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

ULTIMATE
core engine technologies

GT2016-56123

Tomas Grönstedt

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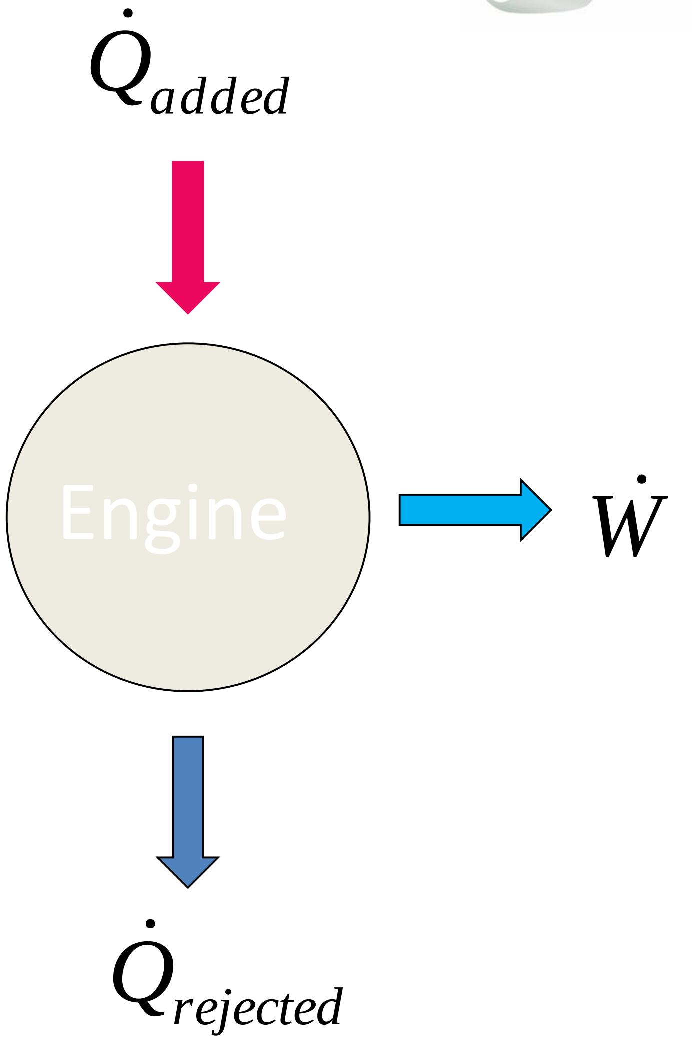
Talk in short

- Irreversibility
  - Categorizing losses & *"The big three"*
- ULTIMATE technologies
- Project approach
- Impact

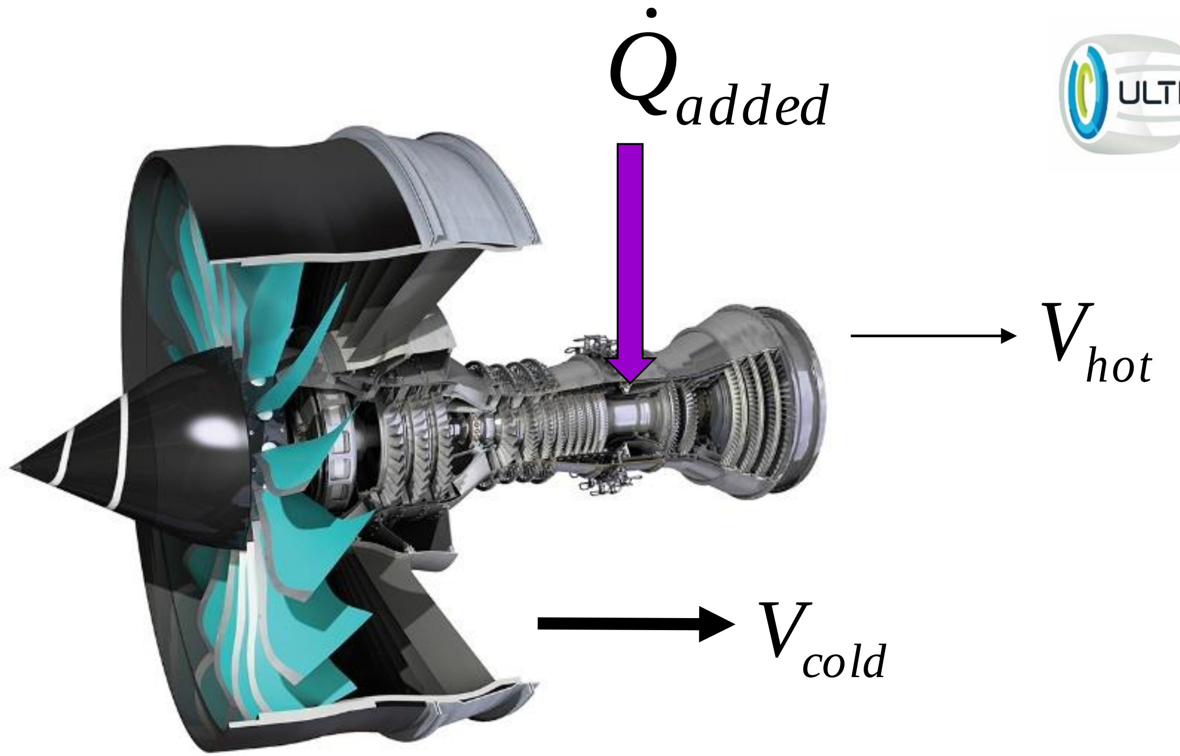
The heat engine

- We add heat ($\dot{Q}_{added}$), usually through combustion of a fuel, to generate something useful (W):
  - Electric power
  - Jet velocity to generate thrust for the aircraft

$$\eta = \frac{\dot{W}}{\dot{Q}_{added}}$$



The jet engine



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

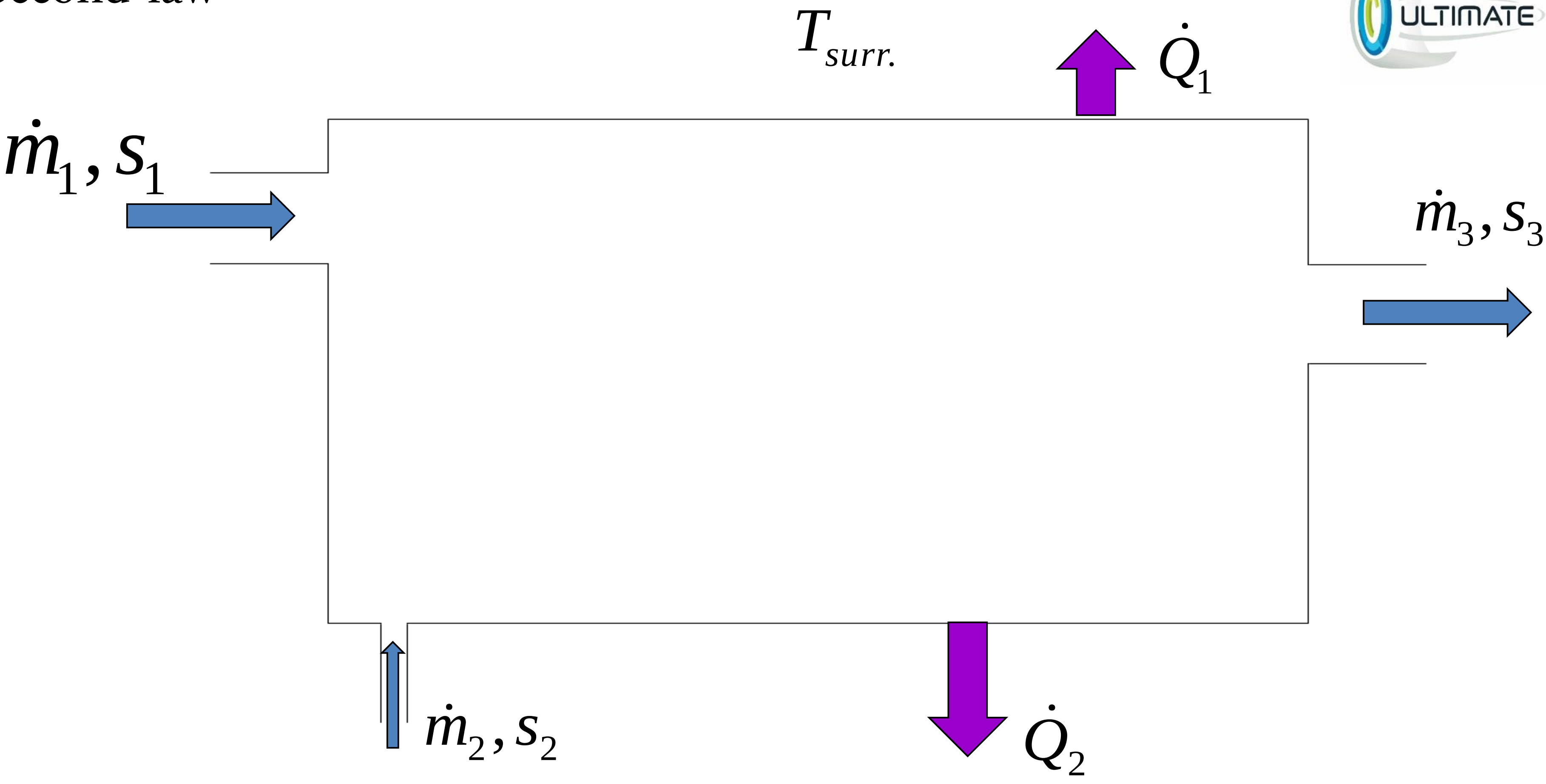
$$SFC = \frac{\text{Fuel mass flow}}{\text{Thrust}}$$

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

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

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

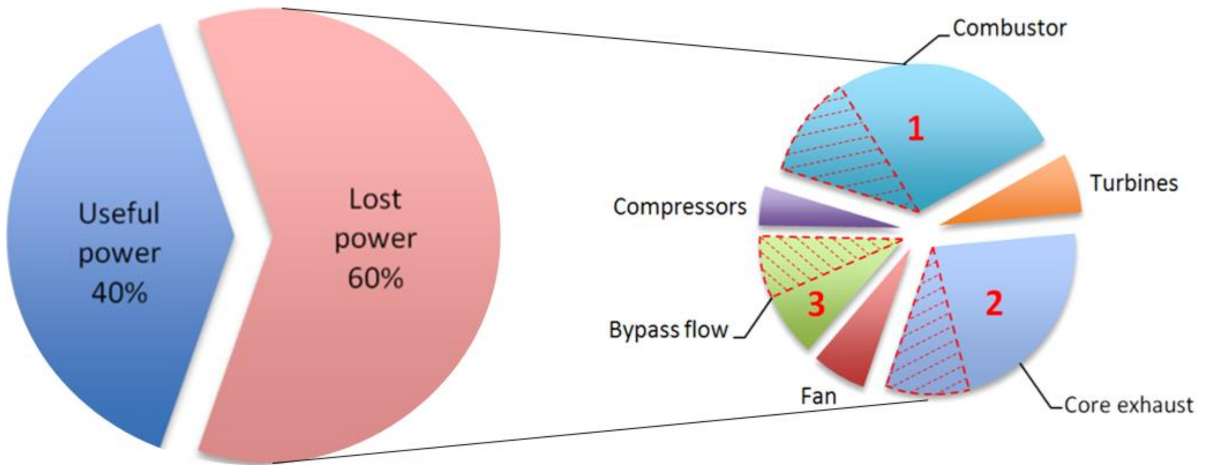
Second law



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

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

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



One needs to attack the "the Big Three"

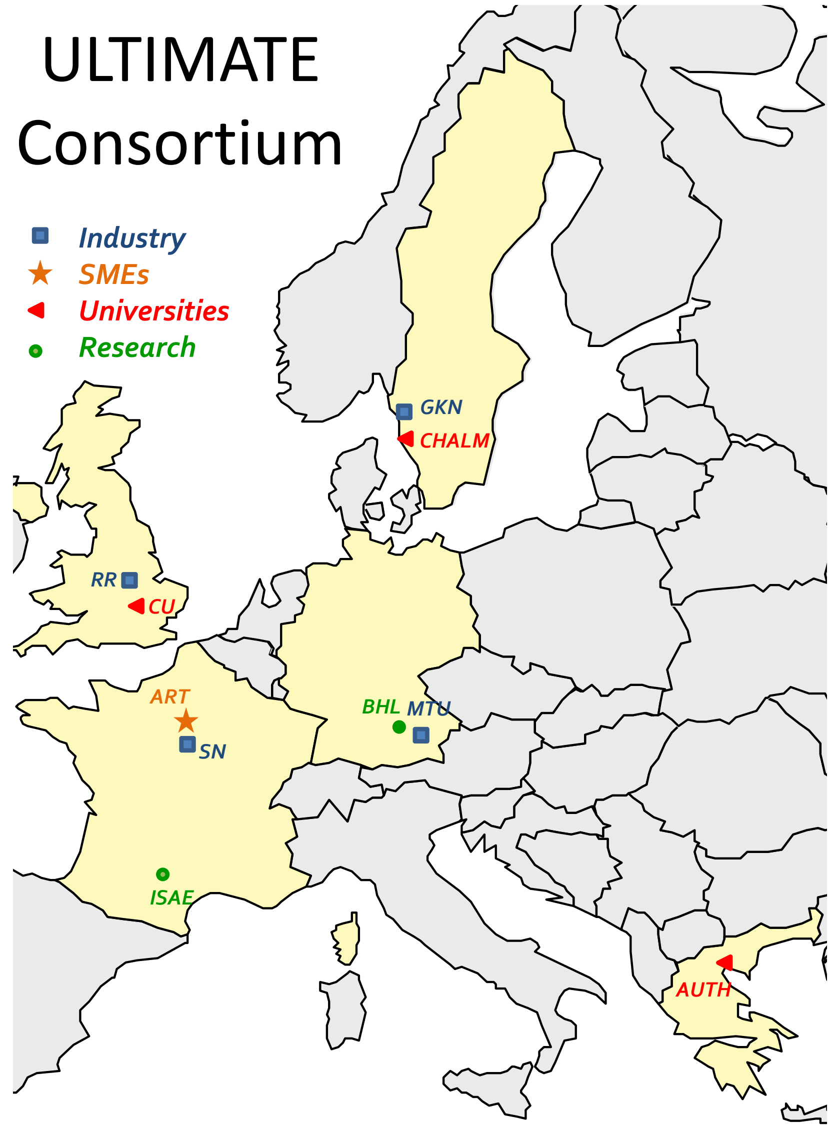
- Combustor irreversibilities (1)
- Core exhaust heat losses (2)
- Excess of kinetic energy in the bypass flow (3)

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

The ULTIMATE project consortium



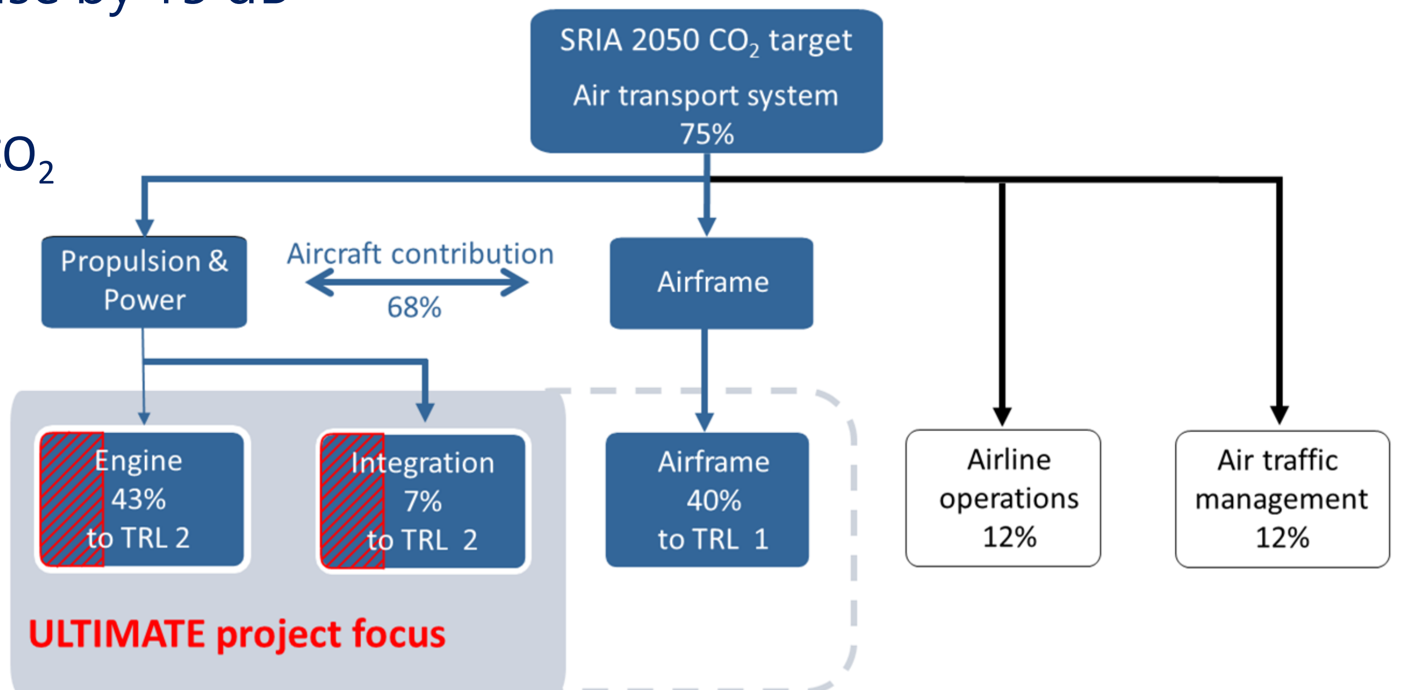
Major challenge (all relative to the year 2000)

- 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

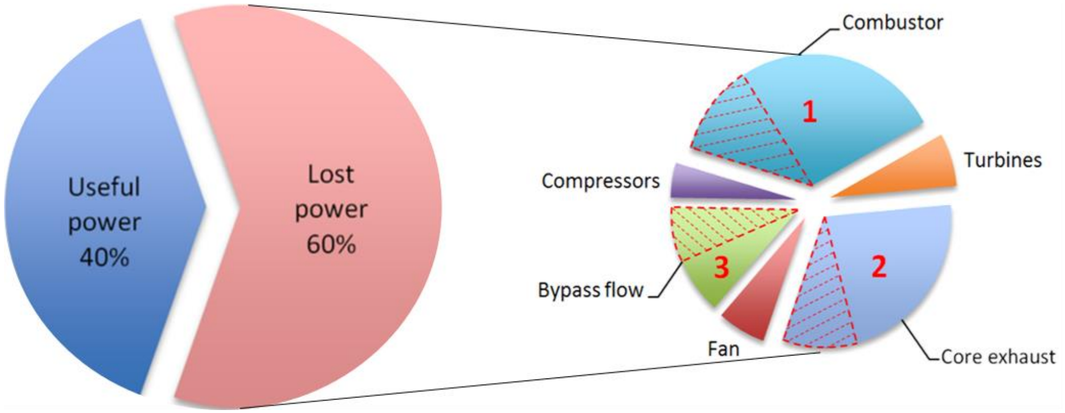
1: Meeting societal and market needs	2: Maintaining and extending industrial leadership	3: Protecting the environment and the energy supply	4: Ensuring safety and security	5: Prioritising research, testing capabilities and education
• European citizens …informed mobility choices. • 90% of travellers within Europe … door-to-door within 4 hours. • A coherent ground infrastructure is developed. • Flights land within 1 minute of the planned arrival time. • 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. • Europe has retained leading edge design, manufacturing and system integration capability and jobs … flagship projects … cover the whole innovation process … • 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. • Aircraft movements are emission-free when taxiing. • Air vehicles are …. to be recyclable. • Europe … centre of excellence... sustainable alternative fuels…. • Europe is at the forefront of atmospheric research …	• ..European Air Transport System has less than one accident per ten million… • Weather and other environmental hazards … evaluated…mitigated… • Air Transport … manned and unmanned … safely operate in the same airspace. • …boarding and security measures…. through security controls without intrusion. • Air vehicles are resilient by design to current and predicted …security threat… • 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… • A network of multi-disciplinary technology clusters…collaboration between industry, universities and research institutes. • Strategic European aerospace test, simulation and development facilities are identified, maintained and further developed…
ULTIMATE measurable objectives				
• Short & long range missions • Flexible missions, 30000-45000 ft alt. • Gate-to-gate better than state of the art	• Propulsion system, technology and top-level module requirements to TRL 2 • Advanced whole engine analysis, Ph.D's & senior researchers with deep knowledge of multi-disciplinary • Exploiting working process	• CO_2: 18% reduction • NO_x: 20% reduction • 3 dB reduction from ULTIMATE propulsion technologies alone • Breakdown of goals – airframe/propulsion system	• Show that propulsion systems are judged tolerant of inclement weather (ice, hail, rain, inlet temperature) • have sufficient system redundancy	• Develop the European academic network of Centres of Excellence in conceptual engine design • 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
- When designing real cycles loss source attacking is more complex
  - Optimization blurs the view
  - Some innovations may attack both loss source 1 and loss source 2

- Intercooling & recuperation
- Advanced low pressure system technology



Concept and approach

… together with an advanced tube and wing configuration

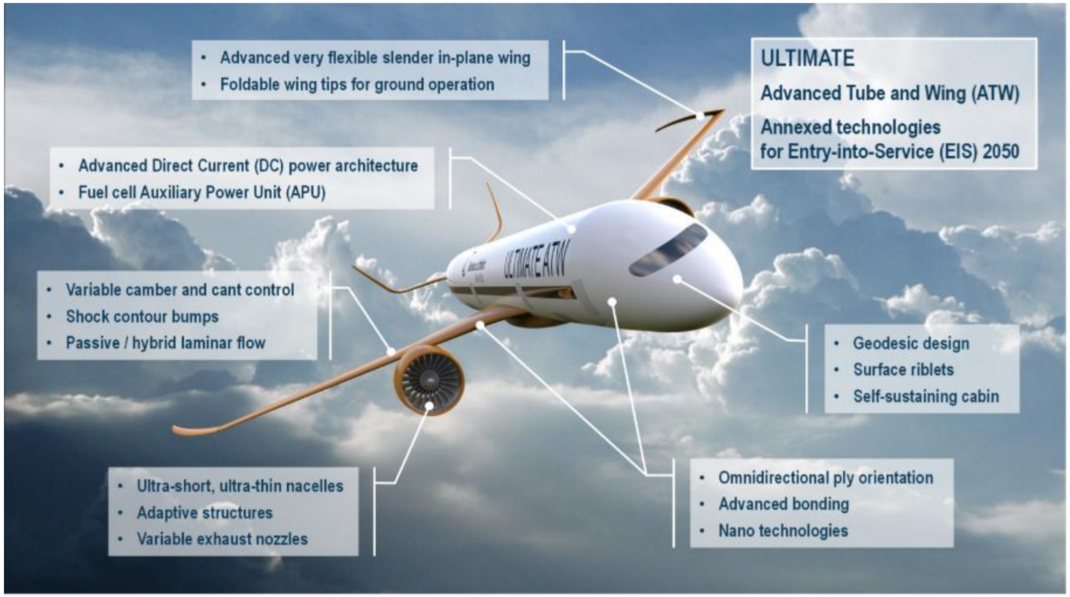


Figure 3: a) Year 2050 Advanced Tube and Wing (ATW) aircraft

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

Recent large improvements shown for configurations with less radical powerplants:

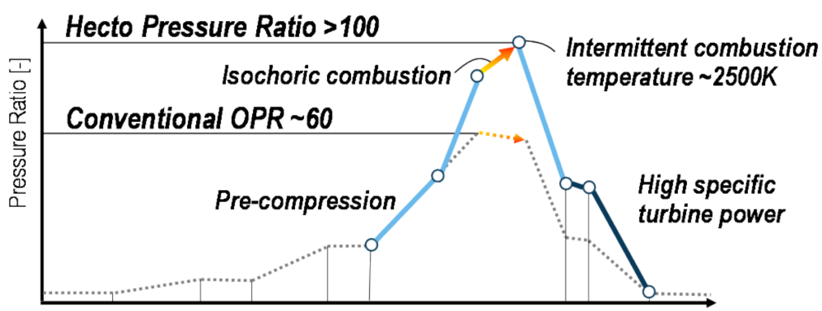
- *Boeing estimated a 54% reduction with a truss-braced high AR wing concept "SUGAR High"*
- *MIT's "double bubble", close to 71% reduction (use of boundary layer ingestion)*

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*

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

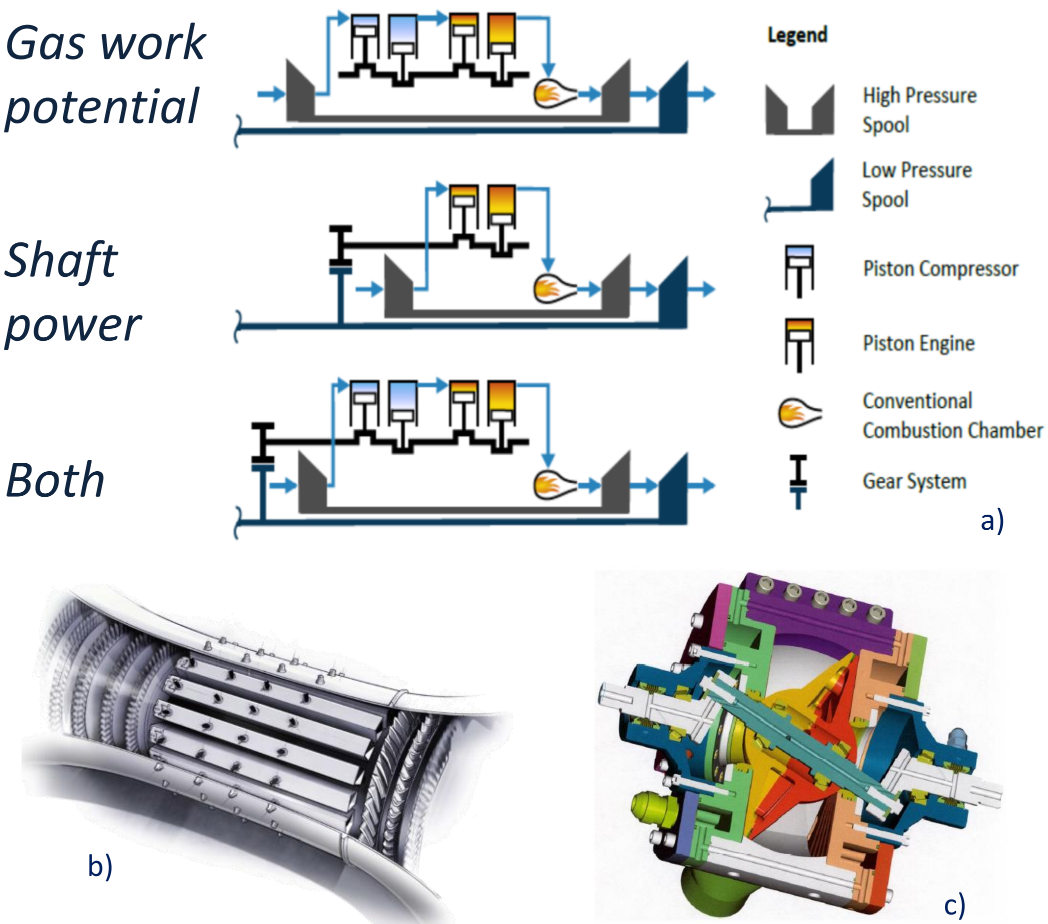
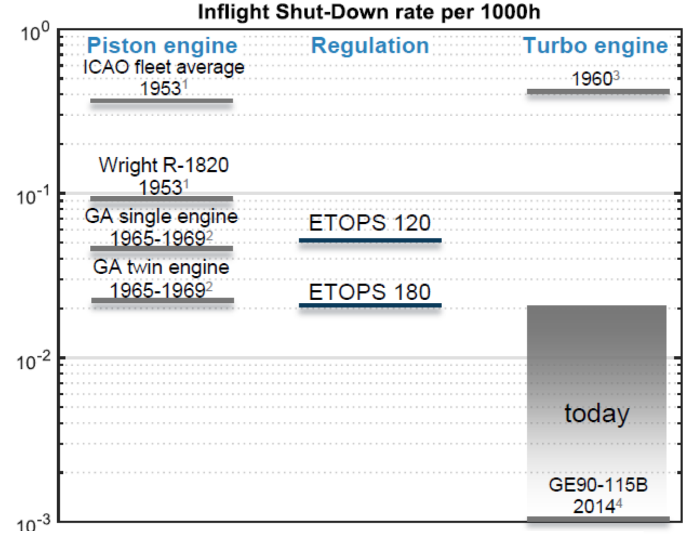
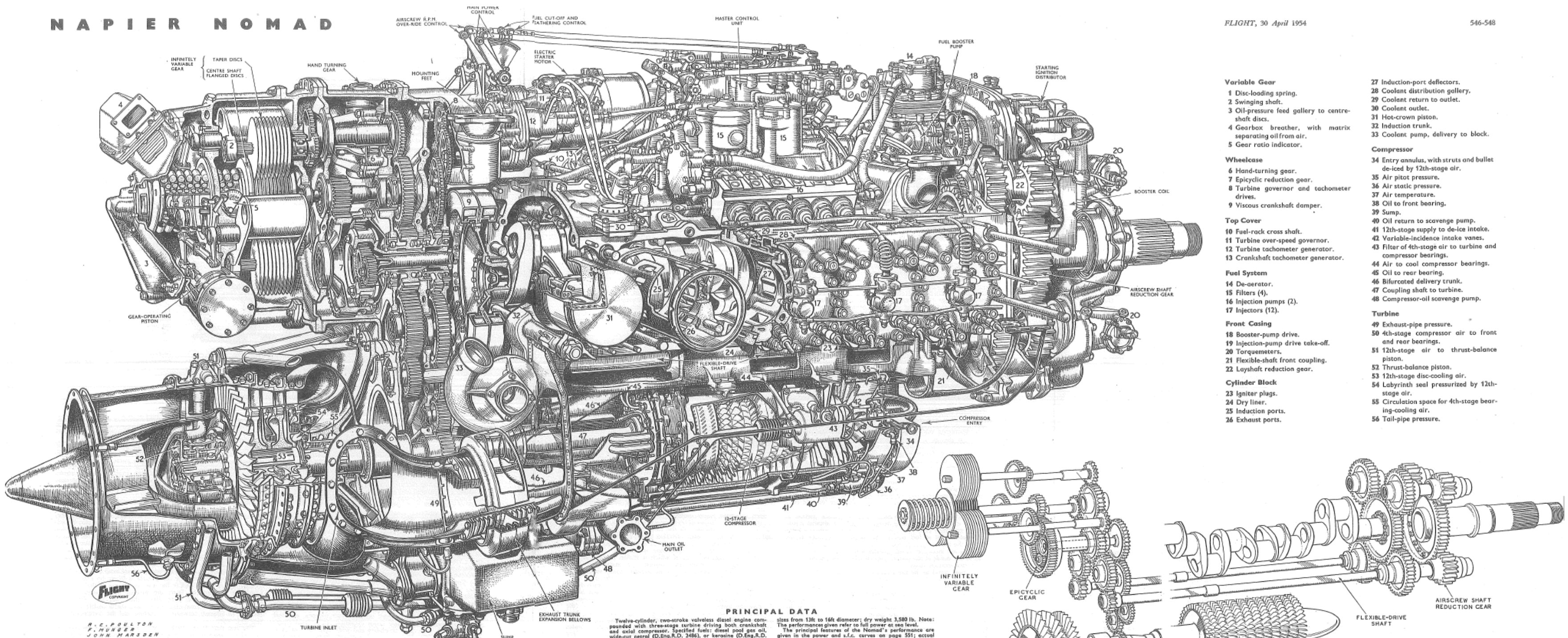


Figure 4: a) Piston based “composite cycle” . b) Pulse detonation core. c) Nutating disc

Source 1 – some historical achievements

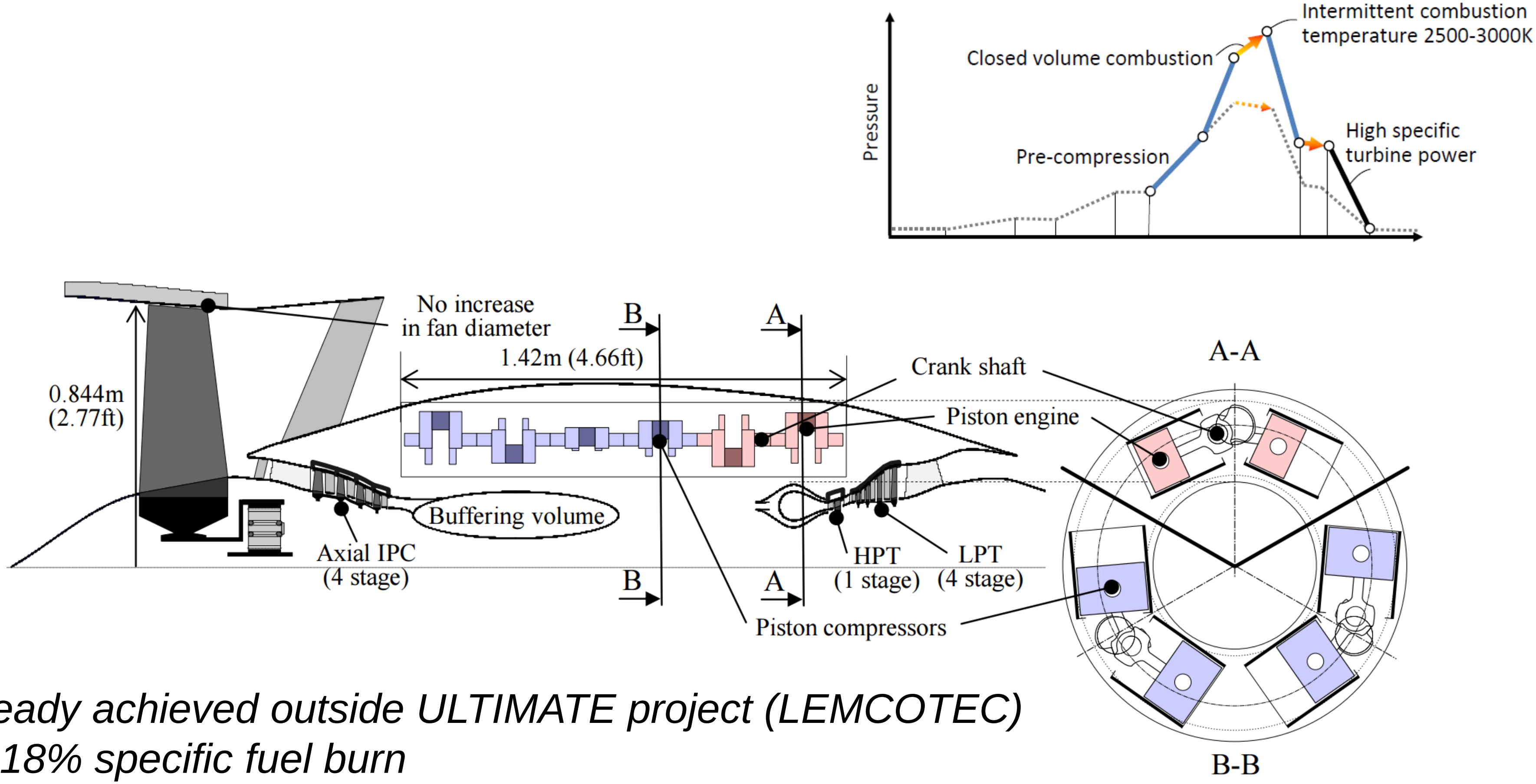
Compound Engines	BSFC @TO SL (lb/shp-hr)	Power-to-Weight ratio (kW/kg)
Wright R-3350 piston engine (1941)[1]	0.38	1.35
Napier Nomad 2 engine (1954)[2]	**0.35**	1.44
Turboprop Engines		
Allison T-56 turboprop engine (1955)[1]	0.52	4.00
RR AE 2100 (1994)[3]	0.41	4.53
Europrop TP400 (2009)[3]	**0.35 (CR)**	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 burn

+ 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
- Recuperation
- Intercooling

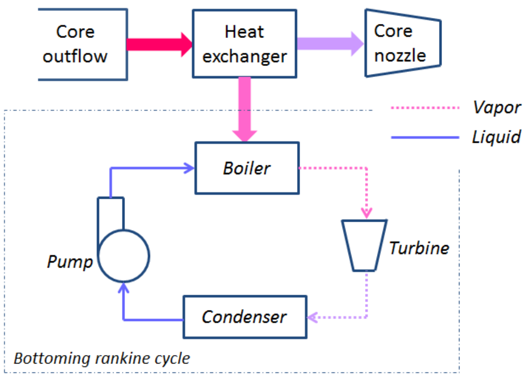


Figure 5: Bottoming Rankine cycle concept

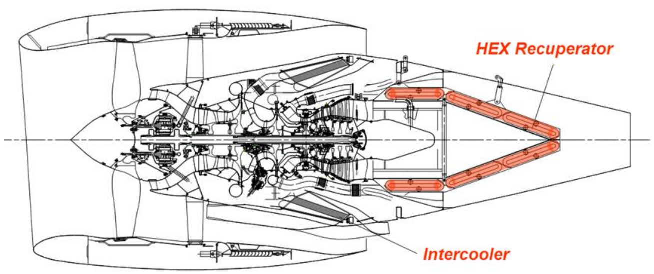


Figure 6: Recuperator conceptual design

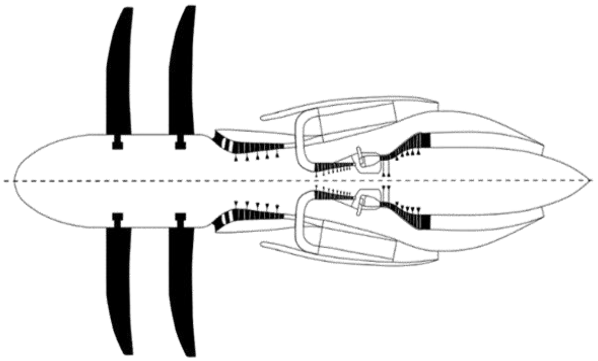


Figure 7: Intercooler integration

- Re-heat

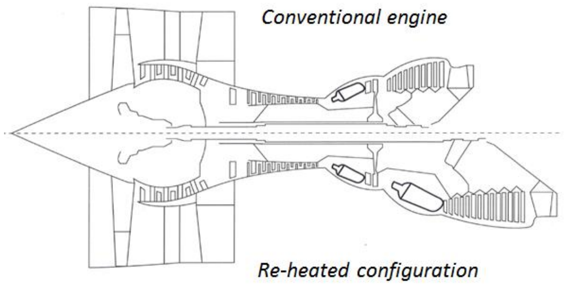


Figure 8: Reheat integration

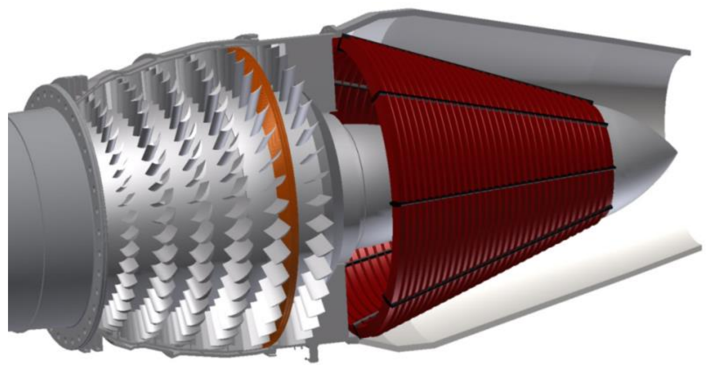
… Possible synergies with

- Intercooling
- Recuperation
- Rankine bottoming

Loss source 2 - core exhaust heat losses

Recuperation

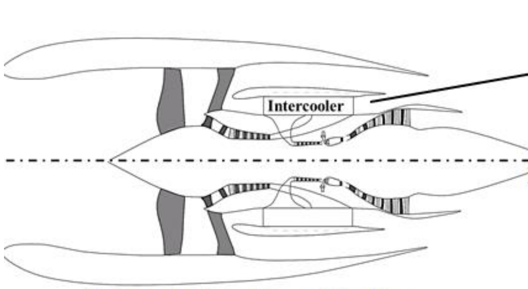
- Alternative recuperation
  - Staged heat recovery (SHR)
  - HEX between IPT-LPT **and** downstream LPT
  - Concept for compact heat exchange
- Secondary fluid systems in recuperation concepts



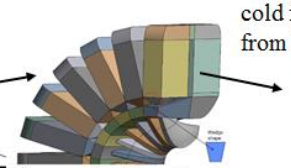
Recuperator conceptual design

Intercooling

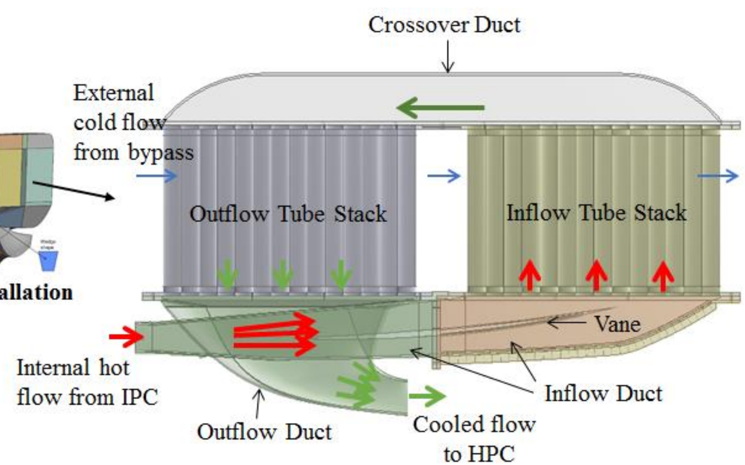
- Possibly harvesting rejected heat with secondary fluid system



Intercooled engine architecture



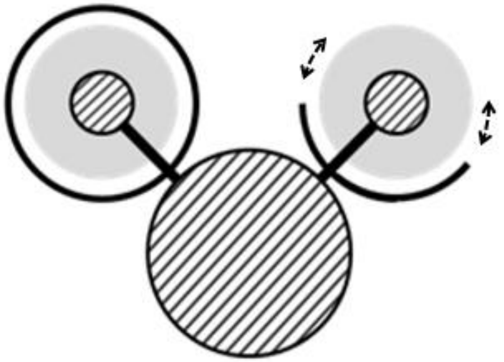
Intercooler installation



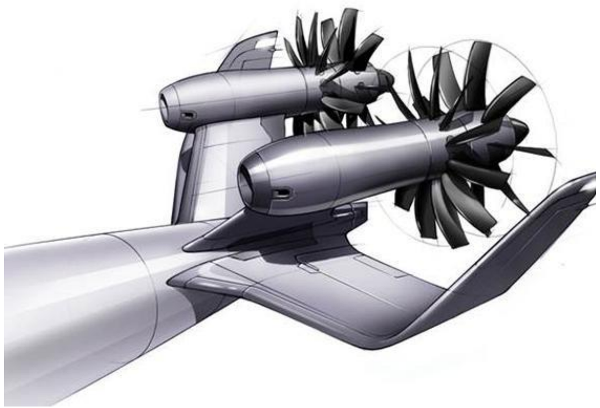
One intercooler module layout

Attacking loss source #3

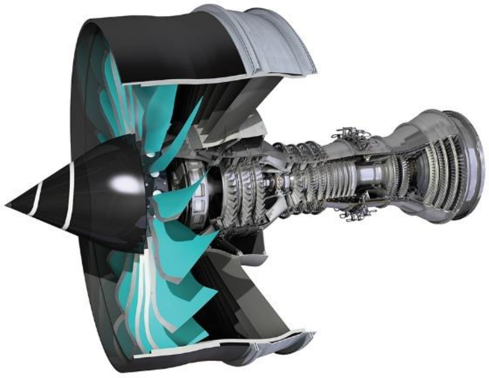
- **ultra-thin adaptive inlet**
- **adaptive external shapes**
- **circumferentially retractable concepts**
- **variable pitch fan rotors,**
- **variable bypass and core nozzles, variable inlet guide vanes**



Retractable nacelle concept



Intra-European configuration



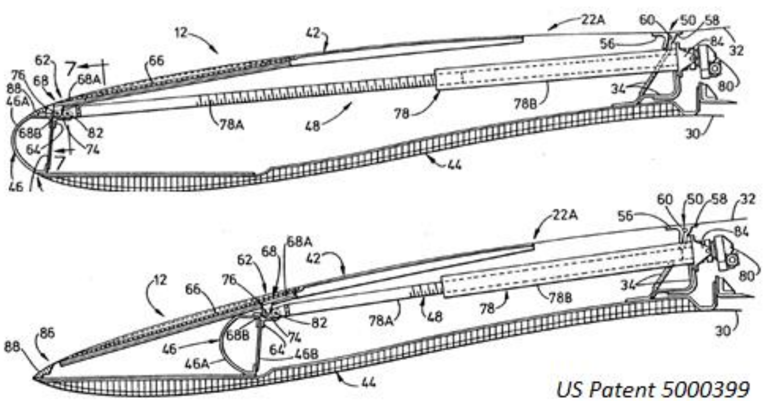
Powerplant for intercontinental configuration (the Rolls-Royce UltraFan concept for 2025 is used to illustrate this configuration)

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

- 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



The search for ultra low emission engines

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

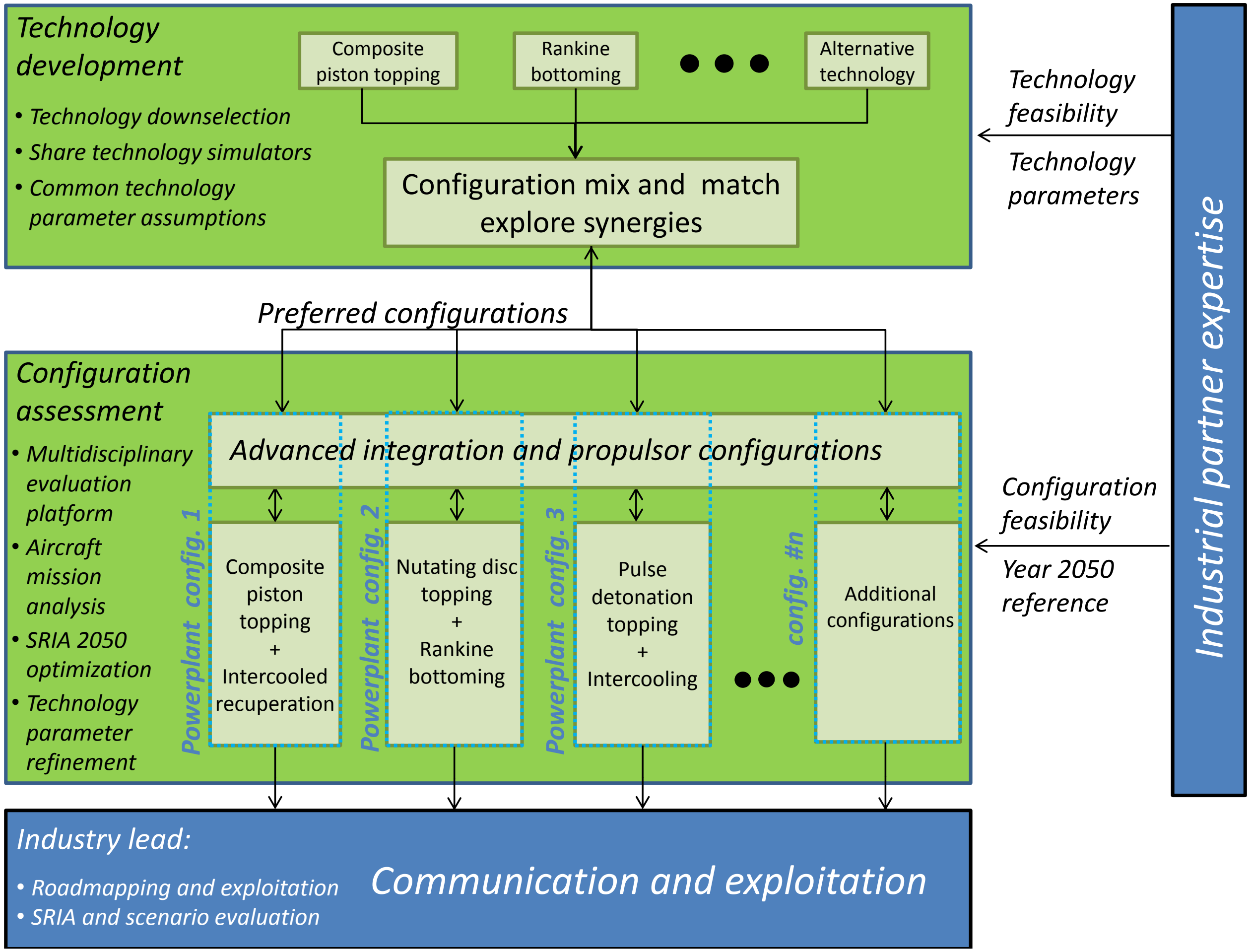


Figure 13. ULTIMATE technology screening and development process

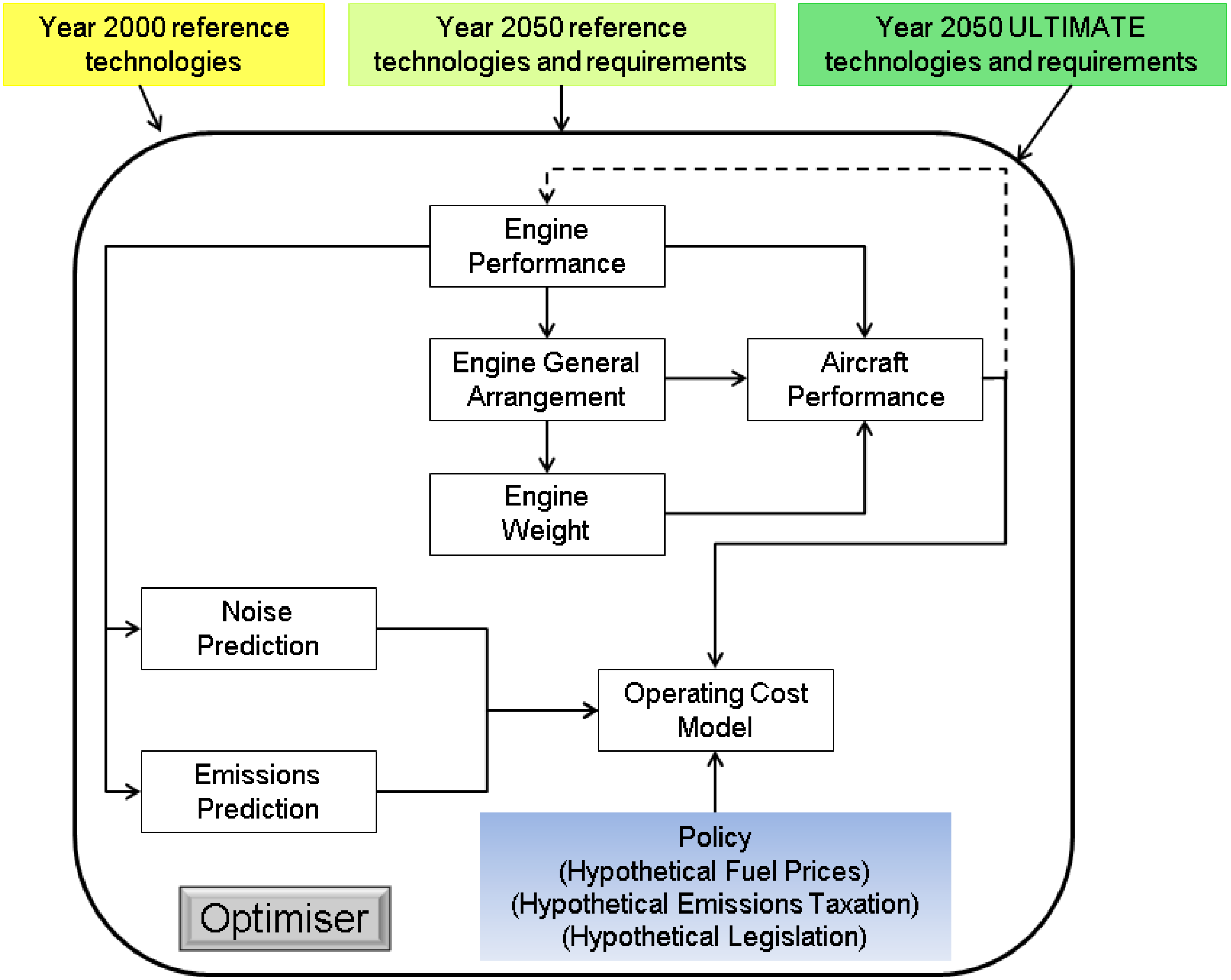
Specific Range (*SR*) – distance flown per unit weight of fuel burned

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

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

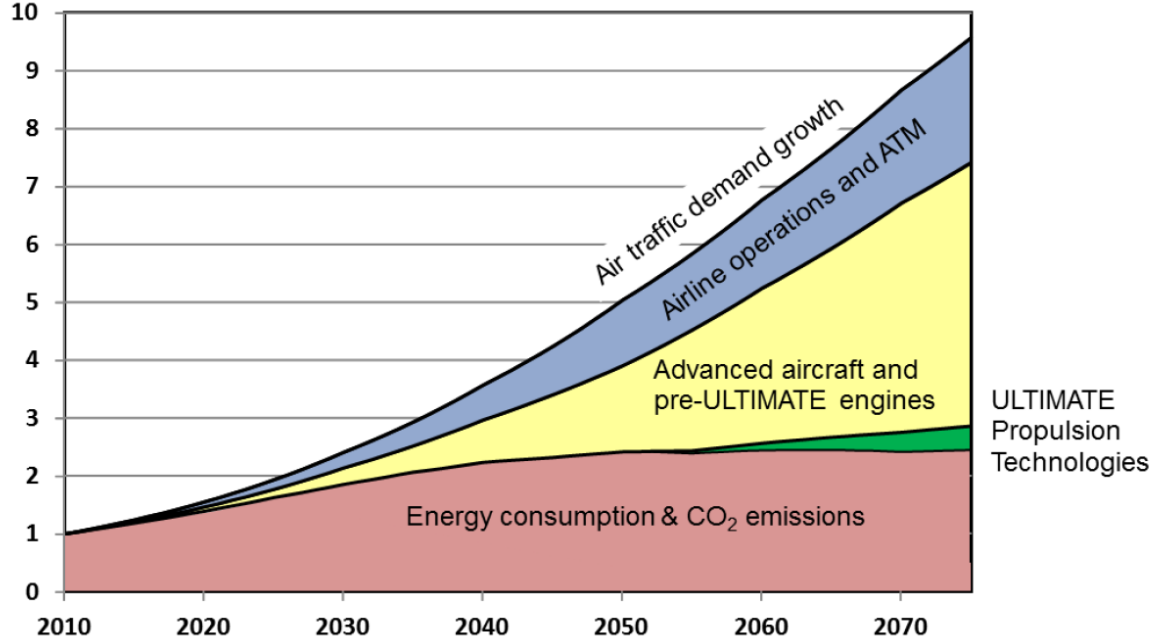
- a – Speed of sound
- M – Mach number
- L/D – Lift to Drag ratio
- W – Weight
- SFC – Specific Fuel Consumption

Evaluation platform – TERA2050 concept



Impact

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



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 outlined