ISABE-2007-1204

Preliminary Definition of a TBCC Propulsion System for a Mach 4.5 Supersonic Cruise Airliner

*Martin Sippel, Keiichi Okai**
Martin.Sippel@dlr.de Tel. +49-2203-6014778, Fax. +49-2203-6012444
Space Launcher Systems Analysis (SART), DLR, 51170 Cologne, Germany
*Visiting Researcher from Aeroengine Technology Center, JAXA, Japan
Hiromasa Kato (hiromasa.kato@cenaero.be), *Apurva Kumar*
Numerical Methods & Optimisation Group – CENAERO, 6041 Gosselies, Belgium

The paper investigates different Variable Cycle TBCC configurations and compares them with an advanced turbojet for the generic configuration of a Mach 4.5 supersonic passenger airliner.

One VCE engine variant and the turbojet are preliminarily designed and their mass including air-intake and nozzle is estimated. The air-intake has been sized and pressure recovery and mass flow in design and off-design conditions is estimated and subsequently checked by the Navier-Stokes CFD code *Argo*.

Nomenclature

D	Drag	N
D_2	Diameter of diffuser exit	m
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
L	Length of subsonic diffuser	m
M	Mach-number	-
T	Thrust	N
W	weight	N
m	mass	kg
q	dynamic pressure	Pa
sfc	specific fuel consumption	g/kNs
v	velocity	m/s
α	angle of attack	-

Subscripts, Abbreviations

BPR1	Front Bypass Ratio of Variable Cycle Double Bypass Engine
BPR2	Aft Bypass Ratio of Variable Cycle Double Bypass Engine
CDFS	Core Driven Fan Stage
HP	High Pressure
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HSCT	High Speed Civil Transport
IGV	Inlet Guide Vane
JP	(hydrocarbon) Jet Propellant (kerosene)
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LP	Low Pressure
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MTF	Mid Tandem Fan
OPR	Overall Pressure Ratio
RANS	Reynolds-Averaged Navier-Stokes
RTA	Revolutionary Turbine Accelerator
SST	Supersonic Transport
TBCC	Turbine Based Combined Cycle
TET	Turbine Entry Temperature
TMC	Titanium Matrix Composite
TVD	Total Variation Diminishing
VABI	Variable Area Bypass Injector
VCE	Variable Cycle Engine
VIGV	Variable Inlet Guide Vane
sfc	specific fuel consumption
0,0	sea-level, static

1 INTRODUCTION

The EU sponsored LAPCAT study investigates different types of advanced propulsion systems for supersonic and hypersonic cruise airplanes [1]. One of the most promising reference vehicles is a supersonic airliner with cruise velocity of Mach 4.5 called LAPCAT-M4.

A turbine based cycle (TBCC) is the natural propulsion system for high speed passenger transport, because one can exploit the tremendous experience in aircraft jet engines. A combination of turbo-engines with RAMjet and kerosene propellant is foreseen as the LAPCAT-M4 propulsion system. Turbojet as well as Turbofan cycle engines had been in operation with the first generation of supersonic passenger airplanes, the Concorde and the Tupolev Tu-144. However, these engines with a fixed cycle had insufficient efficiencies for operation in the full flight regime and thus limited flight range. The demands of subsonic to supersonic flight at very high speed require adaptations of the thermodynamic cycle in order to improve operational efficiency. Variable Cycle Engines (VCE) might offer a good compromise for such applications. Therefore, VCE have been under study for more than a decade. The US started investigations already in the 1970ies and recently pushed this technology for military and space functions (RTA, Revolutionary Turbine Accelerator).

The preliminary design of LAPCAT-M4 [3] is based on a critical recalculation of a 1990 NASA Langley and Lockheed study [2] of a 250-passenger, Mach 4 high-speed civil transport with a design range of 6500 nautical miles (12045.8 km). The LAPCAT mission range Brussels to Sydney is highly ambitious and by almost 40 % larger than NASA's 12000 km, which requires a re-design.

To keep the wing loading in an acceptable range the wing size has been increased to 1600 m^2 (+ 36%). The span grows almost proportionally by 16 %, while the total length reaches 102.78 m which is only slightly longer (+ 8.8 %) than the earlier HSCT proposal.

The general arrangement of the generic airplane geometry is illustrated in Figure 1. Four advanced turbo-RAM-jet engines are mounted in two nacelles on the wing lower surface adjacent to the fuselage. The location of the engine and nacelles is still open for adaptation if required by trim as long as they remain under the wing. The axial-symmetric geometry and the size of the air-intakes, nacelles and nozzles as shown in Figure 1 are not representative of the actual LAPCAT design. A rectangular shape of the air-intake with vertical ramps as in [2] is the preferred design option.

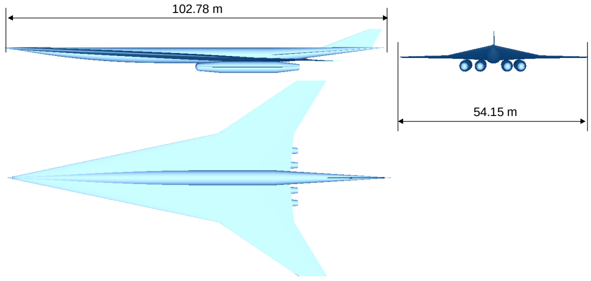

Figure 1: Generic Mach 4.5 supersonic cruise airplane of LAPCAT study (nacelle design not representative)

The large, slightly inclined wing might help to achieve a good maximum L/D of 7.8 at a small angle of attack and cruise Mach number 4.5 according to preliminary DLR-analysis. Actually, a high L/D is essential to achieve the ambitious range requirement.

The total take-off mass of the supersonic cruise airplane has been iterated in a two loop approach to the huge value of 720 Mg, which is well beyond any supersonic passenger aircraft built to date. The dry mass is estimated at 184.5 Mg and the structural index is at a for airplanes low 36.8 %. According to current data the HSCT would be able to transport about 200 passengers with their luggage. More data on the LAPCAT-M4 airliner design is published in reference [3].

2 ANALYSES APPROACH AND ENGINE DESIGN POINTS

The cycle simulations are accomplished with the DLR air-breathing propulsion analysis computer program abp [4]. Engine performance is calculated for a modular arrangement of components by fast, one dimensional analysis. Therefore a method based on known component efficiencies (e.g. generalized compressor maps), and known turbine, and compressor entry temperatures, as well as gasdynamic relations is adapted for high speed airbreathing engines.

The DLR air-breathing cycle analysis tool abp has been developed to rapidly assess advanced and high-speed air-breathing engines for space launcher applications. The program abp is equally capable of calculating high-speed cruise flight A/B-propulsion. Besides delivering performance data ((net) thrust and Isp) in dependence of Mach number and altitude the program supports preliminary sizing and mass estimation.

Table 1 lists all propulsion interface data obtained from the vehicle design simulations of LAPCAT. These data are the basic requirements for the subsequent preliminary design of all TBCC propulsion components. A minimum sea-level take-off thrust at Mach 0.3 of 1800 kN has been defined keeping the runway length requirement within acceptable limits.

Table 1: Propulsion system thrust requirements based on LAPCAT-M4 vehicle design process

Trajectory point 1 (take-off):	
Mach:	0.3
Altitude:	0 m
Total installed thrust:	1800 kN
Trajectory point 2 (cruise 1):	
Mach:	4.5
Altitude:	24300 m
Total installed thrust:	640 kN
Trajectory point 3 (cruise 2):	
Mach:	4.5
Altitude:	29100 m
Total installed thrust:	292 kN

Trajectory point 1 is the major sizing criterion for all turbo engines, while the other two trajectory points operated in RAM-mode are relevant for the air-intake sizing.

An advanced turbojet is regarded as well as three combinations of variable cycle turbofans. A ram burner will be integrated with the convergent divergent nozzle for all cycle variants. This device acts as an afterburner in high altitude acceleration flight and as the single propulsion system beyond the transition Mach number of around 3.5. Cycle temperatures are limited to similar, ambitiously high values. A TET of 1950 K and a maximum afterburner temperature of 2100 K nevertheless seem to be achievable by advanced engines within a development perspective of about 20 years.

3 PRELIMINARY AIR-INTAKE DESIGN

All engines will be fed by the same two-dimensional, variable-geometry, mixed compression inlet. Different designs have been investigated. One of the most promising configurations is an up to six-shock, three variable ramp mixed compression intake. Achievable pressure recovery has been estimated with the DLR code *abpi* [4] using wedge shock relationships. An optimized cruise point pressure recovery of around 70 % at Mach 4.5 could be possible, as can be seen from Figure 2. This translates into an intake efficiency of 0.974 at cruise. The pressure recovery and efficiency at lower Mach numbers can be significantly raised by a suitable selection of the second and third ramp angles. External compression with the terminating shock in front of the lip seems to be advantageous for Mach numbers up to approximately 2.5. The curves in Figure 2 include the effect of forebody compression and the bow shock.

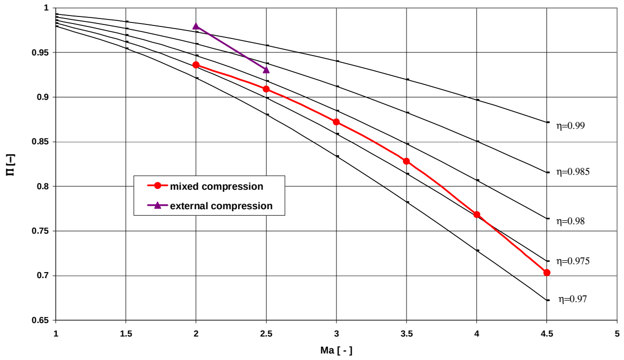

Figure 2: Air-Intake pressure recovery of LAPCAT-M4 3ramp-mixed compression intake according to abpi-calculation and intake-efficiency η

The cycle analyses of the turbojet and of the variable cycle engines presented in the following chapter 4 are based on the pressure recovery data from Figure 2. The capture area of 7.5 m^2 has been checked by abpi-analyses in design and off-design conditions on available air-mass flow and seems to be sufficient in the complete flight mission.

3.1 CFD Analyses of Supersonic Intake Section

At CENAERO the Navier-Stokes CFD code *Argo* is used for recalculation of the design and off-design flow conditions. Argo is a 3-D Navier-Stokes solver which uses a hybrid finite volume and finite element discretization on unstructured tetrahedral meshes. The computation was done using Roe upwind scheme with Venkatapathy TVD limiter for convective flux, and the Spalart-Allmaras turbulence model is used. The temporal integration is carried out with steady flow assumption using local time stepping, and the resulting discrete system of equations is solved by the Newton-Krylov-Schwarz algorithm.

The primary objective of the 2D-CFD simulation is to estimate the displacement effect due to turbulent boundary layer and its influence on the pressure recovery and mass capture performance of the intake. The emphasis here is on the numerical cross-check on the preliminary design described in the preceding section.

The RANS simulations are carried out at three supersonic operating conditions and also at the subsonic take-off condition. In order to ensure sufficient mass capture at take-off, while taking into account the practical implementation of movable ramps, the maximum allowed throat height is set to 3 times that of the on-design configuration. For the supersonic cases, the two movable ramps are adjusted accordingly.

3.1.1 Subsonic Case, M= 0.3

At the LAPCAT take-off condition (compare Table 1), the movable ramps are fully open in order to ensure the required mass flow to the engine (see Table 2). In this study, the two ramps are adjusted to form a single ramp so that the throat height is 3 times that of the M= 4.5 design configuration with minimum throat height. The diffuser section in the CFD calculation is tentatively chosen to be a straight expanding ramp and artificially chosen back pressures are applied at the exit of the diffuser.

Figure 3 shows the Mach number contours around the intake, and Figure 4 shows the velocity vectors in the vicinity of the cowl lip, which is preliminarily assumed with no more than 2 mm radius. Note the flow separation occurring along the inside wall of the cowl lip, spanning approximately 50% of the length. This unwelcome flow situation and practical reason will demand an increased lip leading edge radius, probably in the 1 cm range.

Mass flow rate is found at 471 kg/s satisfying the requirement of 460 kg/s, which allows for some extra by-pass flow around the engine for cooling, etc.

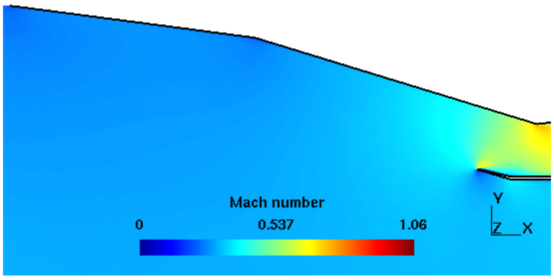

Figure 3: Mach contours at trajectory point 1 (M= 0.3, altitude= 0 m)

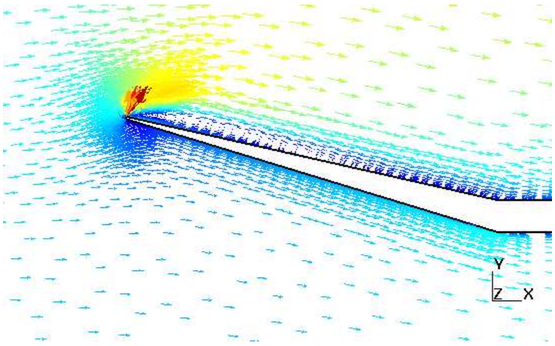

Figure 4: Velocity vectors at trajectory point 1 (M= 0.3, altitude= 0 m)

3.1.2 Supersonic Cases

Due to numerical difficulty in maintaining the terminal shock at the throat, only the shock system up to the terminal shock has been simulated, and the resulting pressure recovery including the terminal shock is analytically computed using normal shock relations. More detailed computations including the diffuser are ongoing.

At intake design condition with a flight Mach number of 4.5, the intake sees incoming flow of Mach 4.22 due to the forebody compression. Figure 5 shows the Mach number contours. It can be seen that the external shock system narrowly misses the cowl lip, spilling a small amount of captured mass flow. This is due to the fact that the abpi analysis which calculates the optimum ramp inclination does not include the boundary layer displacement effect. For the more than 10 m long ramps the displacement is no longer negligible. However, the situation is easily improved by slightly altering the angle of the 3rd ramp and this action is to be included in the next step of full 3D-calculations.

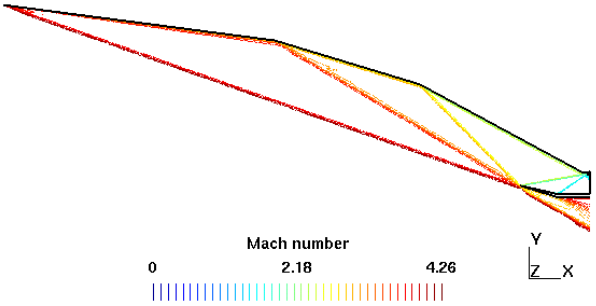

Figure 5: Mach contours at intake design condition, trajectory point 2 (M= 4.5, altitude= 24300 m)

Figure 6 shows the shock structure at the off-design flight Mach number of 3.5. The 2nd and the 3rd ramps are retracted to 8 and 9 degrees, respectively, which results in the 3rd shock impinging on the cowl lip.

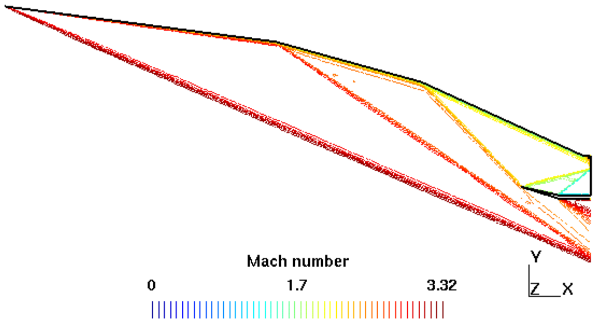

Figure 6: Mach contours at off-design condition, (M= 3.5, altitude= 19700 m)

The final off-design intake-condition of the LAPCAT-M4-3R intake calculated up to now by the Argo code is the Mach 3 acceleration flight shown in Figure 7.

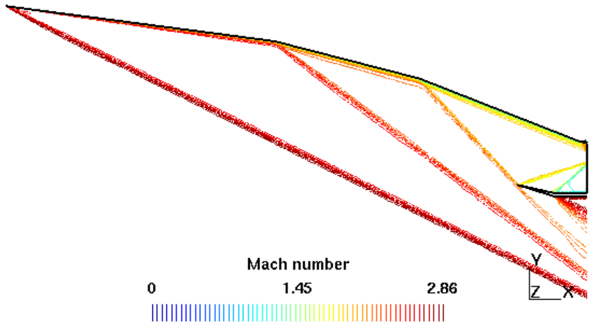

Figure 7: Mach contours at off-design condition, (M= 3.0, altitude= 17800 m)

In general, the CFD-simulations confirm the ambitious pressure recovery data of Figure 2. In fact the numerical recovery performance is found even slightly better than that of abpi. However, one should note that these calculations assume a sharp leading edge of less than 2 mm radius and do not include subsonic diffuser losses as well as 3D-effects. Thus, in order to follow a robust design approach the abpi data of Figure 2 are maintained for the performance calculations.

3.2 Subsonic Diffuser Considerations

The design of the diffuser part of a supersonic intake has two important points. One is to keep the pressure loss minimum and the other is to make the flow near uniform (small distortion). In the present preliminary design, the earlier point is taken into account and the attainment of the latter feature is indirectly checked by comparing existing criteria [7].

The present design considers the isolator length determination and further the diffuser/transition duct design. In the subsonic combustion engine system, the definition of the isolator is a bit difficult compared with that for Scramjets. In this design, the isolator location is determined as the range between the designed terminal normal shock wave position and the start point of expanding diffusing or transition duct. Estimation was conducted using empirical equations based on experiments provided by Waltrup and Billig [8]. With verification of the estimation applying some existing intakes such as for Concorde and XB-70 and HYPR experimental intake, the isolator length is selected as 2 m.

The diffuser length and shape affect the amount of pressure loss. The exit diameter of the duct is close to the dimension of the turbo-engine inlet. With a small margin taking into account, the exit diameter is determined by considering the allowable flow configuration at the turbo engine entry. With a relevant throat section area, the exit Mach number is estimated and the adequate diameter in that section is established. The estimation of the diffuser pressure loss is conducted utilizing a tool composed of collections of empirical equations depicted from Murakami [9]. This tool estimates the pressure loss as the sum of friction and dissipation losses, with parameters of aspect ratio of the diffuser entry, offset of the exit center and so on. A limited number of variables represent the ordinal shapes of the duct, and the empirical equations are verified in [9] by comparison with experimental data. A parametric analysis of the subsonic diffuser's pressure loss depending on the exit cross section and the reduced length is shown in Figure 8 for LAPCAT-M4. The appropriate reduced length of the divergent duct is selected at L/D_2= 4.25. This non-dimensional value is appropriate for small distortion and results in an actual diffuser length of 7.5 m.

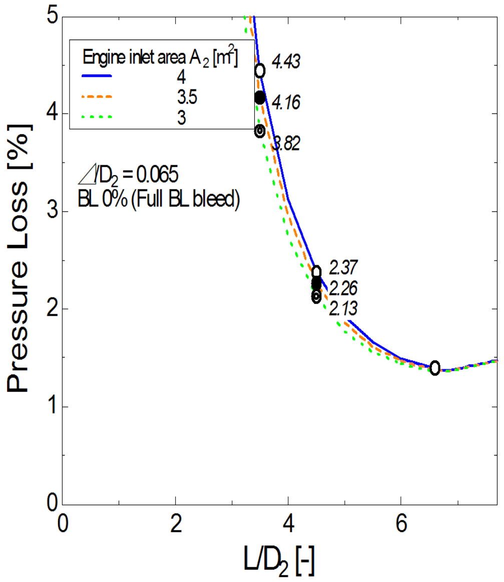

Figure 8: Parametric analysis of LAPCAT-M4 subsonic diffuser pressure loss

3.3 Size and Mass Data

Figure 9 shows the preliminarily sized geometry of the LAPCAT-M4-3R-V3-intake. Maintaining the previous capture area of 7.5 m^2 the total length of the ramps reaches about 9 m and the width is 2.5 m. Total length of the subsonic diffuser including a movable section with rectangular cross section is about 8.6 m and the intake's overall length with the isolator section is more than 19 m.

Geometry data as automatically generated by the abpi-tool or provided as input values allow a first mass estimation which is based on a simplified structural mechanical analysis. The intake's material is mostly selected as an advanced C-SiC composite for high temperature resistance and high strength in an uncooled environment. Due to the extremely light-weight design, a total intake mass without equipment and actuators of slightly above 5500 kg is obtained.

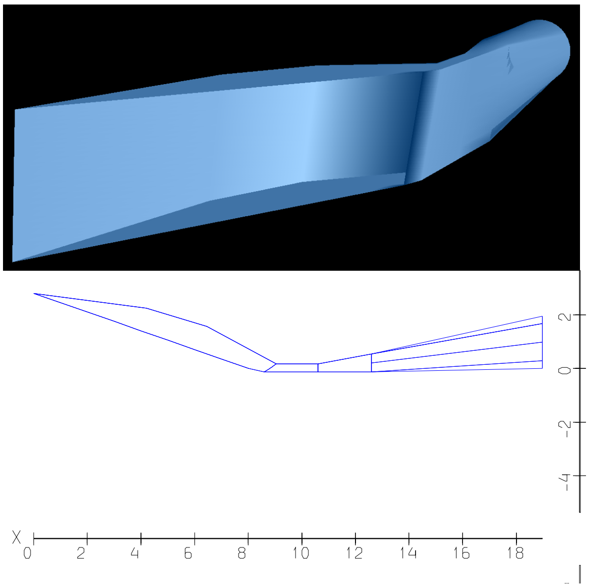

Figure 9: LAPCAT-M4-3R-V3 air-intake geometry displayed in wireframe and shaded mode

4 PRELIMINARY TBCC DESIGN

4.1 Cycle Investigations

The cycle investigations started with the recalculation of historical supersonic cruise airplane engines with different cycles [6], before looking on advanced turbojet- and variable cycle turbofan-RAM engines.

The LAPCAT TJE-6 is a relatively simple and compact design with a six stage core compressor powered by a twin stage HPT. Turbojet type engines (namely the Olympus 593 and the RD36-51A) were already the best compromise in early SST operation, as demonstrated in [6]. Therefore, there is an interest to know if such a design is still competitive with advanced variable cycles assuming similar thermodynamic conditions. Table 2 lists the major cycle specification data of the LAPCAT-M4 TJE-6 engine at sea-level static conditions prior to take off.

The most critical thrust point during take-off run is at about Mach 0.3. The installed thrust of 460 kN [6] is sufficient for the acceleration of LAPCAT-M4. The specific thrust falls to about 1015 Ns/kg because an increasing impulse of the incoming air has to be considered. The total available thrust can be raised to 567 kN (+ 23 %) in case of an engine-out emergency under this take-off condition by igniting the afterburner.

Three different variants of advanced variable cycle engines have been investigated for the LAPCAT supersonic airliner. All are double bypass turbofans principally similar to the RTA-1 design [5], however adapted to the mission and thrust requirements of the LAPCAT-M4. The major differences of the three concepts are in the number of fan or compressor stages and their OPR. A RAM burner will be integrated with the convergent divergent nozzle in all variants.

LAPCAT VCE-114 is a variable cycle engine incorporating a single stage fan with very large blades mounted on the low-pressure spool. The first bypass flow is controlled by the first variable area bypass injector (VABI). This device is followed by the core section, starting with a single fan (core driven fan stage CDFS). After the second VABI the four stage core compressor delivers the remaining air into the combustion chamber. A single stage HPT is followed by a single stage LPT. The bypass flow is controlled by an aft VABI to achieve mixing with the core flow in the complete flight regime.

The **LAPCAT VCE-213** is a variable cycle incorporating a two stage fan with large blades mounted on the low-pressure spool. The first bypass flow is controlled by the first VABI. This device is followed by the core section, starting again with a single stage fan (CDFS). After the second VABI the three stage core compressor delivers the remaining air into the combustion chamber. A single stage HPT is followed by a single stage LPT and the bypass flow is again controlled by an aft VABI to achieve mixing with the core flow in the complete flight regime.

The **LAPCAT VCE-214** is a variable cycle very similar to the VCE-213, besides the number of HPC stages. After the second VABI the four stage core compressor delivers the remaining air into the combustion chamber. Both HPT and LPT are single stage. The VCE-214 is the engine with highest OPR within the LAPCAT-M4 TBCC cycle investigation.

Table 2 lists the major cycle specification data of the LAPCAT-M4 VCE engines at sea-level static conditions prior to take off. Note that both VABIs are closed and both bypass ratios are consequently set to zero to achieve a high specific thrust.

Note also that the VCE-114 has a slightly lower design air-mass flow of 435 kg/s than the two other configurations with double fan stage. By igniting the afterburner to 2100 K the total available thrust can nevertheless be sufficiently raised in case of emergency during take-off by 27 % to 575 kN.

Table 2: LAPCAT-M4's different turbojet and VCE double bypass turbofan cycles' specification data at sea-level static conditions according to abp calculation

		TJE-6	VCE-114	VCE-213	VCE-214
OPR	-	15	23.256	14.887	24.0
Π_{Fan}	-	-	1.9 (1 stage)	2.1 (2 stages)	2.1 (2 stages)
Π_{CDF}	-	-	1.8 (1 stage)	1.7 (1 stage)	1.7 (1 stage)
Π_{HPC}	-	15 (6 Stages)	6.8 (4 stages)	4.17 (3 stages)	6.72 (4 stages)
HP-Turbine	-	2 Stage	1 stage (tbc)	1 stage (tbc)	1 stage (tbc)
LP-Turbine	-	-	1 stage	1 stage	1 stage
Bypass ratio λ_1 (BPR1)	-	-	0.0	0.0	0.0
Bypass ratio λ_2 (BPR2)	-	-	0.0	0.0	0.0
air mass flow	kg/s	450	435	450	450
TET	K	1950	1950	1950	1950
$F_{spec\ 0,0}$, dry	Ns/kg	1116	1129	1109	1126
$F_{\ 0,0}$, dry	kN	502	491	499	506
sfc $_{0,0}$, dry	g/kNs	30.67	28.1	30.7	27.9
$T_{\ afterburner}$	K	2100	2100	2100	2100
$F_{spec\ 0,0}$, afterburner	Ns/kg	1343	1400	1353	1415
$F_{\ 0,0}$, afterburner	kN	589.4	601	603	627
sfc $_{0,0}$, afterburner	g/kNs	43.84	42	43.7	41.8

Figure 10 shows the thrust and sfc at sea-level take-off of all analyzed engines. Note that all differences are small because the bypass ratio is zero in all cases but that the VCE-213 and the turbojet with the least OPR have the least favorable characteristics.

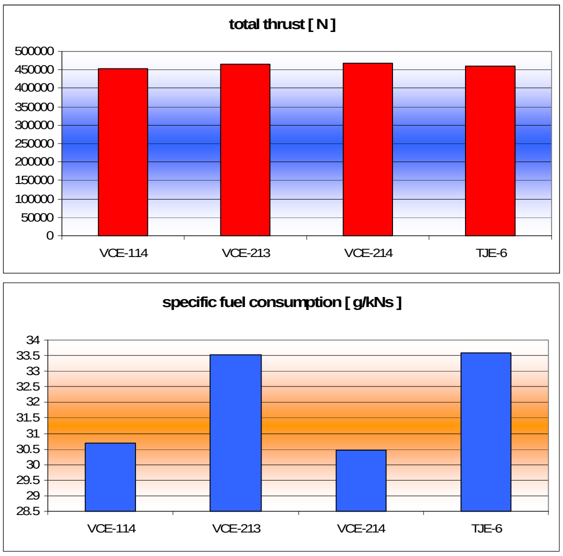

Figure 10: Take-off (Mach 0.3) at sea-level installed dry thrust (top) and sfc (bottom) of LAPCAT-M4 engines

The most attractive feature of a variable cycle engine can be identified as its capability to actively control the bypass flow. Supersonic airliners are usually required of flying a significant portion of their mission in subsonic cruise, at least as long as densely populated areas are over flown. In case of a pure turbojet the TET will be reduced with almost negligible effect on sfc. The VCE open their bypasses and the cruise efficiency can be notably improved. All engines can be throttled between 40 % and 60 % under this condition as has been proven by flight simulations [3]. Figure 11 demonstrates that all VCE could operate under significantly better sfc with the VCE-114 at only 82.8 % of the reference turbojet. A fuel reduction of about 17 % is a notable advantage.

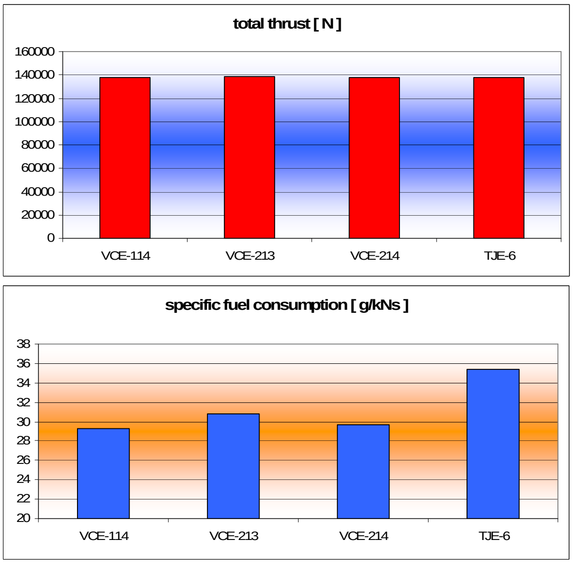

Figure 11: Subsonic cruise (M= 0.8, 9 km) installed dry thrust (top) and sfc (bottom) of advanced LAPCAT-M4 TBCC engines (40 % throttling) based on abp calculation

At the end of subsonic cruise with 60 % throttling the advantage of all VCE compared to the turbojet is even more evident. The specific consumption of the VCE-214 is at only 70.4 % of the reference turbojet.

The more complicated lay-out of the VCE allows an adaptation of the different compressors more or less independently of each other. This feature can be used at higher supersonic Mach numbers. Around Mach 2.5 these engines are switching to an operation mode in which the first fan is transitioning to windmilling. At Mach 3 the low pressure spool is in full windmilling, thus temperature and pressure of the incoming air is no longer altered by this component. The turbofan is operating in double bypass mode with small bypass ratios λ_1 and λ_2 and still at its maximum TET of 1950 K without reaching the compressor exit temperature limitation of 1000 K. The VCE-213 with lowest OPR can thus extend its operation with unthrottled TET up to a flight Mach number of 3.4, hence offering also a fuel consumption benefit.

At around Mach 3.5 the useful operational range of the VCEs with an OPR of around 24 is reached and transition to pure RAMjet is initiated. The VCE-213 could be operated in simulations up to M= 3.7. For all engines the first VABI is opened with BPR1 approaching 0.85. The VABI2 is closed for the VCE-114 while it is kept slightly open for both engines with two-stage LP Fan. This choice is related to a general trend observable in the VCE simulations by abp which showed increased difficulties in mixing the two bypass flows with the larger compression ratio of the VCE-114's CDF stage. However, the performance impact is small because the amount of thrust provided by the turbo engine part is already minor compared to the afterburner / RAM combustor.

The turbo-to-RAM transition point at Mach 3.5 in an altitude of approximately 19700 m shows another interesting comparison with the moderate OPR VCE-213 reaching the by far best performance in thrust and sfc. Note that data provided in Figure 12 are dissimilar to those in reference 6 despite similar engine operation conditions because of an updated installation drag calculation method in the abp-code.

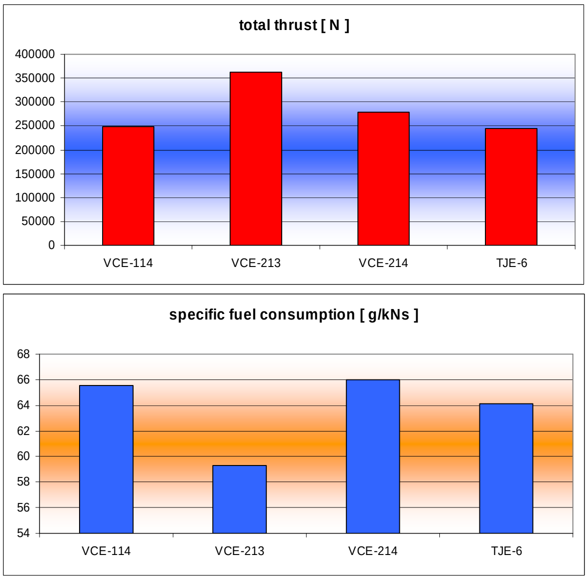

Figure 12: Turbo-RAM-transition (Mach 3.5) at 19700 m installed augmented thrust (top) and sfc (bottom) of LAPCAT-M4 engines

The core engines of VCE will be closed beyond the Mach 3.5 trajectory point and the complete air-flow is directed through the bypass duct to the RAM chamber. Technical solutions for the practical design of such a TBCC might become very challenging. Some preliminary investigations are ongoing. A thermal environment around 1050 K for the windmilling LP-Fan during the several hours of RAM cruise could raise problems. In case of the turbojet these design challenges might become even tougher and a switch to two separate flow passes might be necessary.

The maximum RAM combustion temperature is limited to 2100 K as for the afterburner. This high value is used during the acceleration phase and can be significantly reduced when reaching the cruise flight. Depending on the remaining airliner weight, the combustion temperature is reduced in steady cruise to values between 1850 K and 1700 K. The lower thermal loads ease somewhat cooling concerns because no cryogenic fluid for active cooling is available.

The actual impact of the different cycle variants on the mission performance can be obtained only by flight simulations of LAPCAT-M4. A mission taking into account supersonic flight restrictions has been established [3] and is used for full flight simulations. Figure 13 clearly shows the throttling during subsonic cruise at Mach 0.8 and the subsequent acceleration to the supersonic cruise point at M= 4.5. The VCE-213 demonstrates its superior thrust performance in supersonic flight. Specific fuel consumption is overall close for all engines; however, during the subsonic cruise the turbojet experiences a notable disadvantage.

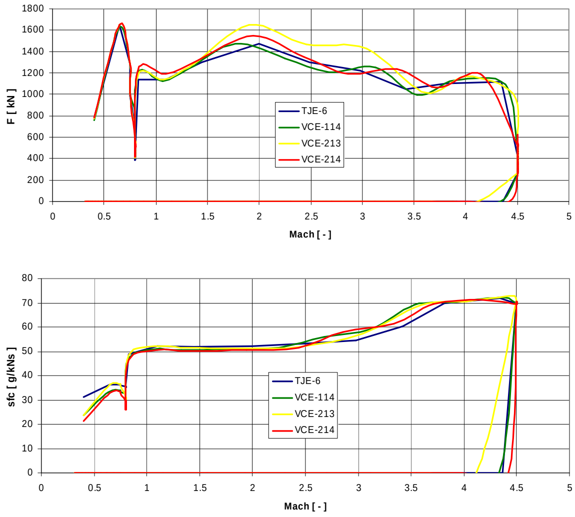

Figure 13: Installed total thrust of all four LAPCAT-M4 engines (top) and sfc (bottom) of different engine types along flight Mach number

The integral fuel consumption for the Brussels to Sydney flight is best for the VCE-214 which is the engine with the highest OPR followed by the VCE-114, the VCE-213, and at the end the advanced turbojet TJE-6. Assuming an identical amount of available fuel and an identical take-off mass, the achievable range of the four engines has the same ranking. However, these assumptions disregard any differences in engine dry mass. Even slight discrepancies could significantly change the picture on the optimum propulsion design.

The range of the VCE is better by about 1000 km (reaching almost 16000 km) than the range of the advanced turbojet. This result, however, is based on the assumption that the propulsion system mass of VCE and TJE is identical. A preliminary sizing and mass estimation of the advanced TBCC, for which the initial steps are described in the next section, should eventually deliver a more precise conclusion on the most promising propulsion system for large supersonic airliners.

4.2 Preliminary Engine Sizing and Mass Estimation

The DLR code abp [4] has a module calculating the turbo engine's preliminary geometry and weight. The program evaluates the values by using on- and off-design performance data. The evaluation of the rotating parts can be done for any selected operating conditions, but is usually performed for the sea level static case. In contrast, the nozzle configuration is usually determined as for the high altitude flight supersonic off-design condition. Design of the combustor parts (core engine combustor and ram combustor) is also at arbitrary condition and is done for LAPCAT at the maximum sea level flight speed case (M= 0.8), where the mass flow and fuel flow take maximum values [11].

Geometrical size determination is done by the velocity diagram estimation for rotation parts, spray, mixing, combustion and cooling part empirical evaluation for combustor parts, and flow field evaluation for the nozzle. The method for the structural weight analysis is quite straight-forward with a small number of variables similar as in the structural analysis [10]. The adjustment and verification of the method was conducted by the recalculation of several existing high speed engines. In the verification, some of the performance criteria are checked by referencing available reports such as Walsh and Fletcher [12], Mattingly and coworkers [10], Oates [13] and Meller [14].

The engine configurations which have been evaluated first are the TJE-6 turbojet and the VCE-114 double bypass turbofan. The very broad range of engine operation from sea-level take-off up to M= 3.5 in more than 20000 m requires a thorough investigation of each component under all relevant conditions. Therefore, currently it is too early to give final and reliable numbers for structurally estimated weight. The preliminary results show that both of the engines can be accomplished with an inlet area of 3 m^2, resulting in an engine inlet diameter of 1.9 m and a maximum engine diameter of approximately 2.1 m. The total length of the engine with nozzle is at least about 7 m. Assuming advanced fibre reinforced materials (e.g. TMC as described in [15]), the turbojet weight is in the 5 tons class and the variable cycle in the 6 tons class, both including nozzle.

Note that the present estimated nozzle weight is for a variable axi-symmetric convergent-divergent type. A larger and more complicated ejector nozzle with advanced noise suppression features will become heavier. The component analysis of the VCE's HPT indicates the requirement to increase another turbine stage to relax the loading factor. Similarly, high bypass-flow conditions are to be investigated to check the LPT-design. Ducting in the VCE engine may require a more complex geometry than currently considered. The structural pre-sizing of the LAPCAT engines will be continued and results will later be published (e.g. in [7]).

5 CONCLUSION

A turbine based combined cycle is an attractive propulsion solution for an advanced ultra long-haul supersonic airliner. The cycle analyses and systems investigations show that robust designs which could power a large vehicle over distances of about 15000 km are technically within reach.

A preliminary high performance air-intake design is carried out and shows promising performance data in all types of analyses including Navier-Stokes calculations. The total length reaches almost 20 m and assuming advanced high temperature composite materials an intake mass of about 5.5 tons is estimated.

The comparison between an advanced turbo-jet and advanced variable cycle engines (VCE) has been performed with similar cycle conditions assumed for all types. A notable advantage of the VCE can be stated if a significant portion of the mission is flown in subsonic cruise. In the subsonic and supersonic acceleration phases the performance of all engine types are very close because the VCE are also operated similar to a turbojet with very small bypass flows.

The range of the VCE is better by about 1000 km (reaching almost 16000 km) than the range of the advanced turbojet if the propulsion system mass of VCE and TJE are assumed identical. First results of an ongoing preliminary sizing and mass estimation of the advanced TBCC types indicate however a potential mass saving of about 1 ton per engine for the advanced turbojet compared to the double bypass turbofan. Analyses are ongoing and more component data results are needed before a conclusive answer can be given on the optimum propulsion system for a Mach 4.5 cruise aircraft.

6 ACKNOWLEDGEMENTS

This work was performed within the ''Long-Term Advanced Propulsion Concepts and Technologies" project investigating high-speed airbreathing propulsion. LAPCAT, coordinated by ESA-ESTEC, is supported by the EU within the 6th Framework Programme Priority 1.4, Aeronautic and Space, Contract no.: AST4-CT-2005-012282. Further info on LAPCAT can be found on http://www.estec.esa.int/techresources/lapcat

The authors gratefully acknowledge the contributions of Mr. Josef Klevanski and Mr. Philipp Voigt in the investigations of the LAPCAT-M4 TBCC propulsion system.

7 REFERENCES

1. N.N.: SIXTH FRAMEWORK PROGRAMME, PRIORITY 1.4, AERONAUTIC and SPACE, Annex I - "Description of Work", Project acronym: LAPCAT, Project full title: Long-Term Advanced Propulsion Concepts and Technologies, Proposal/Contract no.: 12282, Date of preparation of Annex I: 1st of February 2005, Operative commencement date of contract: 26th of April 2005

2. Domack, C. S.; Dollyhigh, S. M.; Beissner, F. L.; Geiselhart, K. A.; McGraw, M. E.; Shields, E.W.; Swanson, E.E.: Concept Development of a Mach 4 High-Speed Civil Transport, NASA Technical Memorandum 4223, 1990

3. Sippel, M.; Klevanski, J.: Preliminary Definition of the Supersonic and Hypersonic Airliner Configurations in LAPCAT, AIAA 2006-7984, November 2006

4. Sippel, M.: Programmsystem zur Vorauslegung von luftatmenden Antrieben für Raumfahrzeuge, abp 2.0, DLR TB-319-98/07, 1998

5. McNelis, N.; Bartolotta, P.: Revolutionary Turbine Accelerator (RTA) Demonstrator, AIAA 2005-3250, May 2005

6. Sippel, M.: Research on TBCC Propulsion for a Mach 4.5 Supersonic Cruise Airliner, AIAA 2006-7976, November 2006

7. Okai, K., Sippel, M.: Component Analysis of TBCC Propulsion for a Mach 4.5 Supersonic Cruise Airliner, accepted for EUCASS 2007

8. Walltrup, P.J.; Billig, F.S.: Prediction of Precombustion Wall Pressure Distribution in Scramjet Engines, Journal of Spacecrafts and Rockets, Vol. 10, No. 9, Sep. 1973

9. Murakami, A.: Empirical method of Total Pressure Loss Estimation of Subsonic Diffuser (in Japanese), JAXA-RM-04-002, 2004

10. Mattingly, J.D.; Heiser, W.H.; Pratt, T.P.: Aircraft engine design, second edition, AIAA Educational Series, 2002

11. Kurzke, J.: Preliminary design, in Aeroengine design: A state of the art, von Karman Institute lecture series 2002-2003, 07-11 April 2003

12. Walsh, P.P., Fletcher, P.: Gas turbine performance, second edition, Blackwell publishing, 2004

13. Oates, G.C., Ed.: Aircraft Propulsion Systems Technology and Design, AIAA education series, 1985

14. Meller, A.M., Ed.: Design of Modern Turbine Combustors, Academic press, 1990

15. Kumpfert, J.; Peters, M.; Kaysser, W.A.: The Potential of Advanced Materials on Structural Design of Future Aircraft Engines, RTO AVT Symposium on Design Principles and Methods for Aircraft Gas Turbine Engines, Toulouse, May 1998

Further updated information concerning the SART space transportation concepts is available at:
http://www.dlr.de/SART