|
| Wright R-3350 piston engine (1941) | 0.38 | 1.35 |
| Napier Nomad 2 engine (1954) | **0.35** | 1.44 |
| **Turboprop Engines** | | |
| Allison T-56 turboprop engine (1955) | 0.52 | 4.00 |
| RR AE 2100 (1994) | 0.41 | 4.53 |
| Europrop TP400 (2009) | **0.35 (CR)** | 4.41 |

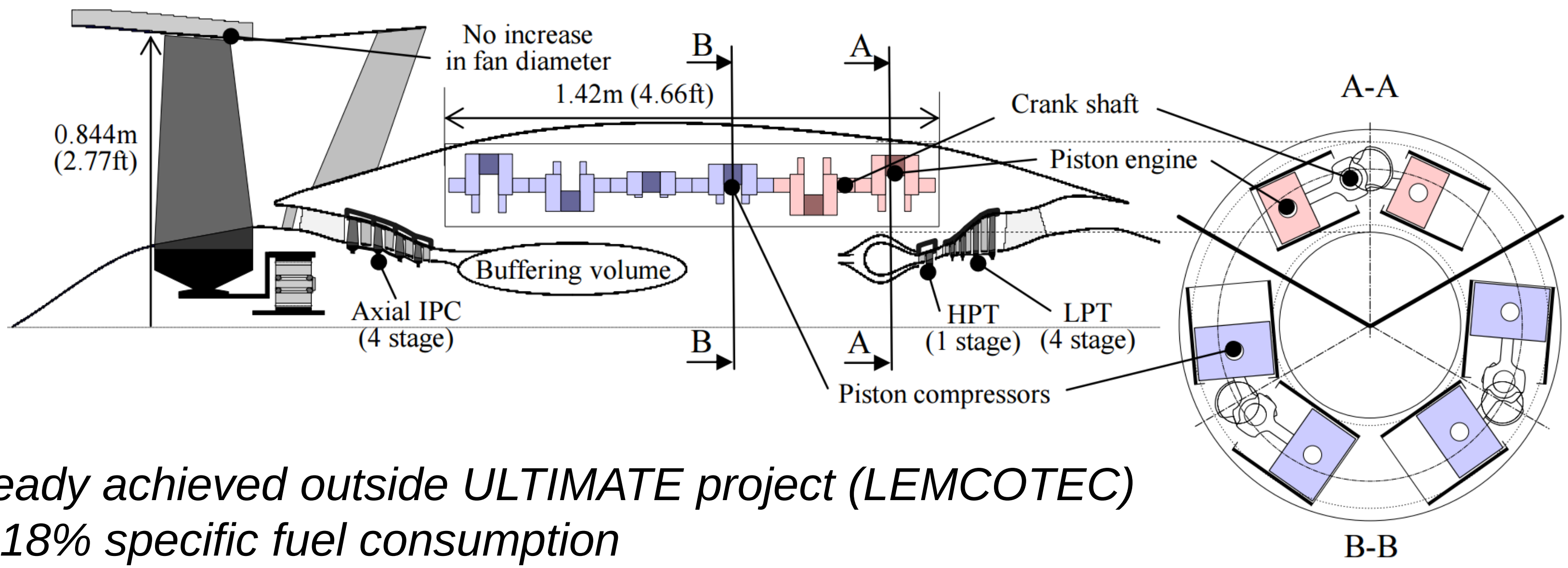



*This special "Flight" copyright drawing displays almost the whole of the internal layout of Napier's diesel compound. On the right is shown the arrangement of the gearing for the airscrew shafts and the drive from the turbine, the latter feeding-in its power through an infinitely variable ratio drive and an epicyclic reduction gear.*

# Source 1 - The composite cycle




*Already achieved outside ULTIMATE project (LEMCOTEC)*

*- 18% specific fuel consumption*

*+ 30% weight increase*

*- 15% fuel burn*

S. Kaiser, S. Donnerhack, A. Lundbladh, A. Seitz, "A Composite Cycle Engine Concept with Hecto-Pressure Ratio", 51st AIAA/SAE/ASEE Joint Propulsion Conference, Propulsion and Energy Forum, (AIAA 2015-4028).

## Attacking loss source #2

### Bottoming Rankine cycle

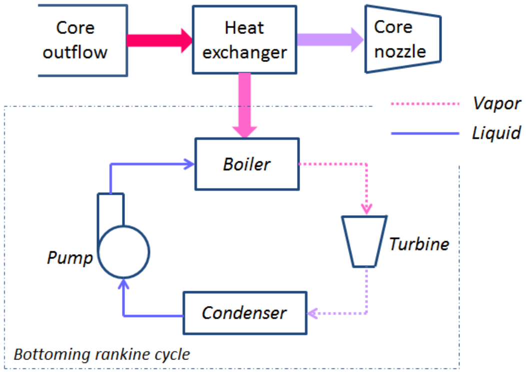



Figure 5: Bottoming Rankine cycle concept

### Recuperation

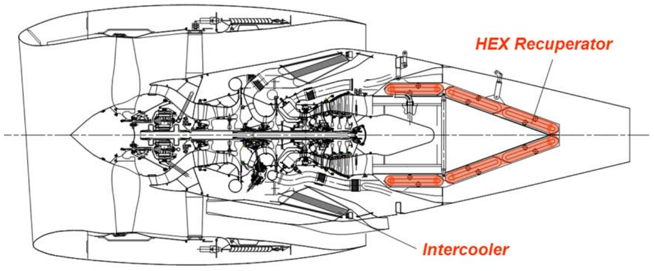



Figure 6: Recuperator conceptual design

### Intercooling

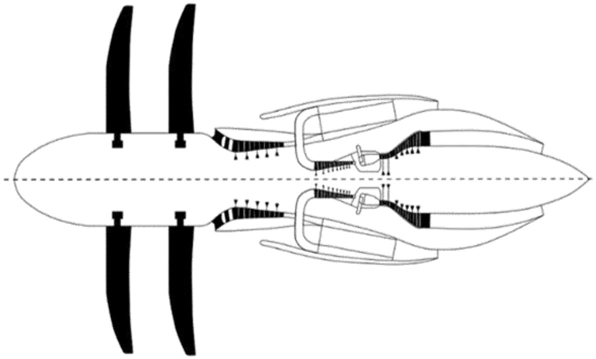


Figure 7: Intercooler integration

### Re-heat

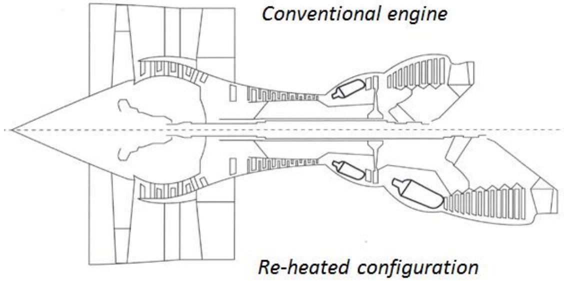



Figure 8: Reheat integration

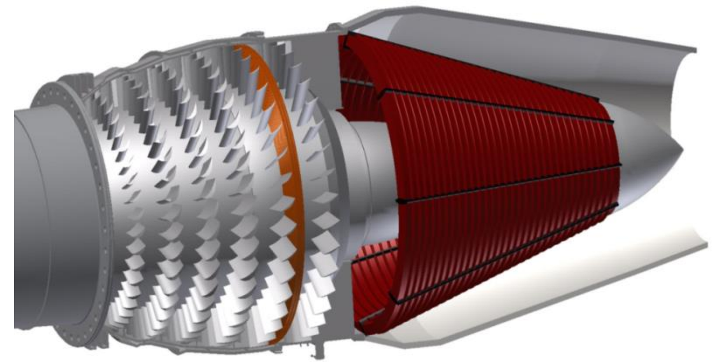
**… Possible synergies with**

- Intercooling
- Recuperation
- Rankine bottoming

# Loss source 2 - core exhaust heat losses

## Recuperation

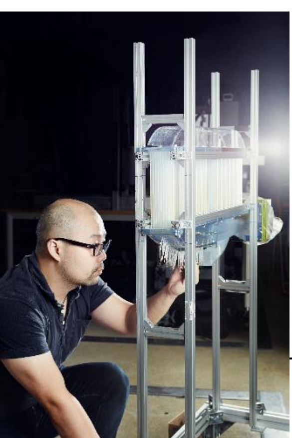
- Alternative recuperation
  - Staged heat recovery (SHR)
  - HEX between IPT-LPT **and** downstream LPT
  - Concept for compact heat exchange
- Secondary fluid systems in recuperation concepts

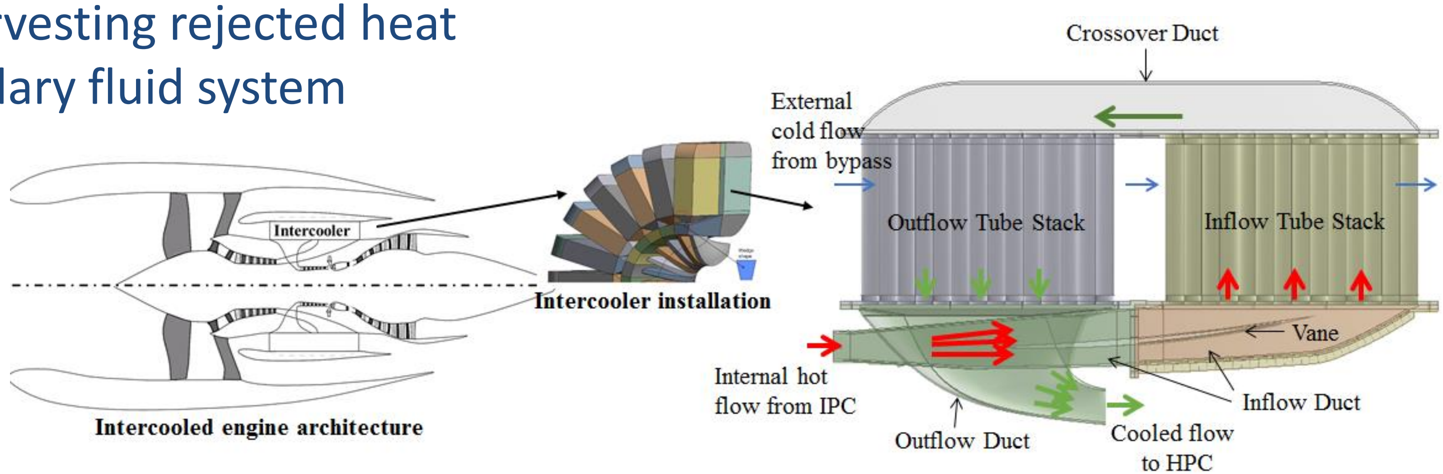


Recuperator conceptual design

## Intercooling

- Possibly harvesting rejected heat with secondary fluid system



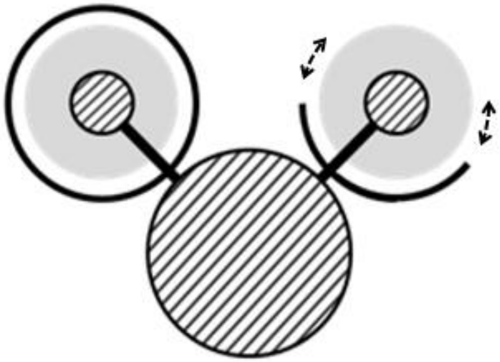



One intercooler module layout

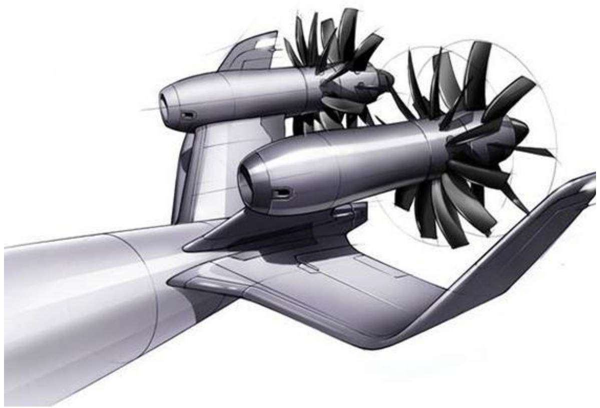
# Loss source 3 – excess kinetic energy

## Attacking loss source #3

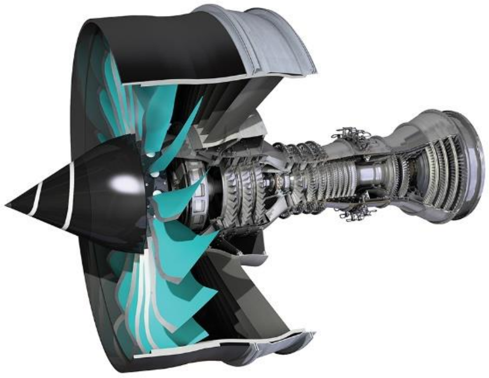
- ultra-thin adaptive inlet
- adaptive external shapes
- circumferentially retractable concepts
- variable pitch fan rotors,
- variable bypass and core nozzles, variable inlet guide vanes



Retractable nacelle concept



Intra-European configuration



Powerplant for intercontinental configuration (the Rolls-Royce UltraFan concept for 2025 is used to illustrate this configuration)

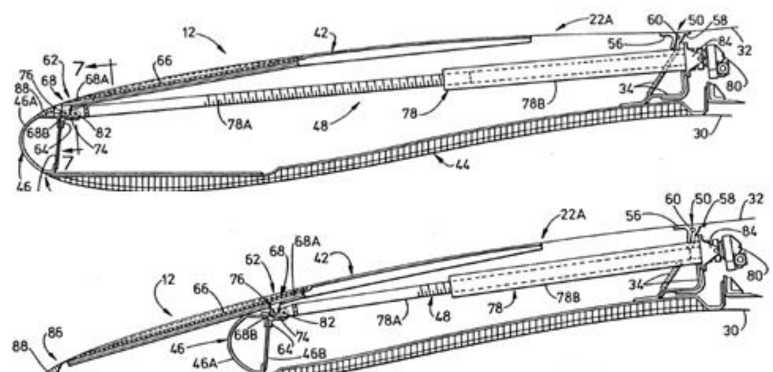
- Open-Rotor architecture for the Intra-European configuration
- Geared architecture for the intercontinental configuration

# Source 3 – some concepts

- Boxprop concept and open rotor concepts being explored
- Boxprop
  - Potentially low noise emissions at competitive efficiencies

R. Avellán, A. Lundbladh, *"Boxprop, a forward-swept joined-blade propeller"*, ISABE-2013-1108

- Evaluating the effect of ultra-thin **adaptive inlet** & adaptive external shapes
- Variable pitch fan concept



*US Patent 5000399*

# The search for ultra low emission engines

- **Development**
  partially qualitative selection
- **Optimization**
  towards the SRIA 2050 targets
- **Exploitation**

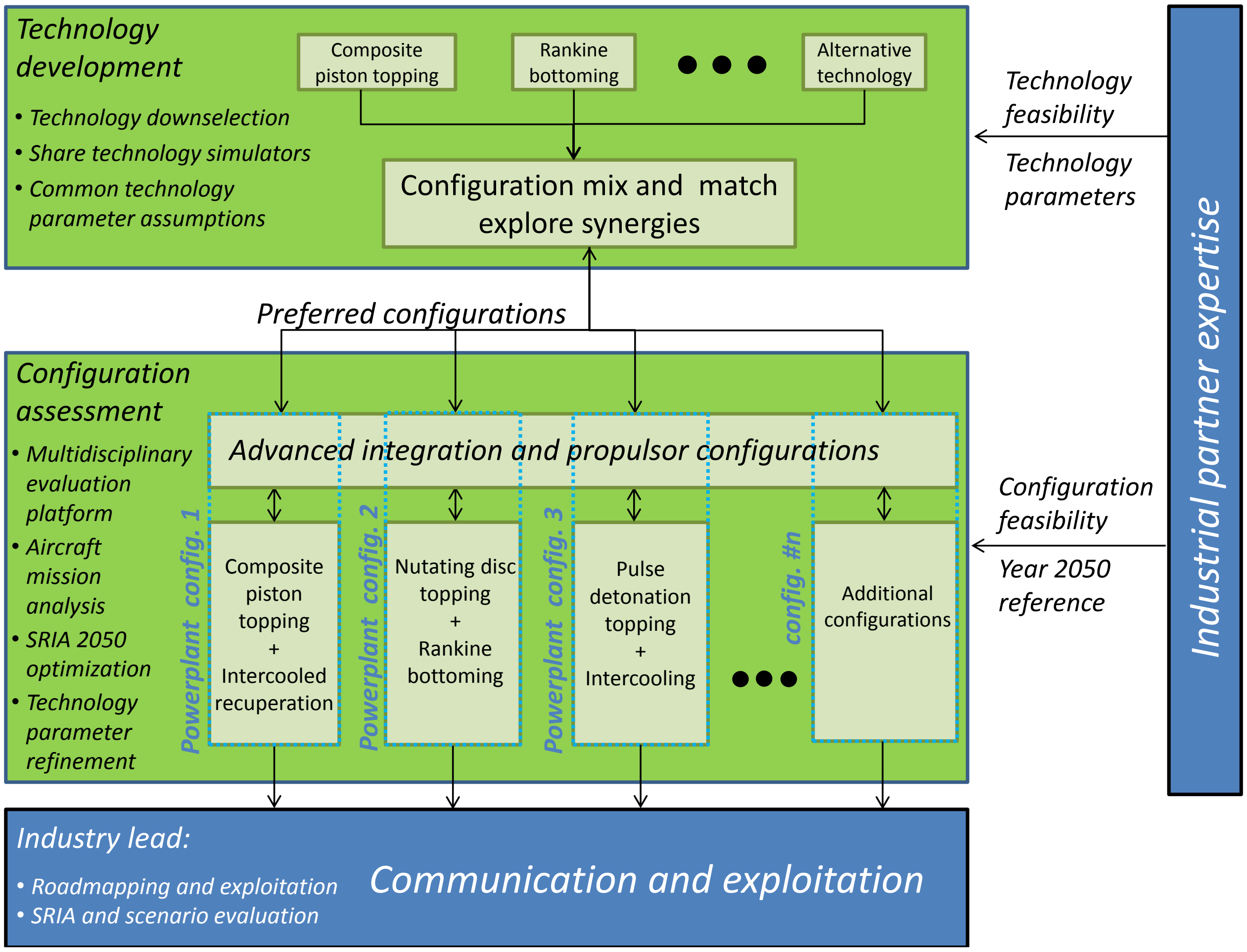



Figure 13. ULTIMATE technology screening and development process

# Quantitative metric for technology ranking

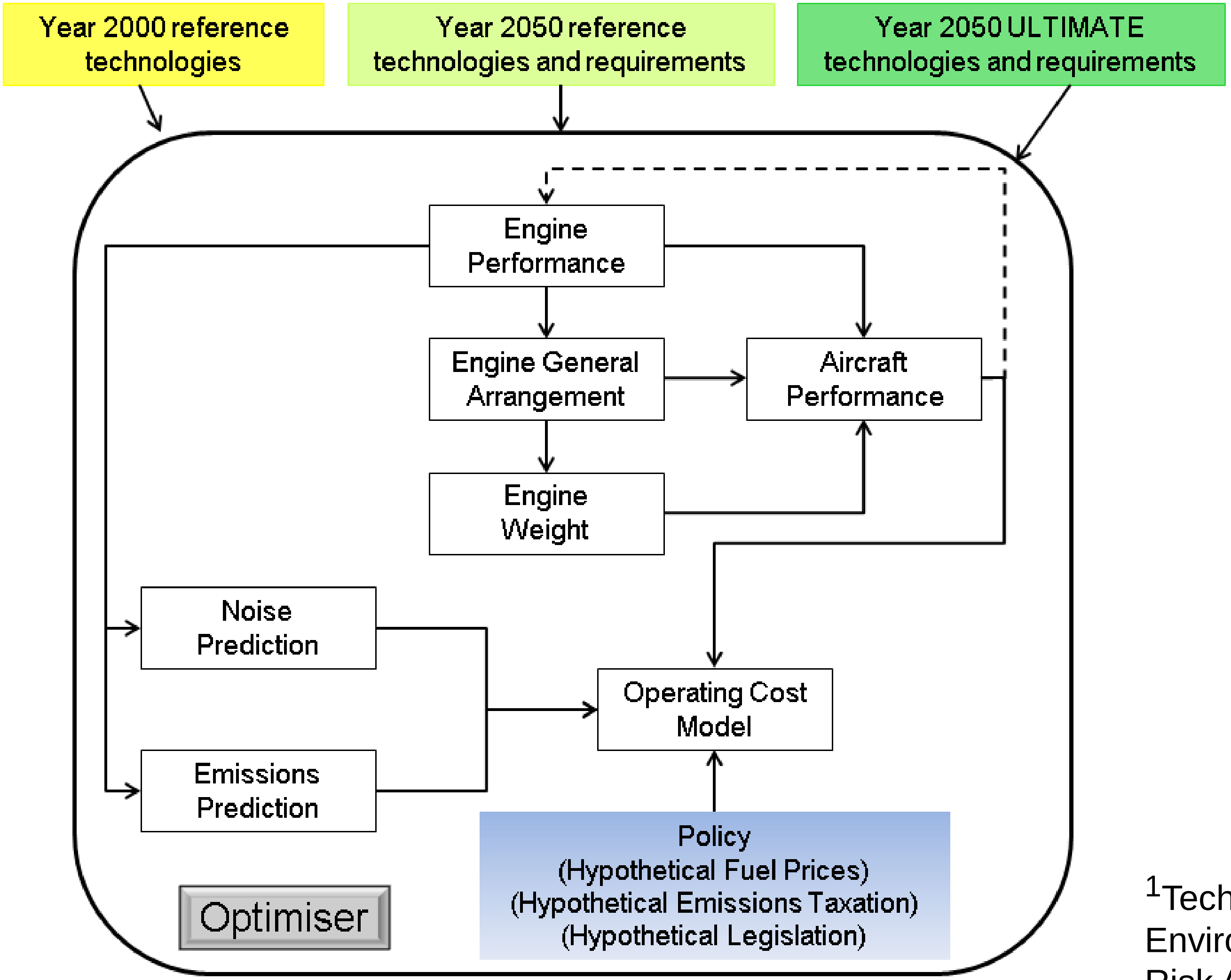
**Specific Range (*SR*) – distance flown per unit weight of fuel burned**

Capture the most critical system performance aspects while avoiding a full mission analysis

$$SR = a \frac{\mathrm{M} \frac{L}{D}}{SFC \cdot W}$$

- $a$ – Speed of sound
- $\mathrm{M}$ – Mach number
- $L/D$ – Lift to Drag ratio
- $W$ – Weight
- $SFC$ – Specific Fuel Consumption

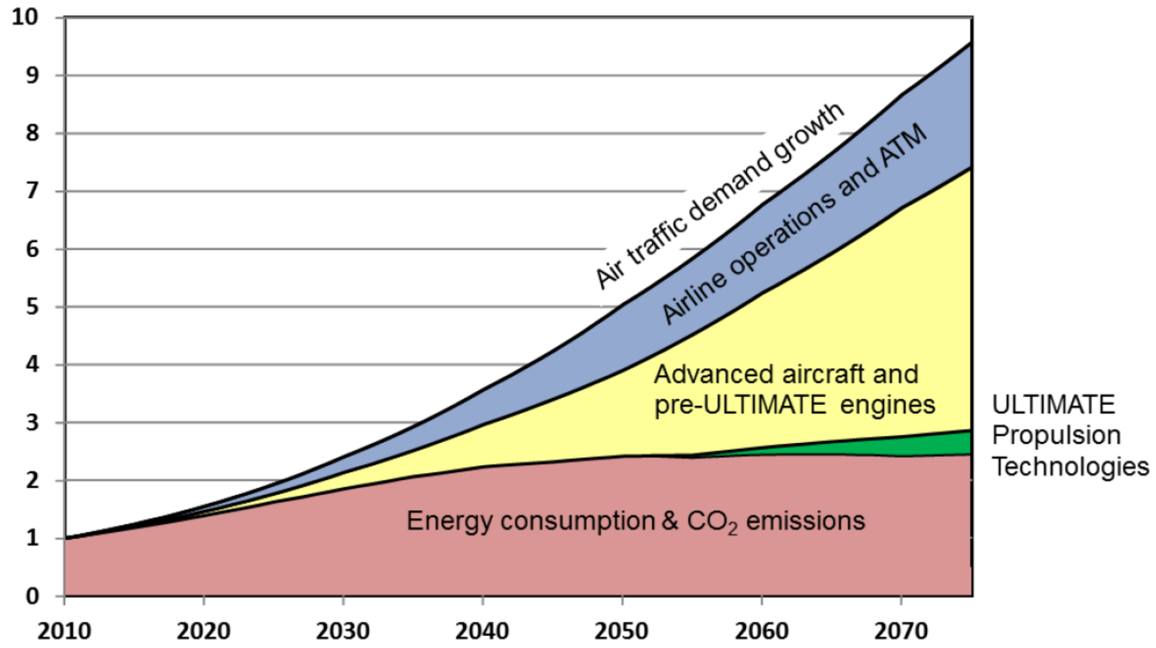
# Evaluation platform – TERA2050[1] concept




[1]Techno-economic, Environmental and Risk Assessment for year 2050

# Impact

- Y2050 introduction
- Potential reduction from ULTIMATE technologies
  - 3 billion tonnes of CO2 reduction in the 25 years beyond entry into service



# Ultimate in the news…

ENVIRONMENT
Special report

# Ultimate project is core focus for EU

Researchers and manufacturers are working together on ideas for ultra-low-emission technology that could revolutionise the layout and appearance of future powerplants

KERRY REALS LONDON

32 | **Flight International** | 20-26 September 2016

*Two pager in flight international (20th of Sept.)*

# Summary

- Great potential exist to improve cycle efficiency with advanced core concepts

- A categorization of losses based on a ”lost work potential” was used for radical powerplants
    - A process for down-selection based on the categorization and specific range

- Several advanced core engine concepts outlined
    - Concepts for integration with more efficient and silent propulsors discussed