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TITLE: European Low Emission Combustion Technology in Aero-Engines

PROJECT CO-ORDINATOR: Rolls-Royce Deutschland Ltd & Co KG
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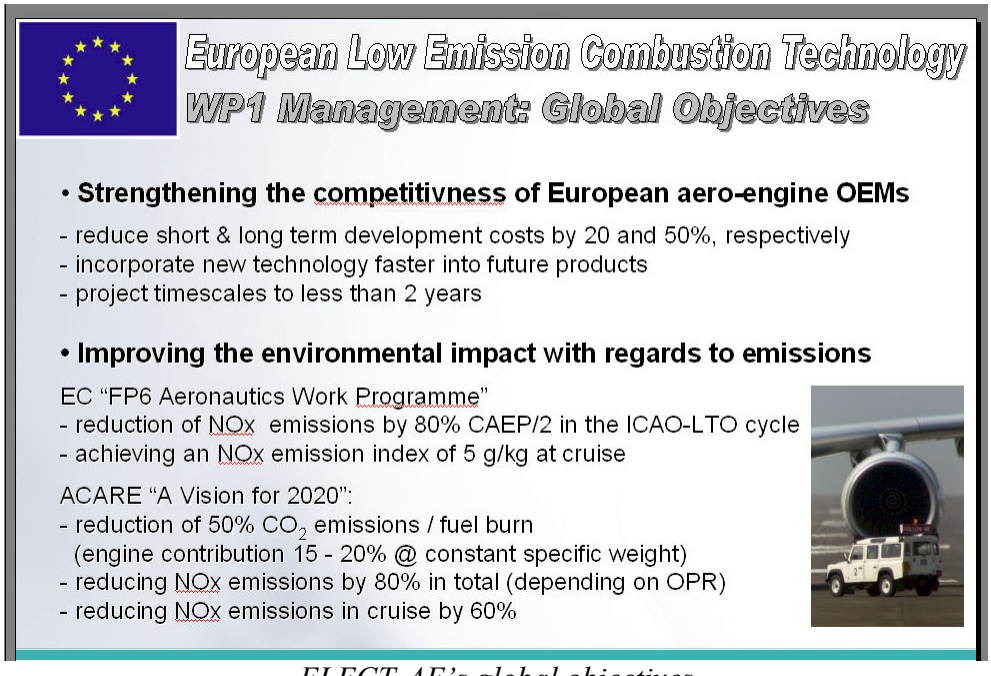
• WP1: Management

All milestones and deliverables have been achieved. The final annual review meeting was carried out on 17 and 18 December 2008 and hosted by the Representation of the Land Brandenburg to the EC. The head of the representation, Dr. Marcus Wenig, welcomed the participants.
Guests were Dr. Sigrun Matthes from DLR (Coordinator of NoE ECATS) and Dr. Philippe Novelli from ONERA. He is Coordinator of SWAFEA, the sustainable alternate fuels project.

Group Photo of the ELECT-AE team at the final meeting on 18 December 2008

Lean-burn technology is essential and has to be driven towards higher technology readiness. A holistic approach, considering component interaction between compressor, combustor and turbine, is required. Thermo-acoustic pressure oscillations remain a key issue. ELECT's results were reported to ICAO's Task Group on Long Term Technology Goals during their NOx review. The review by the independent experts was carried out at the Westminster Conference Centre on 30/31 March 2009 in London.



ELECT-AE's global objectives

The European key aero-engine manufacturers in ELECT-AE were developing a strategy for the environmentally friendly combustion system. The development of this joint research strategy involves complex interactions. However, it is believed that advanced low NOx technology is required and will be successful in the end. The vision for 2020 as formulated by ACARE sets ambitious targets; especially the demand for 80% NOx and 50% CO2 emissions reduction from aviation with reference to the year 2000, requires focused and balanced research and technology initiatives for the near future. The aero-engines are committed to contribute 15 to 20 %-points to the CO2 emission target, other contributors being the air-framers (20-25%), operations and air traffic management (5-10%).

The technology for a new generation of aero-engine combustors has to be prepared on a pre-competitive level of close cooperation and thus generating economic and ecological benefits for the European and the global Society. Targets have been developed, designed to support the establishment of a pre-competitive research strategy consisting of actual measures and actions in the context of combustion system technology for low emissions of pollutants:

• Strategy on technology development

• Integration & strengthening of the European Research Area

• Enhancement of exploitation in Europe

• Dissemination of European research results and exchange of information in Europe

• Search and identification of SMEs and new research partners in the EU25.

The conclusion was that the optimisation of the combustion process is an essential means to reducing NOx production from aero-engines. It has to be noted that advanced low NOx combustion technology contributes to fuel burn reduction by enabling cycles with higher pressures and bypass ratios, with higher turbine entry temperatures and by reducing cooling air and combustor pressure losses.

Research on highly innovative architectures has to be carried out to reduce complexity, size and weight of ultra-low NOx combustion systems. Due to the extremely complex nature of this technological field and the fact that the development of ultra-low NOx technology has by far not yet reached production readiness level, it will not be possible to down-select the successful combustion technology in the near future.

• Latest lean burn fuel injection systems with centrally integrated pilot fuel injection for flame stabilisation have achieved 70 to 75% of NOx reduction at TRL 3 (demonstrated in high-pressure singlesector combustor test rigs) relative to the CAEP/2 standard. High combustion efficiency is mandatory and the engine cycle influence has to be considered.

• A technology deterioration factor, which describes the transition from TRL3 to TRL 6 (successful core engine testing), needs to be considered. It is likely that technological progress by the end of Framework 7 (from 2007 to 2013) will lead to approximately 60 to 65% NOx reduction rel. CAEP/2.

• It is most likely that in Framework 8 research initiatives will focus on further improvements towards 70 to 85% NOx reduction CAEP/2, representing another 50% relative to Framework 7.

• With regard to alternative fuels it can be emphasised that synthetic paraffinic Kerosines (Fischer-Tropsch) and blends with petroleum Kerosine are regarded as a viable alternative energy source. Emissions and operability can be affected. The first experimental result (2007) with one synthetic fuel and one lean burn system suggest that the entire physical and chemical combustion process of FT-Kerosine was not well understood and in-depth research was still required. The target set has been to define Kerosine properties (fuel-spec-design) for an alternative fuel for high thermal stability and for emissions reduction. Coordination with the global industries is required. In this field safety of supply and production costs are regarded as the decisive drivers.

- **WP2: Future Research & Technology Initiatives**

Future engine cycles are making the low NOx challenge more arduous.Lean burn system will meet the ACARE challenge and some sub-technologies still need further maturing and demonstration.

Empirical development is still central to delivering clean technologies. Need:
- High pressure combustion and rigs
- Optically accessible facilities for diagnostics
- Advanced laser diagnostics and instrumentation

Numerical methods are making substantial progress, reducing dependence on expensive testing and still has much more to deliver. Need:
- Accurate sprays modelling (primary break-up)
- Ignition and light around prediction capability.
- Thermo-acoustic models
- Coupled calculations – with stress codes, across component boundaries.

Alternative H/C Fuels
The latest European initiative launched end of 2008 is SWAFEA (DG-TREN).
Alternative Fuels are investigated in DREAM and α-BIRD (DG-RESEARCH).

Liquid hydrogen has been investigated by many organisations and is not considered viable due to the lack of sustainable sources, transportation, storage and distribution problems. Aircraft fuel tanks would need to be 4.2 times larger if a transfer from Kerosine to liquid hydrogen was sought. Alternate fuels have to be drop-in and their qualities have to represent those of Kerosine (DEF STAN 91-91).

- **WP3: Integration and Strengthening of the European Research Area**

Links have been established to the automotive sector (NoE ECO-Engines, IP RENEW), to CA AERONET III , NoE ECATS and to SWAFEA. Michel Cazalens SNECMA, Ralf von der Bank RRD and John Moran RRUK have become members of the Advisory Board of NoE ECATS.

Sigrun Matthes DLR, Coordinator of NoE ECATS, and Chris Wilson from the University of Sheffield, member of NoE ECATS, were attending ELECT-AE meetings. ELECT-AE supported a number of meetings of AERONET III. Stefan Donnerhack MTU presented IP VITAL to the 2nd RTD Workshop.

ELECT-AE attended the ACARE Strategic Research Agenda 2 event. A link to AERO-SME was established and the START New Member States brokerage event was supported. A brokerage meeting with the Universities of Gliwice/Gleiwitz and Budapest had been carried out.

ELECT-AE supported the work of the ICAO WG3 Task Group on Long Term Technology Goals and provided input. Ralf von der Bank RRD has become member of WG3 for this activity.

- **WP4: Dissemination, Information & Communication**

1st RTD Strategy Workshop, 8/9 March 2006, Bois du Lys near Villaroche, SNECMA
- Combustor technology
- CFD methods & design methodology
- Diagnostics & test rigs
- Design life prediction
- Alternative fuels

2nd RTD Strategy Workshop, 6/7 September 2007, Toulouse, ONERA & Turbomeca
- Review of 1st strategy workshop conclusions
- Advanced methods, combustion instabilities
- Sprays and alternative fuels
- Thermal management

3rd RTD Strategy Workshop, 24/25 September 2008, Hyères, La Londe Les Maures, Turbomeca
- Thermo-acoustic and combustion noise
- Components interaction and multi-physics
- Combustor and fuel injection system

Conference participation:

ISABE 2005 (Munich, 4-9 September 2005) DLR, RRD, TM
CER 2005 (Brussels, 14-15 November 2005)
AERODAYS 2006 (Vienna, 19-21 June 2006)
INTELLECT D.M. (R.v.d. Bank), MUSCLES (H. Brocklehurst), TLC (T. Noël), LOPOCOTEP (T. Noël), ELECT-AE (R.v.d. Bank), AEROTEST (I. Vallet) and ICLEAC (L. Hernandez)
ICAS 2006 (Hamburg, 3-8 September 2006)
CEAS / DGLR 2007 (Berlin, 10 -13 September 2007)
ECCOMAS 2008 (Venice, 30.06/4.07.2008) INTELLECT, TLC, TIMECOP, NEWAC, ELECT.

Press Releases:

Flight International Magazine mentioned ELECT-AE activities in three articles:
http://www.flightglobal.com/articles/2009/01/22/321328/consortium-urges-improvements-in-green-engine-research.html
http://www.flightglobal.com/articles/2008/10/23/317662/annular-combustion-is-key-to-green-aviation-say-experts.html
http://www.flightglobal.com/articles/2007/09/19/216862/european-industry-strategy-plans-for-emissions-results.html

Parliament Magazine published two advertorials in 2006 and 2007 about the workshop results.

International exhibitions:

Neither the EIMG nor the EC had a stand in one of the European major exhibitions (Paris Air Show, ILA Berlin, Farnborough International Air Show). Contributions to GIFAS centenary conference and the exhibit of the double head sector (RQL+LPP) from SIA TEAM (PARIS, 2008) were made.

- **Probing at Pressure - The European Infrastructure of Optically Accessible Research Combustors**

Optical sectors are the only means to get reliable information on flame position and combustion flow-field interaction at realistic conditions, but they also have deficits:
- Cooling
- Radiation losses
- Geometry: plenum feed, central outlet
- Pressure
- Multi-burner interaction
- Productivity

Therefore they need to be linked to CFD and more realistic tests!

Europe benefits from effective infrastructure, diversity, capacity and flexibility of test facilities:
- Routinely used in European research programmes
- Mostly complementary
- Need to be part of value generation chain with CFD and more realistic rigs
- Their efficiency also depends on quality of communication between the researchers using these tools (experiments and predictions)

- **Sustainable Way for Alternative Fuel and Energy in Aviation**

- Aircrafts / engines technical aspects: requirements, fuel properties, safety, …
- Aviation transportation aspects: operations, infrastructure, …
- Regulation: certification process
- Environmental impact: aircrafts emissions, life cycle, sustainability aspects
- Business case: economic feasibility, overall market situation, …

The Expected Output:

Roadmap for the introduction of alternative fuels from EU policy point of view:
- Policy measures: framework for fuel specification, incentives
- R&D priorities to be funded by EU
- Demonstration initiative (need to be evaluated and final scenario)

- **Workshop Results: Thermo-Acoustics & Combustion Noise**

New scientific challenges for labs when addressing the validation of simulation of combustion noise: time resolved temperature measurements are needed. Even if predicting the absolute noise level is difficult, predicting the relative noise level response to geometry changes is important. This means that understanding combustion noise processes remains a priority. Tools used in companies today are… far too simplified. Numerical methods: predicting combustion noise in confined flames is a totally new activity. Numerical tools developed for thermo-acoustics might be used but this remains to be demonstrated. Another priority is the control of combustion noise (it can be done with low frequency liners for example):

Possess tools: To predict combustion instabilities within the range of the operating conditions of the engine. At least be able to predict the variation of the noise level between two different combustion chambers.

Common objective: minimise tests to verify if a chamber is stable or noisy. Integrate this knowledge in the global design process of low NOx combustors to be able to optimize the balance between low noise and low emissions. Be able to account for azimuthal modes, which are specific to the gas turbine community and not studied elsewhere at the moment.

Byproduct: health monitoring from noise signature. Listening to the combustor to know how it behaves.

Understand combustion noise sources + propagation:
- Experimental setup(s) to study azimuthal modes (even at atmospheric pressure)
- At least one 360° rig (high pressure) to study noise
- New experimental techniques, which allow measuring entropy and acoustic waves in single but also in 360° combustors (difficult because of limited optical access)
- New numerical tools for sources AND propagation: these tools do not exist today. They can be based on LES and acoustic codes developed for thermo-acoustics but need extensions

Possible additional topic: understand the interaction between combustion and injector vibration. Identification of noise sources and to continue the studies of thermo-acoustics (injector vibration, azimuthal modes and optimisation):

- Existing CFD tools developed in the thermo-acoustics community to be tested for combustion noise
- Re-use existing burner developed in EC projects to validate tools in single burner configurations
- Introduce 360° burner studies on azimuthal modes, which have never been studied before.
- Establish links with High-Performance-Computing centers.

• **Workshop Results: Component Interaction and multi-physics**

Better understanding of the interactions:
• Experimental database on turbine – combustor interface
• Effective coupling between codes
• Validated numerical capabilities
Quantified benefits on cooling and efficiency
Multi-component cooling air optimisation (tools, methods)

Interaction Compressor-Combustor

- Reduced system pressure loss
- Tools for calculating water & hail boundary conditions
- Optimised flow field to the combustor (liner and injector feed)
- Compressor design optimized with combustor features
- In-homogenous flow at Combustor entry
- Acoustic impedance
- OGVs vs. fuel injectors (eg. wakes)
- Impact of wakes on diffusers and injectors
- Pressure loss OGV/combustor entry (diffuser length etc.)
- Water & hail ingestion
- Impact of combustor aerodynamics on compressor

Interaction Combustor-Turbine

- Combustor traverse (OTDF /combustor exit flow field)
- Effects of combustor unsteadiness on turbine HTC
- Impact on NGV cooling (hot streaks and film cooling air from liner)
- Transport of hot streaks within the turbine stages
- Acoustic impedance of NGV
- Secondary airflows & HP NGV cooling (pressure losses)
- Radiative HT on NGV

Multi-Physics

- Model for soot formation coupled with radiation (relative concentration)
- Improved models for predicting fuel preparation (unsteady behaviour & extended régimes)
- Better understanding of supercritical injection
- Coupling of fluid and stress (life prediction) codes
- Effects of varying fuel properties (including future fuels)
- Confidence on predicted emissions, temperatures, stability

- Coupling different fluid codes (RANS/LES, across interfaces)
- Flow and stress code coupling
- Radiation coupling
- Spray, chemistry, soot, NOx modeling capability
- Geometrical tolerance effects / robust design
- Validation for flame transfer functions (incl. adjacent component effects)

- **Future Initiatives: FP7 Fuel Injector Research for Sustainable Transport**

WP1. Fuel Spray Preparation
WP2. Soot Prediction in Complex Systems
WP3. Fuel Injector Development

Fuel Spray Preparation

Develop tools to predict the fuel injector exit boundary condition based upon geometry & flows. Investigate fundamentals of break-up physics in simplified and complex geometries. Develop phenomenological models to relate spray boundary conditions using analogous automotive approach.
Progress fundamental models to predict spray boundary conditions. Validate with high integrity diagnostics – lab scale and complex/industrial nozzles. Air assisted atomisation – prefilmers and jets in cross flow? Scaling laws eg. across different mass flows, pressure conditions, fuels? Able to interface with LES to deliver unsteady flux, velocity, concentration, drop size distributions.

- Fundamental studies - understanding of physical processes
- Improved modelling capability -Direct Interface Simulation: e.g. VOF, Level set
- Industrial fuel injector measurements and modelling
- Phenomenological models for boundary condition representation

Soot Prediction in Complex Systems

Advanced soot modelling for complex combustion systems. Improve the prediction of smoke production and consumption in combustors across range of conditions.

SIA TEAM continuation:
- Develop and deliver improved accuracy soot modelling capability using section or BIN approach.
- Complex industrial modelling predictions using developed sub-models.
- Validation against existing lab scale and industrial data plus some new experiments.

Fuel Injector Development

Exploit revised design rules for definition, design and manufacture of improved, productionisable lean injector technology. CFD prediction exploiting sub-models developed in MOLECULES, SIA

TEAM etc. Rig testing low TRL (low pressure) to high TRL (high pressure single sector). Investigating stabilisation mechanisms, fuel distribution, altitude-relight and emissions.

Lean Module Design and Make
- Design and manufacture of improved low NOx fuel injector
- Low TRL testing of novel low NOx fuel injector designs
- High TRL (high pressure, sector / full annular) testing of low NOx fuel injector
- Computational simulations of fuel injectors

Technical Themes to be studied
- Scaling laws
- Pilot to main interaction
- Combustion efficiency - NOx trade-off
- Smoke - NOx trade-off
- Noise sources and mode characterisation
- Optimising flame stability and weak extinction
- Relight (ignition, stabilisation, light across, light around)

• **Near Term: Future Initiatives:**

Improved design methodologies for low emission combustors based on capabilities derived within INTELLECT D.M. and other FP5-7 projects (parameterisation, modelling, optimisation, robustness analysis). Application and validation of preliminary design methodologies to achieve low NOx combustion systems with sufficient operability over entire operating range (ignition, lean blow-out etc.). Dedicated design studies to highlight trade-offs between rich burn and lean burn combustion systems.

KBE System Development
- further lean combustor system development
- integration of new design rules and models (radiation, effusion cooling, emission prediction etc.)
- integration of external aerodynamics
- optimisation in terms of NOx, soot and exit profile
- validation of KBE systems combustor methodology (detailed CFD analyses, experiments)

Robust design - off design point operation
- methods development
- effect of tolerances on performance, emissions, efficiency etc.

External aerodynamics
- improved dump gap and pre-diffuser design (e.g. taking into account the injector flow field)
- automatic mesh generation (parametric meshing, morphing etc.)
- modelling and CFD analyses (RANS/LES/DES CFD simulations & validation)
- applying improved optimisation techniques

Cooling development
- improved impingement cooling models
- investigation of new film cooling configurations
- development of an automated prelim. cooling design tool (CFD analysis, conjugate heat transfer modelling, development of correlations, tests of configurations and validation of models)

Lean burn injection system development (injector & combustor)
- improved fuel injector design: reduce (pilot) NOx emissions
- modelling and CFD simulation (ignition, relight, spray, improved soot and reduced chemistry)
- increasing combustion efficiency / reduced cooling air combustors
- consideration of alternative H/C fuels

List of publications

von der Bank, R. (presentation)
ELECT-AE - An Overview
START Brokerage Event, Riga, Latvia, 20 April 2005

von der Bank, R. (presentation)
European Research and Technology Strategy on Low Emissions Combustion in Aero-Engines for the 21st Century
ICAO, WG3, Task Group on Long Term Technology Goals Review Meeting 20 - 23 March 2006, Department of Trade and Industry, United Kingdom

von der Bank, R., Berat C., Cazalens M., Harding S. (presentation)
European Research and Technology Strategy on Low Emissions Combustion in Aero-Engines
Aeronautics Days 2006, 19-21 June 2006, Vienna, Austria

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Point of View, Parliament Magazine, p.56, iss 220, 20 March 2006, Brussels, Belgium

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European Low Emissions Combustion Technology in Aero-Engines
Workshop AERONET III, 24-25 January 2006, DLR-Office, Brussels, Belgium

von der Bank R., Berat B., Cazalens M., Harding S. (paper)
ORGANISATION OF EUROPEAN AERONAUTIC ULTRA-LOW NOX COMBUSTION RESEARCH
ICAS 2006, International Council of the Aeronautical Sciences, 03.-08.09.2006, Hamburg, Germany

von der Bank, R (presentation)
European Low Emissions Combustion Technology in Aero-Engines
Thematic Priorities for the Aero-Engine Industry (Combustion + Emissions)
FP7 Information day in Berlin-Brandenburg, Ernst & Young, Berlin Partner, VDI/VDE, ZAB Zukunftsagentur Brandenburg, 15 February 2007, Steigenberger Hotel, Berlin

Schavan, A. (Editor, EC publication)
Success Through Research – Germany's Contribution to European Research Projects
CORDIS Focus – Thematic Supplement, iss. 24, June 2007, EU Publications Office, Luxemburg

von der Bank R., Berat B., Cazalens M., Harding S. (paper)
STRATEGY FOR EVIRONMENTALLY FRIENDLY LOW EMISSIONS COMBUSTION DEVELOPMENT IN EUROPEAN AERONAUTICS
CEAS 2007 / DGLR 2007, 1st European Air and Space Conference, Deutscher Luft- und Raumfahrtkongress 2007, 10-14 September 2007, Berlin, Germany

Rob Coppinger (press article)
European industry strategy plans for emissions results - European project says synthetic fuels could be vital
Flight International Magazine, 19 September 2007

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Dissemination, Parliament Magazine, p.28, iss 255, 29 October 2007, Brussels, Belgium

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Simulation and Validation of Advanced Combustion Technology for Aero-Engines
8th World Congress on Computational Mechanics (WCCM8), 30 June – 5 July 2008, Venice, Italy
5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008)

Rob Coppinger (press article)
Annular combustion is key to green aviation say experts
Flight International Magazine, 23 October 2008

von der Bank, R. (presentation)
Technology Progress in Europe - An Overview
NOx Goals Review and Update
ICAO CAEP, Task Group on Long Term Technology Goals, 30-31 March 2009, London

von der Bank, R. (article)
ELECT-AE: Strategie für umweltfeundliche Triebwerke
FANPOST, Ausgabe 62, Mai/Juni 2009