INTERCOOLED RECUPERATED AERO ENGINE

S. Boggia, K. Rüd
Advanced Project Design,
MTU Aero Engines
München, Germany

1. ABSTRACT

The research on low emission aeronautical propulsion is encouraged by the ever increasing importance of environmental issues: restrictive legislation is being produced worldwide, and engine manufacturers are investing in research towards clean engines, with the goal of a substantial emissions reduction.

A technological innovation that can be extremely beneficial in terms of fuel consumption is the integration of heat exchangers into the aero engine cycle. NOx emissions and noise levels can also be reduced, thanks to different combustion chamber conditions and to a high bypass ratio configuration.

The paper focuses on the thermodynamic cycle and technological innovations necessary for the introduction of the new technology. An intercooler and a MTU-designed exhaust gas recuperator are applied to a 3-shaft, geared turbofan configuration. The engine is optimized for long range applications, with regard to fuel consumption. Two variants with different fan diameters and BPR values are proposed. Status results for the chosen configurations are presented, together with different parametric and optimization studies. Estimations of heat exchanger weight and of engine emissions are finally made.

2. NOMENCLATURE

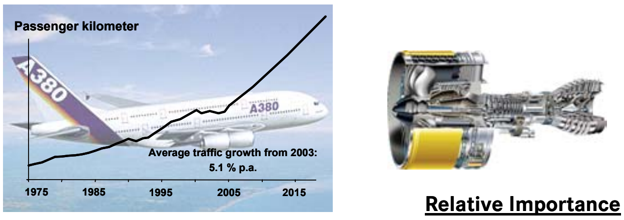
ACARE	Advisory Council of Aeronautical Research in Europe
ATE	Aerospace Technology Enterprise (U.S.)
BPR	Bypass ratio
C/A	Cooling air
CLEAN	Component Validator for Environmentally Friendly Aero Engine (EU)
D_{FAN}	Fan Diameter
EEFAE	Efficient Environmental Friendly Aero Engine
F_N	Net Thrust
HEX	Recuperator
HPC	High Pressure Compressor
I-C	Intercooler
IGV	Inlet Guide Vanes
IPC	Intermediate Pressure Compressor
LCF	Low Cycle Fatigue
OPR	Overall Pressure Ratio
RQL	Rich–Quench–Lean burner technology
SFC	Specific Fuel Consumption
TET	HPT Entry Temperature
ΔP	Pressure Loss
η_{IS}	Isentropic Efficiency
η_{POLY}	Polytropic Efficiency
HPT, LPT	High Pressure, Low Pressure Turbine

3. INTRODUCTION

During the last two decades air traffic has more than doubled, and despite recurring economic downturn cycles the growth trend will continue: the environmental impact of air traffic will therefore gain increasing importance. Government authorities and international political initiatives will further tighten noise and emission regulations for air traffic vehicles. This trend will result in higher noise and emission fees for airlines and customers or even cause flight restrictions: in the end, it may hinder the growth of the aero industry as a whole.

The environmental issues will be in addition to the general demand for more affordable and economic engines, as economics will continue to dominate future aero engine design. Environmental technologies will therefore experience a strong challenge from aggressive cost targets as dictated by the market.

Figure 1 reflects current aero engine industries perception of key buying factors for future engine development. The ranking of the development requirements is in line with the above mentioned customers and regulatory needs. It confirms the extreme importance of traditional design criteria like flight safety and costs; it stresses the increasing importance of environmental criteria such as fuel consumption, NOx emissions and in particular noise.



	Relative Importance
Safety/Reliability	**very high**
Environment	
• **Fuel Burn**	**high**
• **Emissions**	**increasing**
• **Noise**	**strongly increasing**
Affordability/Costs&Price	**very high**

Figure 1: Key customer requirements

From this background, today's aero engine industry is compelled to rearrange its development priorities and to define the appropriate strategies for the future, which is an extremely challenging task in a financially highly stressed business. The fundamental objective is the matching of safety requirements and of economic constraints with future environmental needs, in order to keep the engine development on a competitive path.

4. THE IRA ENGINE STUDY AT MTU

In the context of different programs, among which the EU-funded CLEAN Program (5th Framework Program), MTU is carrying out studies to include heat exchangers in a novel concept aero engine, dubbed IRA: Intercooled Recuperative Aero Engine.

The present paper discusses a detailed study of an advanced high by-pass ratio 3-shaft geared turbofan, with integrated intercooler and recuperator, as shown in Figure 2. The introduction of these additional components makes it possible to recover heat from the hot exhausts to the combustion chamber, and to decrease the burner temperature rise; the fuel consumption is therefore reduced.

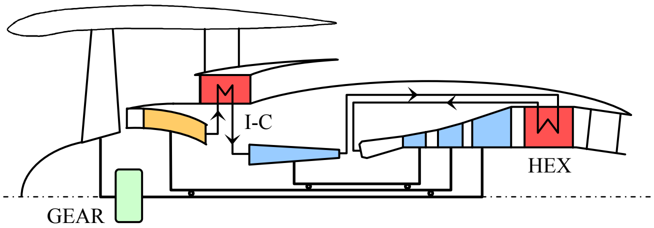


Figure 2: Engine concept

A high temperature level at cruise, necessary to enhance the effect of the recuperator, is obtained by means of variable geometry in the turbine system. The simultaneous use of the intercooler allows the achievement of the required overall pressure ratio with a relatively low compressor exit temperature. Inter-cooling without heat recovery is on the contrary not attractive from a fuel consumption point of view.

The proposed engine configuration is described in detail in section 6, while section 7 describes the results of the study, in terms of fuel consumption, NOx emissions, and additional weight. The paper focuses on the performance and on the thermodynamic cycle analysis of the proposed engine concept, with particular emphasis on cycle optimization, on emissions and on SFC reduction estimates.

The engine is envisioned for long range applications, in which the considerable fuel savings at cruise conditions maximize their effect on the overall aircraft economic balance; the thrust-class is 45 klbf. Two alternative versions of the engine have been considered and optimized, corresponding to different fan diameters; a mechanical design layout is proposed, which overcomes several constructive challenges in the integration of the additional components.

	M.Cl.	Avg.Cr.	T/O	Rot.
Altitude	35000 ft	35000 ft	SL	SL
Mach No.	0.82	0.82	0.00	0.25
Δ ISA	+10 K	ISA	+15 K	+15 K
Net Thrust	9.5 klbf	7.1 klbf	45 klbf	36 klbf

Table 1: Design and off-design conditions

The selected configurations (D_{FAN} = 92in and D_{FAN} = 109.9in) have been simulated at different operating points with MTU-developed gas turbine performance modeling software; design point is Max Climb, chosen for iteration convergence reasons. Ambient and engine conditions for relevant operating points are presented in Table 1 (*"Max Climb"*, *"Average Cruise"*, "*Take Off*" and *"Rotation"*).

5. FUNDAMENTALS - CYCLE INNOVATIONS

Current trends in engine development drive towards an ever increasing level of economic efficiency. For a given engine, this can be represented by specific fuel consumption improvements. It can be shown that for turbofan engines SFC is inversely proportional to overall efficiency, as in equation (1):

$$\frac{1}{SFC} \approx \eta_{OV} = \eta_{CORE} \cdot \eta_{PROP} \quad (1)$$

Fuel consumption reductions can be traced back to an improvement of the core efficiency η_{CORE} and of the propulsive efficiency η_{PROP}.

Core efficiency is an indication of the quality of the thermodynamic cycle, indicating the efficiency with which the core power necessary to produce propulsive thrust is generated. An efficiency increase can be obtained from either more advanced component technology (isentropic efficiencies for turbomachinery and pressure losses for ducts), or a change in cycle characteristics (higher TET, OPR) or a different overall thermodynamic cycle; an example for this third case is the introduction of unconventional components, such as the intercooler and the recuperator used for this study. Measures to increase the core efficiency are addressed in sections 5.1 and 5.2.

Propulsive efficiency in turbofan engines measures the efficiency with which the available core power is translated into aircraft propulsion power. Propulsion efficiency is maximized when jet velocity nears flight velocity, e.g. by increasing the BPR and the fan diameter (lower specific thrust). Very high BPR values can be obtained only through the so-called "geared" configuration, in which a reduction gearbox is located between the low-speed fan and the high-speed booster. For this reasons a gearbox has been introduced in the IRA model, as described in sections 5.3 and 6.

5.1. Recuperated cycle

The critical cycle modification in the IRA engine is the presence of heat exchanger modules in the hot exhausts, with the purpose of bringing back thermal energy from engine exit to combustion chamber. Given a fixed TET, this concept allows fuel savings, because part of the required burner temperature rise is provided by the exhausts, which are discharged at a lower temperature. In order for the heat exchange process to be effective, there must be a sufficient temperature difference between compressor exit and turbine exit temperature at all operating points. A low HPC exit temperature can be obtained with the use of inter-cooling, as can be clearly seen in Figure 3. A high turbine exit temperature at different operating points can be obtained with a variable geometry turbine system (section 5.4)

5.2. Intercooled and recuperated cycle

The combined effect of the two heat-exchange processes maximizes the heat transfer in the recuperator, therefore improving the efficiency benefit. Figure 3 shows the thermodynamic cycle for the selected IRA cycle in the h-S plane for OPR = 30 and T41 = 1800K. The chart illustrates that the amount of recuperated heat can be substantially increased by using the intercooler: the dotted line shows the compression process without inter-cooling.

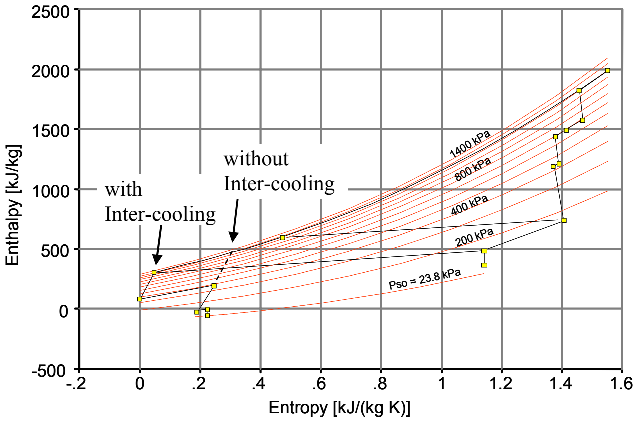


Figure 3: Engine cycle in h-S diagram

The effect of the different cycle innovations is shown in Figure 4, where the core efficiency is calculated for different but consistent cycles (consistent technology level and same simulation tool). A considerable improvement in the performance of the recuperated engine can be achieved by adding the inter-cooling module, despite the detrimental effect of additional pressure losses.

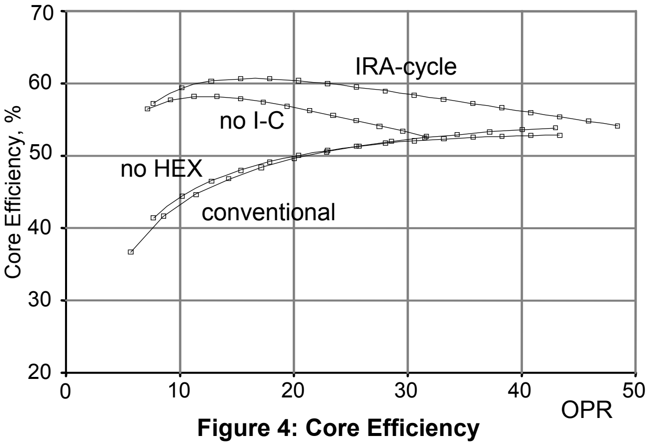


Figure 4: Core Efficiency

The figure also confirms that in comparison to conventional engines IRA cycles offer higher efficiencies with lower OPR values, as this is a prerequisite for a high heat exchange level. The low OPR also offers other advantages, such as a lower NOx emission level and a weight reduction in the core turbomachinery.

5.3. Geared Turbofan

The benefit in propulsion efficiency resulting from high BPR values suggests a fan diameter increase. However, for conventional turbofan configurations the maximum gain in propulsive efficiency will be limited: with BPR values beyond 10 or 11 the engine will suffer from an increasing stage-count in the low pressure system: the increasing fan diameter implies lower pressure ratios and lower rotor speeds; this must be counteracted by increasing the stage count for LPC and LPT to retain acceptable efficiencies for these components. In addition, the increasing torque associated with the reduced LP shaft speed requires bigger shaft diameters.

A solution can be found by introducing an additional reduction gearbox between the fan and the remaining components in the low pressure system (booster, shaft and turbine).

The reduction gear allows both fan and low pressure system to run at their optimum speeds. The fan speed can be selected as low as required to achieve maximum efficiency and minimum fan noise. On the other hand, the LP shaft speed can be higher and therefore allow a considerable reduction of LPC and LPT stages. Both low pressure system and engine core are more compact, with benefits for costs and weight. A further advantage is the LPT tonal noise being shifted into higher frequencies: a significant engine noise reduction is the outcome, especially during approach and landing.

Figure 5 schematically illustrates the benefits from the GTF configuration: fan noise reduction and lower stage-count for the high-speed components. The adoption of a high BPR GTF configuration can have a significant influence on fan noise, which is approximately varying with the 4th power of fan speed, and on jet noise, which decreases with lower jet velocities. Furthermore, the high speed booster and LPT show better efficiencies and a significantly lower stage-count.

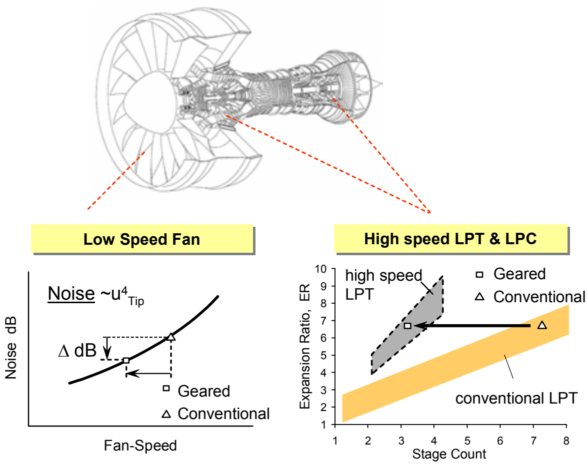


Figure 5: The Geared Turbofan concept

Since more than 15 years, Pratt and Whitney America, Pratt & Whitney Canada, Avio and MTU Aero Engines are jointly working on the development of geared turbofan engine technologies for small and large thrust class applications. In 1992 the partners successfully run the *Advanced Ducted Propfan* (ADP) demonstrator engine for bypass ratios up to 14, to demonstrate the technology for fuel efficient long range applications. More recently they introduced the *Advanced Technology Fan Integrator* (ATFI) representative of smaller thrust class engines (reference [7]). In addition to demonstrating superior fuel efficiency this engine was used to show the advantages in terms of noise and costs.

5.4. Variable Geometry

One of the necessary requirements for a performance optimized IRA configuration is a high heat exchange level in the recuperator modules. This is in turn depending on a sufficiently high temperature at LPT outlet. Given that the temperature drop in the turbine system is determined by the necessary compression power, a high LPT exit temperature can be guaranteed only by a high turbine inlet temperature. While the burner temperature level is sufficient at T/O conditions, it may become too low particularly during cruise, which is however the economically most important operating point for long-range applications. A conventional turbine design results in cruise turbine entry temperatures usually 300K – 400K lower than the corresponding T/O values. In such a case, the temperature deficit at cruise would not allow a recuperated configuration.

The solution has been provided by a variable geometry LP turbine design. The inlet guide vane nozzle area is varied for every operating point, in order to keep the HPT inlet temperature as constant as possible: a value of 1750K has been chosen for most flight conditions, with 1800K selected for hot day Rotation and hot day Max Climb. Figure 6 shows for selected operating points the temperature values at significant engine stations: HPT inlet, LPT inlet, and recuperator matrix inlet.

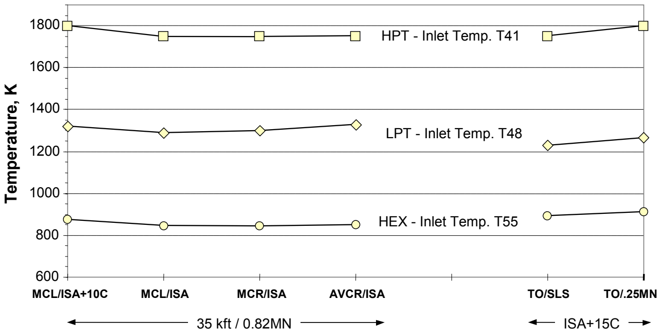


Figure 6: Temperature profiles

Figure 7 shows for the same operating points the required IGV settings. Taken the design point “Max Climb” as basis, nozzles must be closed (up to 20%) for cruise conditions, or opened (up to 24%) for T/O conditions. The range between the two positions is extremely wide, and poses with no doubt a serious constructive challenge. Moreover, the additional constructive complexity of the turbine system will add to the high manufacturing and operating costs of the engine.

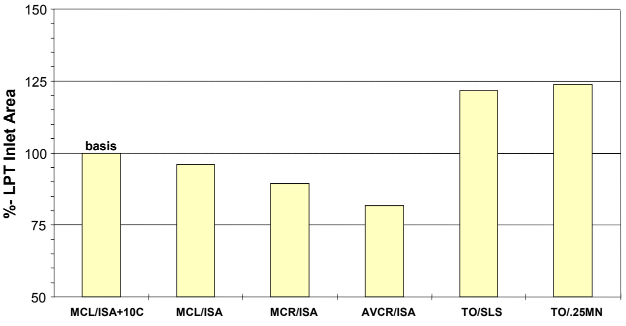


Figure 7: LPT-IGV settings

A secondary outcome of the variable geometry design is that the flat temperature profiles for different operating points may reduce the thermal fatigue to which turbines, piping system and heat exchanger modules are exposed. The corresponding chart for a conventional turbine design would present far greater temperature differences for every T/O – cruise – landing cycle. However, an opposite influence would come from the high temperature level, with a resulting creep effect. Recuperator life has been investigated with experimental and analytical means in the AEROHEX study (see section 8.2).

6. THE IRA - ENGINE CONFIGURATION

The specific configuration chosen for the IRA Engine study is an advanced high bypass ratio, 3-shaft geared turbofan. The primary components of the engine have been shown schematically in Figure 2, and are here summarized:

- advanced technology fan
- reduction gearbox on the LP-shaft
- axial-radial IPC
- flat plate intercooler
- radial HPC
- combustion chamber
- variable geometry turbine system
- exhaust heat exchanger and piping system
- three-nozzle system

The component characteristics (efficiencies, pressure losses, maps) are derived from experience and from MTU technology forecasts for the year 2020. Relevant cycle parameters for the two optimized variants are shown in Table 2.

6.1. Mechanical Design

A general arrangement for the 92in fan diameter configuration is presented in Figure 8. The challenge included finding feasible solutions for the arrangement of the additional components: especially the layout of the recuperator modules and of the piping system, because of the limited available space in the exhaust section.

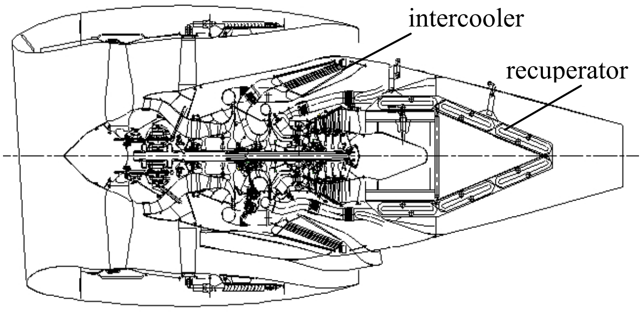


Figure 8: General Arrangement (92in configuration)

The cold flow for the intercooler is extracted from the bypass flow, by means of an additional flow-splitter in the bypass stream. The intercooler itself features a single passage, counter-flow arrangement providing the compressor air with a temperature drop of approximately 100K. The cooling flow is accelerated and discharged by a third additional nozzle; the higher exit temperature of the cooling flow results in a higher exhaust velocity, which helps compensating the pressure losses due to the additional components.

The arrangement of the cooling flow path can be seen in Figure 9, where the scoop inlet, the duct to the inter-cooling module, the heat exchanger matrix and the following additional nozzle are detailed. A total of eight intercooler modules are provided, tightly arranged around the core components.

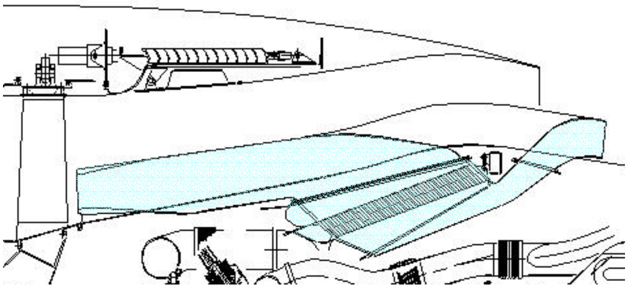


Figure 9: Intercooler and ducts

The recuperator is located in the hot exhausts area; a system of collectors, splitters and tubes delivers the compressed air to the heat exchanger modules and afterwards returns it to the combustion chamber inlet, as will be shown in Figure 19; a view of the installed configuration is presented in Figure 10.

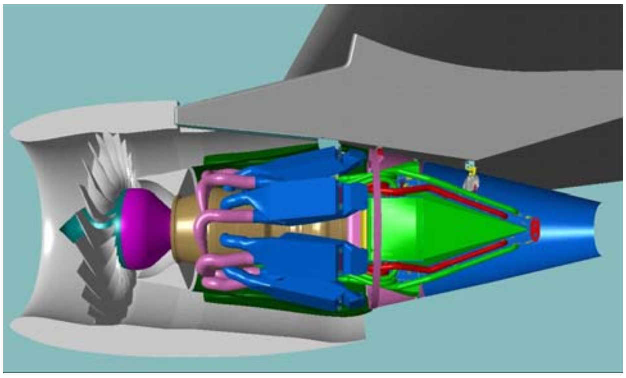


Figure 10: On-wing Installation (92in configuration)

The temperature rise for the HPC exit air is about 200K. The recuperator is made up of eight cross-counter-flow modules; the profile-tube design, developed by MTU, is for high-temperature levels remarkably superior to other configurations. The installation offers a robust design against vibrations and thermo-mechanical shock loads.

6.2. The MTU profile-tube heat exchanger

An airworthy heat exchanger design is the prerequisite for the realization of the IRA engine concept. The construction must take into consideration the many technical challenges posed by the harsh environment of the hot exhausts: the modules are subject to a maximum temperature in excess of 900K, and go through major thermal cycles. Important requirements are therefore unrestricted thermal expansion, good resistance to thermal fatigue and to corrosion. A proved, existing solution is the MTU-patented profiled heat-exchanger shown in Figure 17, developed for and successfully integrated into recuperated tank gas turbine engines, where it proved to sustain high thermal and mechanical loads. The profile tube heat exchanger combines benefits from high heat transfer effectiveness with minimum aerodynamic pressure losses.

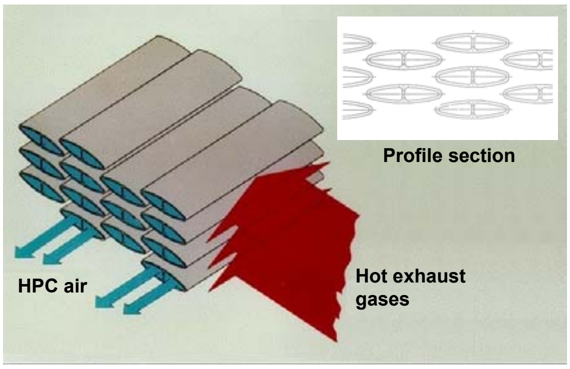


Figure 11: MTU profile tube heat exchanger

The heat exchanger matrix structure, featuring a cross counter flow design, is illustrated in Figure 11: the HPC exit air is delivered by means of pipes and manifolds to the profiled tubes, while the hot gases flow in the spaces left among them. The elliptical shape of the tubes increases the available exchange surface while offering low pressure losses through the exhaust path. The optimization of the heat exchanger has been the focus of the European “AEROHEX” study (section 8.2).

7. RESULTS AND THERMODYNAMIC ANALYSES

The cycles selected for this study are the result of predesign concept studies and optimization analyses (see references [1] and [2]), in which several cycle parameter have been taken into consideration: BPR, OPR, temperature levels, component characteristics. Main constrains for this preliminary phase were the need to maximize the fuel consumption benefit on the conventional configuration, and the requirement for a low NOx and low noise engine, as will be shown in sections 7.1 to 7.4.

7.1. Selected cycles

Table 2 summarizes significant engine data for the two selected cycles. The SFC value is compared to a reference turbofan engine (conventional turbofan, BPR = 5, 1995 technology status).

D_{FAN}	92 in	109.9 in
F_N @ T/O	45 klb	45 klb
F_N @ M.Cl.	9.5 klb	9.5 klb
F_N @ Avg.Cr.	7.1 klb	7.1 klb
BPR @ Avg.Cr.	17.1	26.5
Core Size @ M.Cl.	3.20 kg	2.99 kg
Gear Ratio	3.1	4.3
OPR @ M.Cl.	30.0	30.0
T4 @ M.Cl.	1943K	1944K
T4 @ Cruise	1899K	1899K
T41 @ M.Cl.	1800 K	1800 K
SFC@ Avg.Cr. [lb/h/lb]	0.509	0.493
ΔSFC vs. reference @ Avg.Cr.	-16.0 %	-18.7 %

Table 2: Cycle characteristics

An OPR value of 30 and a TET limit of 1800K have been chosen for both engine versions at design conditions. The "Core Size" parameter shown in the table is calculated from HPC inlet mass-flow corrected with HPC exit conditions, as specified in equation (2). It is approximately proportional to HPC exit area and can therefore be assumed as a rough indication of the core dimensions.

$$(2) \quad CoreSize = W_{25} \cdot \frac{\sqrt{T_3 / T_{STD}}}{P_3 / P_{STD}}$$

Due to the inherently low OPR and high TET of the IRA concept, the engine needs less core mass flow than a conventional engine, which drives the BPR beyond 25 even though the fan diameters are within an usual range. The gear ratio values have been determined in order to optimize both the LPT rotational speed and the fan tip corrected speed, to achieve maximum efficiencies in both components.

The overall result, exceeding 18% SFC reduction on the 1995-technology reference engine, is well in agreement with long-term goals and would result in approximately an 8% advantage on a same technology level GTF engine.

7.2. NOx emissions

A NOx emission assessment has been carried out for the 109.9in configuration. Burner inlet conditions have been used to calculate the ICAO-NOx parameter, shown in Figure 12 together with data relative to existing modern engines. The resulting value of 29.2 g/kN offers a 60% reduction on ICAO-96 requirements; this can be explained in terms of lower fuel consumption and of different combustion chamber inlet conditions, particularly as the burner inlet pressure is lower than in conventional engines. For the calculation a "first-generation" type of RQL-technology was assumed; a potential further reduction up to 80% could be achieved with fully advanced RQL-technology.

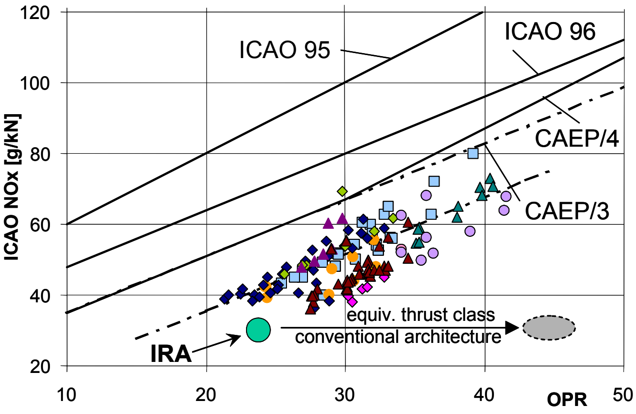


Figure 12: NOx assessment

A low NOx emission level is a result of great importance for an engine that balances mechanical complexity and more expensive advanced components with fuel savings and with environmental improvements. As indicated in Figure 12, an engine in the same thrust class, but with a conventional architecture is designed at a significantly higher OPR. An application based NOx-assessment would therefore result in a higher margin of the IRA engine to the ICAO-96 limits.

7.3. Recuperator weight

Particularly important for aeronautical applications is the effect of the IRA concept on engine weight. The additional components add to the overall engine weight: the intercooler and relative ducts, the additional third nozzle, and especially the recuperator and the piping system between HPC exit and recuperator modules. Preliminary weight estimations for the recuperator and its accessories have been carried out in the context of the AEROHEX study, using the geometrical arrangement of the 92in configuration as pictured in Figure 19. The total weight of the exhaust system is approximately 1000 kg per engine. Partial compensation of the additional weight can derive from the limited core size of the IRA configuration and from the low core turbomachinery stage count, reduced due to the low OPR. The high total weight of the heat exchanger system is a challenge for an aeronautical application and leaves room for improvement and for an optimization of the arrangement.

7.4. Parametric and optimization studies

The following sections offer an overview on some of the cycle analyses carried out in the context of the IRA engine study. Some of the parametric studies were useful to identify the design area for the optimization, to propose further cycle improvements, or to create the basis for further analyses (as is the case of the trade factor study).

7.4.1. Effect of T4, BPR

Figure 13 shows the effect of basic engine parameters on engine performance and size. Calculations are made for design point conditions (Max Climb).

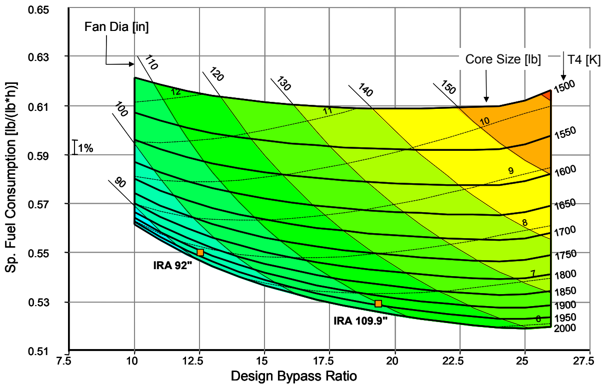


Figure 13: Parametric study (T4 and BPR effect) (@ Max Climb)

Parameters varied in the simulation were burner temperature and BPR (OPR = 30 constant). To avoid unreasonably large fan diameters, the Max Climb BPR has been limited to a value of 26. Engine net thrust is kept constant by iterating the engine total inlet mass flow as necessary, while SFC is shown on the vertical axis as performance indicator. Engine size (fan diameter and core size) is shown in the plot by a carpet of dotted lines.

As can be seen in the chart, the two selected cycles are a compromise between design goals (lowest possible SFC and core size) and design constraints (over maximal temperature and maximum fan diameter). A further improvement in fuel consumption or in core size could only be achieved at the cost of significantly higher temperatures or larger fan diameter. Figure 13 also shows that better SFC values can be reached with higher burner exit temperatures; this can be explained with the higher heat exchange level achieved when the temperature difference in the exhaust heat exchanger is increased. However, gains get smaller with increasing temperatures.

7.4.2. Effect of OPR

Figure 14 shows the effect of OPR variation for a range of different BPR values and different fan diameters. As a consequence of the analysis of Figure 13, the combustion temperature has been kept constant (1943K at design point). The IPC and HPC pressure ratios are adjusted in order to maintain the worksplit between the two compressors at an optimized value. A significant result of the simulation is that an increase toward higher OPR does not bring further relevant SFC improvements.

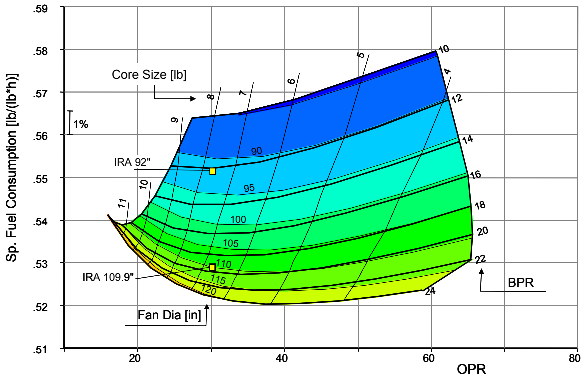


Figure 14: Parametric study (OPR and BPR effect) (@ Max Climb)

The design point chosen value of 30 therefore limits the mechanical complexity and the weight of the axial-radial components while achieving a near-optimum SFC result. The reduction in core size which is observed at higher OPR values is due to the lower total engine inlet mass flow necessary to achieve the required constant thrust.

7.4.3. Effect of worksplit IPC / HPC

Given a fixed selected OPR an important setting for the engine configuration is the worksplit between the compressors: due to the presence of the intercooler this setting acquires in IRA engines a far greater influence on the overall cycle than in conventional configurations. The optimization could be carried out with the goal of minimizing SFC; however, as can be seen in Figure 15, only minor variations can be achieved at cruise conditions for a wide range of worksplit settings. All engine settings except worksplit are constant in the analysis. More meaningful is the possible balance between fuel consumption and component size reductions, resulting from an increased IPC loading.

The parameter shown on the x axis represents the worksplit and is calculated as in equation (3):

$$X = \frac{IPC\ Specific\ Work}{HPC\ Specific\ Work} \qquad (3)$$

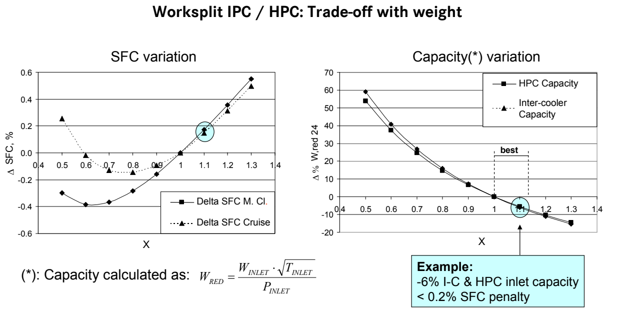


Figure 15: IPC-HPC worksplit

The trade-off example highlighted in Figure 15 simulates a 10% increase in the IPC loading (X= 1.1); this would only result in a 0.2% SFC penalty at cruise, while reducing the inter-cooling and the HPC inlet capacity by approximately 6%.

7.4.4. Best / Worst / Ideal cases

A study with best-, worst- and ideal-case characteristics for the heat exchange modules and the piping system has been carried out for the 109.9in configuration. The component properties taken into consideration were pressure losses and effectiveness for both intercooler and recuperator. A reasonable range has been chosen for each property: for example a 3% to 6% range has been adopted for the recuperator matrix hot-side pressure loss (for which the value used in the final cycle is 4%). Finally, an "ideal" case has been evaluated, in which pressure losses are neglected and heat exchanger module effectiveness is set to 100%.

This "theoretic" ideal heat exchange process would imply a 9% SFC gain against real component conditions; the SFC differences of the best/worst scenarios are in the range +/- 3% percentage points against the results presented in section 7.1. These values, given the relatively narrow range, can be used to confirm the overall result of the thermodynamic analysis.

7.4.5. "Hot cooling bleeds"

One further cycle improvement, here not presented in detail, is the use of "hot" cooling air for the HPT, i.e. bled at a higher temperature after the passage in the recuperator; in the current IRA configuration the cooling air for the turbine system is taken directly after HPC exit. Such a modification, according to a preliminary investigation, would imply an increase in HPT stator cooling air requirements (+2% C/A) but would recuperate more energy from the exhausts to the combustion chamber. The overall result of the modification is an additional SFC improvement of about 2.4%, which would bring the overall SFC-benefit over 20% vs. the conventional 1995 turbofan. On the other hand, the dimensions of the recuperator and of the piping system should be increased to include the additional C/A flow.

7.4.6. Trade Factors

The relative effect of the technology level on overall engine performance (measured in terms of SFC variation) has been calculated for each engine component. The resulting trade factors are useful for future optimizations and trade-off studies, as for example could be variations in component configuration or technology level to achieve weight reductions. A variation of one percentage point for each component characteristic has been assumed, as shown in Table 3. Each characteristic is varied singularly.

Component Characteristic	Assumed Change	ΔSFC (%)
1. Fan OD η_{IS} Fan ID η_{IS}	- 1 % - 1 %	+ 0.65 + 0.08
2. Gearbox efficiency	- 1 %	+ 0.82
3. LPC η_{POLY}	- 1 %	+ 0.47
4. Intercooler η ΔP cold flow (%) ΔP hot flow (%)	- 1 % + 1 % + 1 %	+ 0.07 + 0.12 + 0.24
5. HPC η_{POLY}	- 1 %	+ 0.36
6. HPT η_{IS} C/A stator (%W29) C/A rotor (%W29)	- 1 % + 1 % + 1 %	+ 0.16 + 0.19 + 0.47
7. IPT η_{IS} C/A stator (%W29) C/A rotor (%W29)	- 1 % + 1 % + 1 %	+ 0.18 + 0.47 +0.55
8. LPT η_{IS}	- 1 %	+ 0.57
9. Recuperator η ΔP cold flow (%) ΔP hot flow (%)	- 1 % + 1 % + 1 %	+ 0.16 + 0.27 + 0.27

Table 3: Trade factors for SFC

The results indicate that the efficiencies of the low-spool components, such as fan, gear and LPT, play a dominant role, as can be expected from a very high BPR engine. The exhaust gas recuperator has a relatively small influence on overall engine SFC, whereby the pressure loss in the recuperator is of greater importance than the heat exchanger effectiveness.

8. TECHNOLOGY PROGRAMS

The IRA engine study is part of a MTU long-term strategy for the development of a "green engine" and is supported by the EU. In order to prepare the technology path to this goal, the company is involved in international research programs focusing on the development and on the experimental testing of advanced concept engines and on the integration of heat exchangers into aero engines. The following sections briefly describe the two EU programs "CLEAN" and "AEROHEX".

8.1. CLEAN

The "Clean" technology demonstrator is part of the EEFAE technology platform in which major European aero engine manufacturers are participating, in the context of the EU 5th Framework Program.

Technologies required for geared turbofan engines and, in the long term, for recuperated aero engines are tested under the program, which aims at improving the environmental impact of future aero engines. One goal is the reduction of fuel consumption, and of CO_2 emissions, by as much as 20%. Also being investigated are novel combustor concepts for NO_X reductions up to 80%. The demonstrator (shown in Figure 16) combines advanced core technology testing with the demonstration of high temperature turbine and exhaust section technologies typical to IRA type engines. The demonstrator consists of:

- An advanced core engine (Snecma and Avio)
- A highly loaded high-speed LPT (MTU and Volvo)
- An exhaust duct profile-tube heat exchanger (MTU)

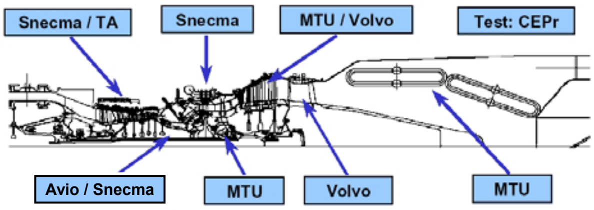


Figure 16: CLEAN-Engine and Partners

The high core inlet air is supplied by the test facility's own compressor system at the appropriate pressure level, while the power generated by the high-speed LPT is dissipated by a water brake. The technology demonstrator will make its first run in September 2004, using the altitude test facilities at the University of Stuttgart. Partners for the demonstrator are Snecma Moteurs, Volvo Aero, Avio and MTU.

8.2. AEROHEX

The heat exchanger technology program AEROHEX, also supported by the EU 5th Framework Program, is running parallel to the CLEAN program. It focuses on the heat exchanger segment development and on manufacturing processes. The project addresses the design optimization of the heat exchanger matrix arrangement as well. Figure 17 shows the compact arrangement of the profile tube heat exchanger, as described in section 6.2.

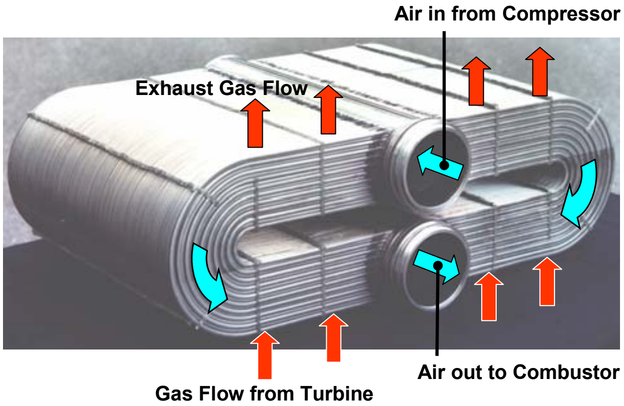


Figure 17: Recuperator matrix

Three main study areas ("Work Packages") are included in the project:

- Recuperator Design
- Flow Investigations
- Manufacturing Methods

Particularly interesting themes are studied within the first work package, for example the optimum recuperator lay-out, thermal and structural analysis, life analysis. For life cycle study purposes a heat exchanger matrix specimen has been built and LCF tests have been carried out. For the same purpose a finite element model of the specimen has been created, as shown in Figure 18.

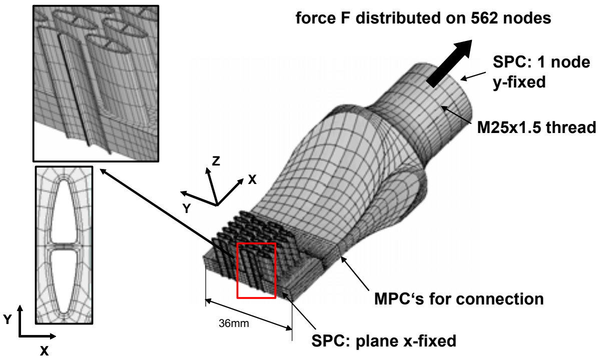


Figure 18: AEROHEX, model of LCF specimen

The second work package investigates the flow behavior in the hot exhaust area, with both experimental tests and CFD analyses; the goal is the development of recuperator and piping arrangements for an optimized configuration. One arrangement, used for the IRA Engine construction detailed in section 6.1, is shown in Figure 19.

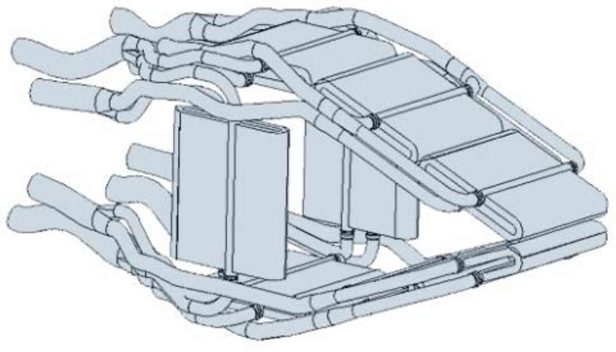
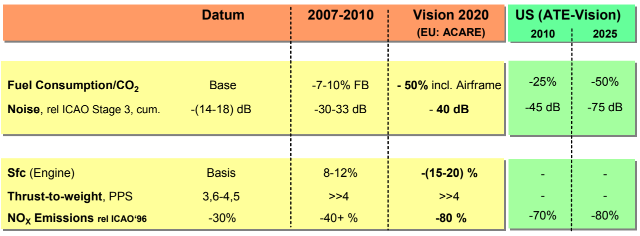


Figure 19: Recuperator Layout

Other themes considered in the “Manufacturing Methods” work package are mainly concerned with production costs reduction measures.

9. FUTURE PERSPECTIVES

Future targets and environmental design constraints can be specified into short- to mid-term customer needs and long-term visions, as projected for example by European and US aerospace organizations such as ACARE and ATE. Figure 20 quantifies future targets for fuel consumption, noise and NOx emissions. In the mid-term scenario (2007-2010) fuel burn and CO_2 emissions will have to be reduced by up to 10% (EU) and up to 25% (US).



	Datum	2007-2010	Vision 2020 (EU: ACARE)	US (ATE-Vision) 2010	 2025
Fuel Consumption/CO_2	Base	-7-10% FB	**- 50%** incl. Airframe	-25%	-50%
Noise, rel ICAO Stage 3, cum.	-(14-18) dB	-30-33 dB	**- 40 dB**	-45 dB	-75 dB
Sfc (Engine)	Basis	8-12%	**-(15-20) %**	-	-
Thrust-to-weight, PPS	3,6-4,5	>>4	>>4	-	-
NO_X Emissions rel ICAO‘96	-30%	-40+ %	**-80 %**	-70%	-80%

Figure 20: Mid- and long-term requirements

Noise is expected to be strongly reduced by more than 15 dB (cumulative) relative to current standards, which is roughly equivalent to –5 db for each ICAO noise measurement point (takeoff, sideline, approach). This requirement should be achievable on the basis of mainly existing technologies. On a long-term basis the requirements are significantly increased, particularly concerning fuel burn, with a 50% target reduction; 15% to 20% of this value should be contributed by the propulsion system itself; the remainder will be provided by improved aircraft configurations and air traffic management. Stronger constraints will be imposed by reducing NOx and noise emissions. Since such visions are far beyond the improvement capabilities of existing designs, they are anticipated to challenge new and unconventional technologies.

Figure 21 highlights the anticipated benefits from the new engine concepts relative to a 1995 technology status turbofan. For conventional turbofan architectures only moderate gains in fuel burn are envisioned, since the remaining possible BPR increase will be limited. Noticeable improvements in noise and emissions will be achieved with more advanced component technologies and with the use of advanced noise reduction systems.

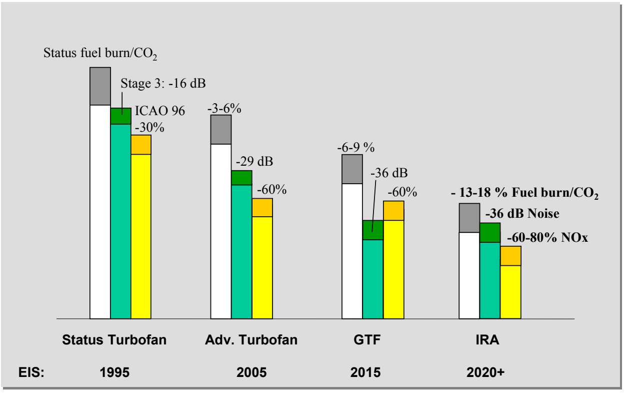


Figure 21: Projected benefits, new engine concepts

The introduction of the geared turbofan configuration may double the improvements concerning fuel burn and noise, thanks to BPR values beyond 12 or 13. Further benefits derive from the IRA engine concept, as highlighted in the previous sections. The significant reduction in NOx emissions is envisioned due to advanced combustion technologies, to fuel burn improvements and to the low OPR value. The benefits in noise and emission levels may contribute to reducing landing fees and to increasing operational flexibility, therefore improving aircraft operating costs.

The IRA concept complies with the long term engine requirements beyond 2020, as discussed in Figure 20. By that date, demonstrator programs will have prepared technologies for both the GTF and IRA configurations.

10. SUMMARY AND CONCLUSIONS

The use of inter-cooling and heat recuperation in aero gas turbine engines has been studied in order to investigate the potential for emission and fuel consumption reductions. After a preliminary cycle study and an optimization process, a mechanical arrangement has been produced for the integration of the advanced components into the engine (gearbox, intercooler, recuperator). The main goal of the cycle analysis has been the optimization of various engine parameters: maximum cycle temperature, OPR and fan diameter, BPR, position of inter-cooling. Different, innovative configurations have been explored, and the potential for further performance gains has been identified: the use of heated C/A bleeds for turbine cooling has shown for example a prospective 2% further reduction in SFC.

Parallel analyses have been carried out on the heat exchanger modules, the piping system and the combustion system, in order to provide a reliable estimate of the pressure losses and of the heat exchanger effectiveness to be used in the cycle simulation. Assessments of NOX emissions and of recuperator weight have been carried out to complete the study.

The comparison between the final IRA concept and the reference, 1995-technology turbofan showed a SFC reduction of 18.7%. NOx emissions would be about 60% lower than the corresponding ICAO-96 limit, with potential for further reductions towards -80% thanks to novel combustor technologies. The comparison with a 2015-status GTF engine has shown an improvement in SFC of about 8%.

To counter-balance these benefits, there are increased complexity in the engine construction, additional expensive components and additional reliability and life issues associated with the high temperature loads and the new heat exchanger modules. Any additional component contributes to the increased total engine weight, while high-technology modules (especially the two heat exchangers and the variable geometry turbine system) would contribute to a general increase of manufacturing and maintenance costs. Such economic penalties must be balanced against better operating costs, deriving from lower fuel consumption and from potentially lower landing fees.

In order for the IRA concept to be profitable, the engine is envisioned for long range applications, in which the considerable fuel savings at cruise conditions maximize their effect on the overall aircraft economic balance. The IRA Engine concept is a “green engine” solution for the long-term vision (2020+).

The task of producing a cost effective and reliable IRA-configuration includes several challenges, which will require technology programs for the development of the necessary know-how. The most critical points for the successful implementation of the concept are: the high manufacturing costs for the additional components; the high thermo-mechanical stress in the hot-section, which could affect safe life and increase the maintenance costs; the design complexity of the variable geometry system in the turbine section; the development of constructive solutions to reduce the overall engine weight.

11. ACKNOWLEDGEMENTS

The authors would like to thank Rolando Gumucio, who worked on the IRA concept definition before retirement in 2002, and Hermann Klingels, for his work on mechanical design and on weight assessment.

12. REFERENCES

[1] Schiel, “Konstruktion eines Flugtriebwerks mit Abgaswärmetauscher und Zwischenkühler”, Diplomarbeit, FH Binden, 1999

[2] Grieb, “Rekuperatives Kerntriebwerk”, Technicher Bericht – MTU Aero Engines, 004-92M, 1992

[3] Walsh, Fletcher, “Gas Turbine Performance”, Asme Press, 1998

[4] Pilidis, Gas Turbine Performance Course Material, Cranfield University, 2000

[5] Kurzke, GasTurb, http://www.gasturb.de, 2004

[6] Krammer, Rüd, Trübenbach, “Technology preparation for green aero engines”, AIAA Symposium, Dayon, 2003

[7] Rüd, Henrich, Westphal, Hain, “Entwicklung und Bereitstellung einer hochbelasteten schnelllaufenden Niederdruck-turbine für die Erprobung in einem Demonstratortriebwerk”, Proceedings of the DGLR Conference, Hamburg, 2001

[8] Pellischek, “Compact high performance heat exchangers for ICR aircraft gas turbines”, European Propulsion Forum: Future Civil Engines and the Protection of the Atmosphere, DGLR-Paper 90-021, Köln-Porz, Germany, 1990

[9] Niehuis, Rüd, “Entwicklung schnelllaufender Niederdruck-turbinen für künftige wirtschaftliche und umweltschonende ADP Triebwerke”, Proceedings of the DGLR Conference, Munich, 1997

[10] Wilfert, Massé, “Technology integration in a low emission heat exchanger engine”, 8th CEAS European Propulsion Forum, Nottingham, 2001

[11] Schönenborn, Ebert, Storm, Simon, “Thermo-mechanical Design of a Heat Exchanger for a Recuperative Aero Engine”, ASME IGTI Conference, Vienna, 2004