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ABSTRACT
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It is recommended for VHBR and UHBR simulators to increase the core nozzle pressure ratio to arrive at realistic turbine designs rather than increasing the size of the turbine and the core nozzle. This approach leads to much smaller changes in the outer jet diameter and retains the correct pressure distribution on the core cowl.
For the low fan nozzle pressure ratios of UHBR engines at take-off and climb the nozzle mass flow and gross thrust become sensitive to local pressure variations induced by the external flow near the nozzle exit or by the presence of the airframe components. These effects must be taken into account by measurement of the static pressure in the nozzle exit resulting into a local nozzle pressure ratio rather than using the classical definition of the nozzle pressure ratio based on the free stream static pressure.

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POSSIBILITIES AND LIMITATIONS OF VHBR AND UHBR TURBOFAN SIMULATIONS IN ENGINE/AIRFRAME INTEGRATION WIND TUNNEL EXPERIMENTS

by

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Contents

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NOMENCLATURE

A	area
B	bypass ratio
c_p	specific heat at constant pressure
D	diameter, subscripts see fig. 1
m	mass flow
M	Mach number
NPR	nozzle pressure ratio (p_{tj}/p_0)
p	(static) pressure
p_t	stagnation pressure
P	power
OPR	overall pressure ratio (p_{t3}/p_{t2})
T	(static) temperature
T_t	stagnation temperature
T_{gross}	gross thrust
T_{net}	net thrust
V	flow velocity
γ	ratio of specific heats c_p/c_v
η_t	polytropic turbine efficiency
Π_{fan}	fan pressure ratio
Π_t	turbine pressure ratio
σ	NPR_{fan}/NPR_{core}

subscripts

des	design point
e	nozzle exit
j	fully expanded jet
N	nozzle
0	free stream, flight
2	fan entry
3	compressor exit
3f	fan exit
4	turbine entry
45	between hp and lp turbine
5	behind turbine(s)

ADP	Advanced Ducted Prop
CRISP	Counter Rotating Integrated Shrouded Propeller
CRUF	Counter Rotating Ultra High Bypass Fan
DUPRIN	DUcted PRopfan INvestigation
HBR	High Bypass Ratio
TPS	Turbo Powered Simulator
UHBR	Ultra High Bypass Ratio
VHBR	Very High Bypass Ratio

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1. INTRODUCTION.

Turbopowered simulators (TPS) are considered to provide the most realistic engine flow simulation for turbofan engine/airframe interference tests in wind tunnels. Claimed accuracies on gross thrust are about 0.2 percent of the full thrust value, leading to very useful data on engine installation drag, including interference effects.

During the past ten years increasing interest emerged into the possible merits of further increasing the bypass ratio of turbofan engines from the present-day value of about 5 to significantly higher values. The GE90 engine of General Electric with a bypass ratio of 9 and the Pratt and Whitney ADP (Advanced Ducted Prop) with a bypass ratio of 15 are typical examples that already exist. At the extreme upper end the CRISP (Counter Rotating Integrated Shrouded Propeller) of MTU should be mentioned with a bypass ratio of about 26 (lower values have been mentioned as well). The CRISP project has led to an extensive research programme in Germany and inspired the development of the CRUF turbopowered simulators that were used a.o. in the joint European research programme DUPRIN.

This increase in bypass ratio has led to new requirements, problems and solutions in the application of TPS units. A number have been touched upon during the International Forum on Turbine Powered Simulation at DNW last year [1]. The purpose of the present paper is to put these into a broader perspective while providing some additional physical background.

2. CHARACTERISTICS OF HIGH TO ULTRA HIGH BYPASS RATIO TURBOFAN ENGINES.

In order to evaluate the possibilities and limitations of Turbo Powered Simulators first some characteristics of the corresponding real engines must be established. These are in particular the fan and core nozzle pressure ratios at various flight conditions and the main dimensions of the inlet and the nozzle system.

For the present paper the characteristics of "typical" turbofan engines with bypass ratios B = 5, 9, 15 and 20 have been determined using a simple thermodynamic model with realistic efficiency and gas property values. Some details are found in the apendix. For off-design conditions where a non-choked core nozzle may influence the low-pressure turbine pressure ratio, the method outlined in [2] was used as summarized in the appendix.

B = 5 is typical of "conventional" High Bypass Ratio (HBR) turbofans, B = 9 represents the Very High Bypass Ratio (VHBR) engines like the GE90 and B = 15 and 20 fall into the category of ultra high bypass ratio (UHBR) engines. The design point for all four engines was for cruise at Mach 0.8 at 35,000 ft when an ideal net thrust of 25 kN should be delivered. This results into an engine of the CFM56-5 class as used on the Airbus A320.

For a given flight condition four independent engine parameters define the cycle of a turbofan engine. Here the following parameters were chosen: the overall pressure ratio OPR = p_{t3} / p_{t2}, the turbine entry temperature T_{t4}, the bypass ratio B and $\sigma = NPR_{fan} / NPR_{core}$. For all engines the pressure ratio of the fan nozzle was assumed to be 1.1 times that of the core nozzle at the design point (σ = 1.1). This assumption leads in combination with the other parameter values to realistic values of bypass ratio versus fan pressure ratio combinations.

For the B = 5 engine design point, an overall pressure ratio OPR = 30 was assumed and a turbine entry temperature T_{t4} = 1400 K, leading to a fan pressure ratio of about 1.77, which is according to current practice.

For the other engines OPR = 40 was selected and T_{t4} = 1530 K. This closely conforms to the UHBR study in [3], where values of 38 and 1530 K have been used. For the B = 9 VHBR turbofan this results in a fan pressure ratio of 1.54 at the design point.

For B = 15 the ADP offers a design guide line. The ADP with a fan pressure ratio 1.33 [4] has a gearbox (gear ratio 4:1) to better match fan and turbine blade speeds. Also the fan blades have variable pitch angles because for a given fan speed the axial flow velocity shows considerable variations with flight Mach number when the nozzle pressure ratios are well below the critical value. For the ADP the variable pitch is also used for thrust reversing during landing. For the present calculations T_{t4} = 1530 K resulted into the same value for Π_{fan} as for the ADP.

A bypass ratio B = 20 or even higher is currently considered as beyond optimum even for a long range application due to its weight based on present technology. B = 20 is included here to show the possible problems that may arise when TPS units are to be used for engine flow simulation for this type of engine. Using the previous assumptions, for the B = 20 UHBR engine a fan pressure ratio of 1.25 was found at the design point with the chosen parameter values. Note that for the CRISP a fan pressure ratio of 1.24 was selected for a bypass ratio 26.

Table 1 reviews the main data at the design point (Mach 0.8 at 35 kft). T_{t4} and T_{t45} are the total temperatures at the entry of the high pressure (hp) and the low pressure (lp) turbine respectively.

For these conditions the gross thrust of the B = 5 turbofan is 2.32 times its net thrust value. This factor increases to a value 4.42 for the UHBR turbofan with bypass ratio B = 20. This multiplier indicates the sensitivity of the net thrust to variation or prediction errors in the gross thrust. The thrust specific fuel consumption TSFC values are given for reference to actual engine data.

Table 1. Reference turbofan engines at cruise design conditions

B		5	9	15	20
OPR		30	40	40	40
T_{t4}	K	1400	1530	1530	1530
$\Pi_{t,hp}$		4.451	5.248	5.511	5.625
T_{t45}	K	1008	1062	1051	1046
$\Pi_{t,lp}$		3.980	5.188	5.707	5.951
Π_{fan}		1.770	1.535	1.329	1.249
fan NPR		2.698	2.340	2.026	1.904
core NPR		2.453	2.127	1.842	1.731
m_{core}	kg/s	23.12	18.90	17.68	17.15
$T_{tj,core}$	K	744	740	716	707
$A_{N,core}$	m^2	0.2706	0.2543	0.2706	0.2782
$A_{N,fan}$	m^2	0.7644	1.2674	2.2295	3.0368
T_{gross}	kN	58.0	69.8	99.8	110.5
T_{gross} / T_{net}		2.32	2.79	3.99	4.42
TSFC	kg/hr/kN	61.6	55.8	52.2	50.7

As a next step the performance of these engines was calculated for take-off conditions. The parameters have been calculated for 0 m ISA and at a turbine entry temperature T_{t4} that results into a net thrust value of 90 kN for the B = 5 and B = 9 turbofans. This corresponds to a lapse rate of 3.6 with respect to 25 kN at top-of-climb and is comparable to the assumption in reference [5]. For the B = 15 and B = 20 turbofans the same T_{t4} value as for the B = 9 turbofan was assumed (same turbine technology level), leading to a higher lapse rate, typical for the UHBR turbofans.

For the B = 5 and B = 15 reference engines some data are shown in table 2. These data will be used later to define the TPS power settings that are required for duplication of the fan nozzle pressure ratio.

The fan pressure ratios are lower than the cruise design values. This is mainly caused by the lower engine temperature ratio T_{t3} / T_{t2} and the fact that due to the subcritical core NPR the lp-turbine pressure ratio has become lower than its design value.

For both engines the fan nozzle pressure ratio NPR_{fan} increases but the fan pressure ratio Π_{fan} decreases with increasing flight Mach number.Although the low presure turbine delivers more power to the fan due to the increasing core NPR (towards the choked condition, increasing $\Pi_{t,lp}$), this increase is not sufficient for the fan to maintain its pressure ratio because of the increasing fan entry stagnation temperature with Mach number.

Table 2. Reference turbofan engines performance versus flight velocity up to Mach 0.4 (0 m ISA)

B_{des}		5	5	5	15	15	15
B		5.12	5.17	5.31	13.96	14.37	15.51
T_{t4}	K	1575	1575	1575	1685	1685	1685
Mach		0	0.20	0.40	0	0.20	0.40
$\Pi_{t,lp}$		3.844	3.862	3.888	4.757	4.782	4.858
Π_{fan}		1.702	1.690	1.657	1.301	1.290	1.264
fan NPR		1.702	1.738	1.850	1.301	1.327	1.412
core NPR		1.533	1.544	1.581	1.279	1.284	1.299
T_{gross}	kN	113.5	117.7	130.6	137.0	147.0	178.3
T_{net}	kN	113.5	94.1	80.7	137.0	103.3	81.9
T_{gross} / T_{net}		1	1.215	1.620	1	1.422	2.175
$V_{j,core} / V_{j,fan}$		1.422	1.404	1.356	1.569	1.522	1.402

Before being able to further specify the required TPS units, the dimensions of the fan and the nacelle should be defined in more detail. With reference to figure 1 the following dimensions were selected, using the data of table 1 and some rules-of-the-thumb derived from existing engines.

The fan diameter is determined by assuming that the average flow Mach number at the fan face is equal to 0.65 at the design point (cruise). The effective flow area is taken equal to the flow area between the hub diameter D_{hub} and the fan tip diameter D_{fan}. For B = 5 and 9 the hub/tip ratio was taken as 0.35 and for B = 15 and 20 a value 0.40 was assumed. Taking the fan nozzle diameter $D_{N,fan}$ equal to the fan tip diameter, the shoulder diameter of the core cowl D_s follows.

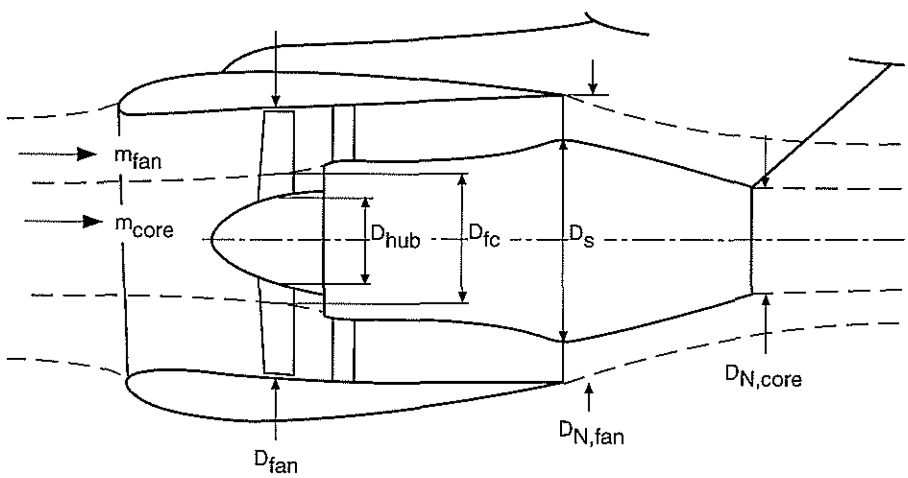

Figure 1: Diameters of reference turbofan engines to be used for the corresponding TPS designs.

The bypass and core flow are split at the fan at diameter D_{fc} and the flow at the fan face is assumed as uniform. The resulting diameters are shown in table 3.

Table 3. Resulting diameters of the reference turbofan engines

B		5	9	15	20
$D_{fan} = D_{N,fan}$	m	1.562	1.823	2.280	2.572
D_{hub}	m	0.547	0.638	0.912	1.029
D_{fc}	m	0.810	0.836	1.051	1.150
D_s	m	1.211	1.308	1.536	1.685
$D_{N,core}$	m	0.587	0.569	0.587	0.595

The next sections will discuss how the various turbofan characteristics can be implemented into Turbo Powered Simulator units and how they may differ from full scale engines.

3. TURBOFAN FLOW SIMULATION BY TPS UNITS.

The Turbo Powered Simulator was developed to simulate the engine flow effects on the (external) flow around the airframe plus the nacelles and pylons of aircraft wind tunnel models. The simulation aims at duplication of the position of the engine flow stream tube. For the inlet flow the mass flow ratio is the parameter to be duplicated. For the nozzle flow the nozzle pressure ratio (jet Mach number) and the jet-to-freestream velocity ratio (mixing process) are the simulation parameters.

By definition, the lift and drag forces on the airframe are generated by pressure and friction forces from the external flow. The presence of the simulated engine flow stream tube should create the correct external flow conditions near the engine installation. The wind tunnel force balance measures the external flow forces plus the net thrust, generated by the simulator. Subtracting the net thrust from the balance data will thus yield the required aerodynamic airframe data, including engine installation effects.

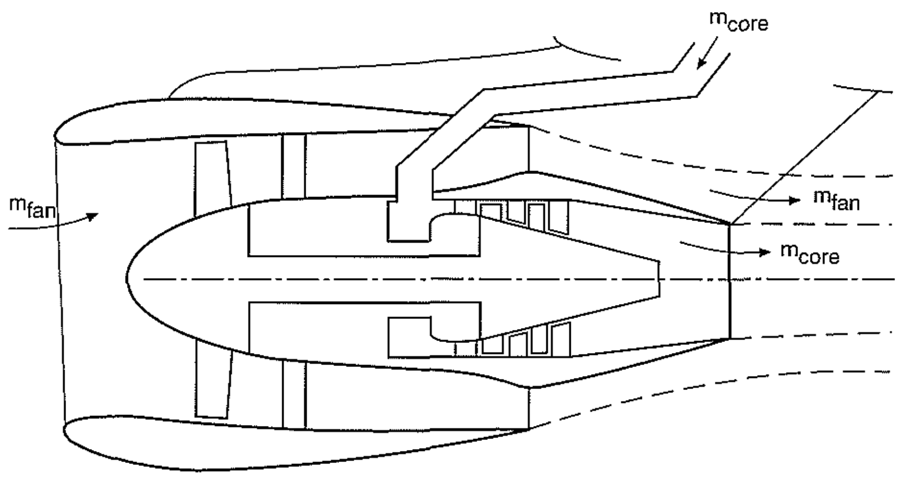

Figure 2: Principle of the Turbo Powered Simulator (TPS).

The thrust (vector) of the simulator itself is not a simulation parameter but must be precisely known for the force bookkeeping procedure. Also the flow phenomena inside the jet are not important as long as they do not affect the flow at the mixing layer between the fan flow and the external flow. This statement is only valid for engine / airframe interference testing where only the (drag and lift) forces on the airframe are of interest.

Figure 2 shows the principle of the Turbo Powered Simulator. The TPS uses an air turbine to drive the fan that should provide the same pressure ratio as the actual turbofan engine. In combination with the correct ram pressure ratio (or wind tunnel flow Mach number) a duplication of the fan nozzle pressure ratio and free stream velocity to jet velocity ratio is accomplished. The fan nozzle pressure ratio duplication ensures that the location and strength of shock and expansion waves in the jet flow are correct and the velocity ratio duplication (and temperature ratio duplication) ensures that the mixing process in the jet boundary is correctly simulated (apart from Reynolds number effects that may be of some importance in specific situations).

On the other hand, still some principal differences exist with respect to the actual turbofan engine. Apart from scale effects the following differences are to be mentioned for the TPS:

(1) core jet temperature well below rather than well above ambient,
(2) turbine entry temperature ratio T_{t4} / T_{t2} close to 1 rather than ~5,
(3) core mass flow from external supply rather than through inlet.

Only items (1) and (2) are relevant for the further discussions. Besides it is noted that the effect of a lower mass flow ratio by a factor B/(B+1) resulting from item (3) diminishes with increasing bypass ratio.

For the B = 5 reference turbofan at cruise conditions table 4 shows the differences in jet velocities are that found with a TPS that is designed for nozzle pressure ratio duplication at cruise with a core jet total temperature of 130 K below the tunnel total temperature of 298 K. The wind tunnel Mach number is duplicated at Mach 0.8. The difference in $M_{j,core}$ is due to different gas properties.

Table 4. B = 5 turbofan and TPS jet velocities at cruise conditions with fan and core nozzle pressure ratio duplication

		Turbofan	Turbofan	TPS	TPS
		core	fan	core	fan
NPR	-	2.453	2.698	2.453	2.698
V_e	m/s	494	315	237	348
M_j	-	1.228	1.280	1.209	1.280
V_j	m/s	586	384	281	423
V_0	m/s	237	237	261	261
V_e / V_0	-	2.08	1.33	0.91	1.33
V_j / V_0	-	2.47	1.62	1.08	1.62
$V_{j,core} / V_{j,fan}$	-	1.53		0.66	

If it is assumed that the fan flow is fully expanded when the station of the core nozzle exit is reached, the thickness of the 1/10 scale fan flow annulus is equal to 0.0207 meter (assuming no mixing with the external flow). This is to be compared to the diameter 0.0587 meter of the core nozzle. Using the empirical correlations in [6], it is estimated that the fan flow potential core ends at about 2.5 core nozzle diameters behind the core nozzle exit plane. This holds both for the engine and the TPS because in both cases the highest velocity is in both cases about 1.5 times the lowest velocity (same velocity ratio m in [6]).

The resulting velocity profiles are indicated schematically in figure 3. More downstream the effect of the core flow becomes visible in the jet boundary with the outer external flow.

Increasing the TPS core nozzle pressure ratio above the full scale engine value will stretch the mixing layer, and the turbulent mixing between the core and fan flow is eliminated completely if $V_{j,core} = V_{j,fan}$.

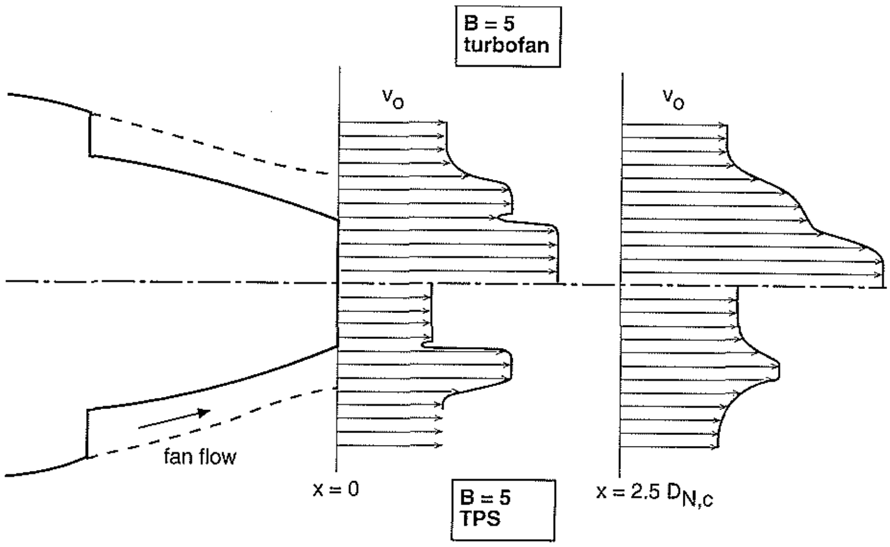

Figure 3: Comparison of turbofan and TPS jet velocity profiles.

It is an open question whether a mixing layer from an inverted flow profile or no mixing layer at all is to be preferred from a flow simulation point of view.

A second difference between the full scale turbofan engine and the TPS is the much lower turbine entry temperature of the TPS. This requires considerably higher TPS turbine pressure ratios to drive the fan. The consequences are discussed in more detail in the next section.

4. CONSEQUENCES OF TPS LOW TURBINE ENTRY TEMPERATURES.

The TPS turbine entry temperatures T_{t4} are much lower than the low pressure turbine entry temperature of the actual turbofan engines. As a consequence, the turbine temperature ratio T_{t4}/T_{t5} and hence the turbine pressure ratio must be much higher for the TPS for the same temperature drop ($T_{t4} - T_{t5}$). This follows from the well known turbine power equation:

$$P_{turb} = m_4 c_p (T_{t4} - T_{t5}) = m_4 c_p T_{t4} (1 - \Pi_t^{-\eta_t/3.5}) \tag{1}$$

where P_{turb} is the power delivered by the turbine, m_4 is the turbine mass flow, t4 and t5 are turbine entry and exit stagnation conditions, Π_t is the turbine pressure ratio and η_t is the polytropic turbine efficiency.

For most TPS applications the turbine drive air temperature T_{t4} is taken at or slightly above tunnel stagnation conditions. This procedure reduces the temperature corrections to be applied on the wind tunnel balance. In the following it will be assumed that the turbine entry temperature is equal to the tunnel stagnation temperature unless otherwise indicated.

Table 5 shows the resulting TPS characteristics to achieve duplication of the fan and core nozzle pressure ratios at cruise conditions according to table 1. Relative dimensions are according to table 3 and for simplicity a scale factor 1/10 has been selected for all following examples. This results into a fan diameter of 156 mm for a B = 5 simulator and 228 mm for B = 15.

For the fan a polytropic efficiency of 85 percent was chosen and for the turbine an efficiency of 70 percent (the likely maximum, see [7]). In practice the turbine efficiency tends to decrease with increasing bypass ratio due to the decreasing turbine tip speed. For a UHBR simulator a gearbox will be needed to maintain the turbine efficiency on a high level, adding to the complexity of the design. The design options with a lower turbine efficiency (without gearbox) are discussed later (see table 6).

Turbine total entry temperature T_{t4} was taken equal to the tunnel stagnation temperature T_{t0} = 298 K and the tunnel stagnation pressure was taken as 1 bar. the turbine exit total pressure p_{t5} was assumed equal to the core jet total pressure $p_{tj,core}$.

Table 5. TPS characteristics for design point Mach 0.8 and 70 percent turbine efficiency with duplication of the core nozzle pressure ratio

B		5	9	15	20
Π_{fan}		1.770	1.535	1.329	1.249
NPR_{fan}		2.698	2.340	2.026	1.904
$A_{N,fan}$	mm^2	7644	12674	22295	30368
m_{fan}	kg/s	2.878	4.238	6.613	8.555
P_{fan}	kW	182.2	196.5	198.5	198.7
NPR_{core}		2.453	2.127	1.842	1.731
$A_{N,core}$	mm^2	2706	2543	2706	2782
m_{core}	kg/s	1.368	1.222	1.166	1.139
T_{t5}	K	165.4	137.8	128.4	124.3
p_{t4}	bar	30.55	65.96	81.36	100.9
Π_t		18.98	47.27	67.33	88.82

It is observed from table 5 that between B = 5 and B = 20 the power P_{fan} that is required by the fan (from the TPS turbine) remains much the same. The core NPR decreases with increasing B (simulation requirement) and this is the main cause of the decreasing core nozzle and hence turbine mass flow with increasing B.

According to eq.(1) this lower mass flow requires a proportionally greater turbine temperature drop (for the same power) and hence a higher turbine pressure ratio Π_t. For a given temperature ratio T_{t4}/T_{t5}, Π_t increases with decreasing turbine efficiency η_t and hence also the turbine entry pressure p_{t4} ($p_{t5} = p_{tj}$ is given).

Turbine pressure ratios are limited by requirements of minimum blade height in the first stage in combination with the flow area at the turbine exit, and of course by the pressure levels available at the wind tunnel facilities and by model design considerations. A turbine pressure ratio value 33 has been demonstrated by TDI [7] and a value $\Pi_t = 30$ is taken here as a practical limit. Such high pressure ratio designs are usually choked at the exit guide vanes (EGV) as imposed by the available flow area at the turbine exit.

Table 5 shows that for the VHBR and UHBR simulators the resulting turbine pressure ratios are beyond the practical limits, even for a geared design with turbine efficiencies as high as 70 percent.

5. OPTIONS FOR A UHBR SIMULATOR TURBINE AND CORE NOZZLE.

According to eq.(1), if Π_t and η_t remain constant, the turbine power can only be increased to the required level by increasing the turbine mass flow or the turbine entry temperature T_{t4}.

Increasing T_{t4} reduces the turbine mass flow which is proportional to $p_{t4}/\sqrt{T_{t4}}$ at choked turbine conditions. The result is that the power increases proportional to $\sqrt{T_{t4}}$. This is a principal difference with a real engine where the turbine power increases more than proportional to T_{t4}, because the mass flow increases rather than decreases with T_{t4}. Increasing the turbine entry temperature is therefore less effective to increase the power of the TPS turbine than expected at first sight.

Increasing p_{t4} increases the mass flow and hence the power proportionally but also the core nozzle pressure ratio. The core nozzle pressure ratio can be reduced by increasing the exit area, for instance until the engine core NPR has been restored but at the expense of non-scaled core nozzle.

Leaving the turbine unchanged, increasing the core nozzle exit results into p_{tj} becoming lower than p_{t5} if the turbine is choked at the exit guide vanes (EGV) as will mostly be the case at these high turbine pressure ratios [7]. Opening up the core nozzle will then lead to a supersonic flow behind the choked EGVs and total pressure losses are generated by shock waves that hopefully remain confined inside the tailpipe. Usage of a metal foam behind the EGV could be useful to improve the flow uniformity in the nozzle exit plane but has the risk of oil clogging. It is advised to make the EGV flow area and the core nozzle throat area the same, in this case by increasing the turbine size, resulting into $p_{tj,core} = p_{t5}$ as was assumed for all previous calculations.

Note that for a given mass flow (choked turbine), nozzle exit area, total temperature and ambient pressure, the NPR or total pressure in the nozzle exit plane results as a dependent variable. Adding a pressure drop device in the upstream duct between the turbine and the exit nozzle does not alter this situation.

These options will be illustrated by taking the B = 15 simulator defined earlier as an example. It is assumed that the turbine is choked at the exit guide vanes. The turbine has a polytropic efficiency of 50 percent (no gearbox to avoid complexity) and has a pressure ratio that is at or below the practical limit of 30. The turbine must generate a power of 198.5 kW. The results are shown in table 6.

Table 6. Turbine options for a TPS simulating a B = 15 UHBR turbofan

option		1	2	3	4	5
Π_t		30	30	30	30	20
T_{t4}	K	930	298	298	298	298
NPR_{core}		1.842	3.253	1.842	1.842	3.702
$A_{N,core}$	mm^2	2706	2706	4781	4781	2706
p_{t4}	bar	36.25	64.04	64.04	36.25	48.57
p_{t5}	bar	1.208	2.134	2.134	1.208	2.428
$T_{t5} = T_{tj,core}$	K	572	183	183	183	183
$p_{tj,core}$	bar	1.208	2.134	1.208	1.208	2.428
m_{core}	kg/s	0.552	1.724	1.724	1.724	1.906
$m_{4,corr}$	g/s	27.73	27.73	27.73	49.02	40.43
$V_{j,core}/ V_0$	-	1.646	1.245	0.932	0.932	1.300
$V_{j,core}/ V_{j,fan}$	-	1.237	0.936	0.700	0.700	0.977
$m_{core}\ V_{j,core}$	N	236.7	559.0	418.2	418.2	645.4
$D_{j,core} / D_{N,ref}$	-	1	1.060	1.329	1.329	1.086

The corrected mass flow $m_{4,corr}$ is the actual turbine mass flow times $\sqrt{(T_{t4}/288K)}$ / (p_{t4} /101.3 kPa) and it is a measure for the required flow area in the first stage of the turbine.

Options 1-3 use the same turbine but for options 4 the turbine linear dimensions have increased by a factor 1.33 to pass the higher corrected mass flow and to restore the required condition $p_{t5} = p_{tj,core}$. Option 5 uses a different turbine design with $\Pi_t = 20$ rather than 30. The pros and cons of the various options will now be discussed in more detail.

The first option (T_{t4} = 930 K) introduces a number of technical complications and an internal burner like the one proposed in [7] might be considered for further study. The advantage of a variable turbine entry temperature is that the TPS is provided with an other cycle variable. This makes it possible to vary the core NPR independent of the fan NPR. Also, for a confluent nozzle with internal mixer, a simulator that provides NPR plus temperature ratio duplication may be attractive. For VHBR and UHBR simulators with separate fan and core nozzles the other options are considered by far preferable.

Options 3 and 4 use a core nozzle diameter that is 33 percent larger than according to engine scale in return for duplication of the core NPR. For option 3 the turbine is the same as for options 1 and 2 and in the tailpipe the flow from the EGV first accelerates to supersonic speed and shock waves reduce the total pressure from 2.13 to 1.72 bar (throttle process).

Options 2 and 5 retain the nacelle dimensions down to the core cowl and core nozzle. Their core NPR is much higher than for the actual engine. Their fully expanded jet velocities are however still lower than the fan flow jet velocities: to simulate the full scale engine a value $V_{j,core} / V_{j,fan} = 1.53$ would be required. The diameters of the fully expanded jets are 6.0, resp. 8.6 percent larger than the core nozzle exit diameter. This will hardly change the diameter of the fan jet flow, taking into account that the core nozzle area is only 12 percent of the fan nozzle area.

Option 4 uses a larger turbine where no throttle process is needed between the EGV and the nozzle exit. It is expected that a much better core nozzle flow quality is achieved than with option 3. In addition, with the same mass flow, the turbine entry pressure p_{t4} is reduced from 64 to 36 bar. The core nozzle diameter remains as for option 3, i.e. 33 percent larger than according to scale. Option 4 is preferred over option 3 if a larger turbine can be accommodated.

Option 5 uses the correctly scaled core nozzle diameter as for option 2 but a turbine with $\Pi_t = 20$ is used rather than 30. A value 20 is more according to current practice and may require fewer stages. Compared to option 2 the turbine entry pressure p_{t4} is reduced from 64 bar to 49 bar and the turbine mass flow has increased slightly. The core jet flow velocity is now very close to the fan flow jet velocity although their Mach numbers are quite different ($M_{j,core} = 1.51$ and $M_{j,fan} = 1.06$).

By keeping the core cowl and nozzle according to scale, the fan flow boundary location and also the pressure distribution on the core cowl is much better represented than option 4. This favours options 2 and 5 (NPR_{core} higher than for engine) over option 4 ($A_{N,core}$ larger than for engine).

Figure 4 shows the comparison in terms of flow areas and velocity ratios. For options 2 and 5 the preferable turbine pressure ratio will depend on the allowable diameter (increases with decreasing Π_t due to increasing $m_{4,corr}$) and length (-number of stages increases with increasing Π_t).

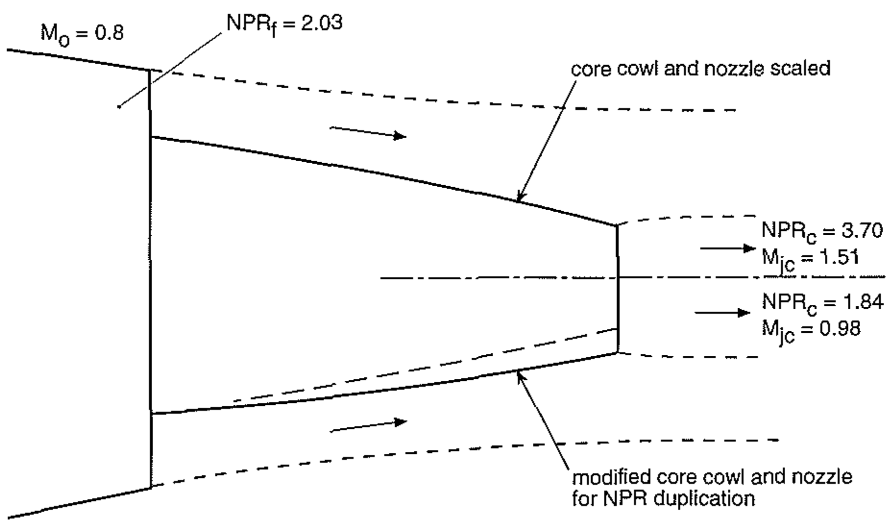

Figure 4: B = 15 simulator with duplication of core nozzle diameter (options 2 and 5) or core nozzle pressure ratio (option 4).

In connection to the load range of the wind tunnel force balance some remarks are made on the effect of the much higher core NPR on the net and gross thrust of the simulator. The fan flow gross thrust in the present case is equal to 2293 Newton and the total gross thrust of the simulator increases by 8.3 percent when changing from option 4 to option 5. The fan flow net thrust at Mach 0.8 is 570 Newton, so the net thrust of the simulator will increase by 23 percent when changing from option 4 to 5.

It is concluded that no particular difficulties will arise with respect to bookkeeping procedures and test accuracies when a TPS is used that duplicates the core cowl and nozzle geometry but operates at a too high core nozzle pressure ratio.

If nevertheless option 4 is chosen, the preferred geometry adaptation is to shorten the core cowl to accommodate a larger core nozzle and leave the upstream contour intact as applied in [8]. Modification of the core cowl contour as applied on the CRUF [9] is less desirable but stemmed in that case from the requirement for a very low core jet flow velocity to obtain a realistic value of fan to core net thrust ratio. The core cowl diameter of the CRUF had to be increased compared to scale to accommodate the resulting turbine.

The CRUF I turbine design maintains subsonic flow throughout the turbine flowpath and uses an orifice plate downstream of the EGV with a geometrical flow area of about 80 percent of the flow area just downstream of the EGV plane. This configuration in combination with the absence of a nozzle contraction is less desirable if a high flow uniformity in the exit plane is wanted.

6. TPS CHARACTERISTICS WITH UNMODIFIED CORE NOZZLE.

In the present chapter some on- and off-design characteristics of TPS units will be presented which exhibit an unmodified core cowl and core nozzle but core nozzle pressure ratio duplication is no longer required. Apart from the B = 5 simulator, the designs will differ from those in table 5 due to the constraint of a maximum turbine pressure ratio $\Pi_t = 20$ and a polytropic turbine efficiency of 65 percent for the B = 9 simulator and 50 percent for the B = 15 and 20 simulators. The results of a number of design calculations are shown in table 7.

Table 7. TPS characteristics for design point at Mach 0.8 with true scale core nozzle without the need for duplication of core NPR

B		5	9	15	20
Π_{fan}		1.770	1.535	1.329	1.249
NPR_{fan}		2.698	2.340	2.026	1.904
$A_{N,fan}$	mm^2	7644	12674	22295	30368
m_{fan}	kg/s	2.878	4.238	6.613	8.555
$V_{j,fan}$	m/s	423.1	386.0	346.8	329.2

Table 7 (cont.). TPS characteristics for design point at Mach 0.8 with true scale core nozzle without the need for duplication of core NPR

B		5	9	15	20
Π_t	-	18.98	20.00	20.00	20.00
η_t		0.70	0.65	0.50	0.50
p_{t4}	bar	30.55	39.15	48.57	47.26
$T_{tj,core}$	K	165.4	170.8	194.2	194.2
NPR_{core}		2.453	2.983	3.702	3.603
$A_{N,core}$	mm^2	2706	2543	2706	2782
m_{core}	kg/s	1.368	1.539	1.906	1.907
$V_{j,core}$	m/s	274.1	303.3	348.8	345.8
T_{gross}	N	1592	2103	2958	3476
T_{net}	N	843	998	1235	1246
T_{gross}/T_{net}		1.889	2.106	2.396	2.789

Compared to table 5 it is observed that with turbine pressure ratios limited to more realistic values $\Pi_t = 20$ also the turbine entry pressures have been reduced and are below 50 bar which is well within current wind tunnel practice. For all cases the core jet velocities are higher than the tunnel flow velocity $V_0 = 260.6$ m/s. For B = 5 and 9 the core jet velocity is lower than the fan jet flow velocity. For the UHBR simulators $V_{j,core}$ is slightly higher than $V_{j,fan}$.

To relate the thrust force to the drag force a scale factor equal to model scale squared times wind tunnel to full scale static pressure must be used scaling (dynamic pressure is equal to $0.5\ \gamma\ p\ M^2$). The scale factor then becomes 1 : 36.45. So the engine net thrust of 25 kN at cruise conditions should become 685.9 N on model scale. For B = 5 the net thrust is a factor 1.23 too high compared to the aerodynamic forces on the model. For B = 15 this has increased to a factor 1.80. With NPR duplication of the core flow this factor would become 1.47 which is still significant. This aspect should be considered when selecting the proper wind tunnel balance but no other particular problems are expected when applying thrust minus drag bookkeeping procedures.

To conclude this chapter, in table 8 the characteristics of the TPS units for B = 5 and 15 from table 7 are shown at take-off thrust conditions up to Mach 0.4. The fan pressure ratios of the full scale engines according to table 2 are duplicated. It is assumed that when the core nozzle is choked (as is also the case in table 7), the turbine is operating with choked EGV with the condition $p_{t5} = p_{tj,core}$ (no supersonic flow behind the EGV allowed). As soon as the core nozzle becomes unchoked the turbine pressure ratio starts to decrease according to the method outlined in [2].

Table 8. TPS characteristics with fan NPR duplication according to table 2 up to Mach 0.4 but without core NPR duplication

B_{des}		5	5	5	15	15	15
Mach		0	0.20	0.40	0	0.20	0.40
V_0	m/s	0	68.9	136.2	0	68.9	136.2
fan NPR		1.702	1.738	1.850	1.301	1.327	1.412
m_{fan}	kg/s	2.834	2.829	2.804	5.668	5.749	5.963
$V_{j,fan}$	m/s	317.6	322.9	338.1	217.6	224.7	246.3
p_{t4}	bar	28.10	27.62	26.20	38.38	37.62	35.78
core NPR		1.538	1.549	1.583	1.919	1.934	1.997
m_{core}	kg/s	1.259	1.237	1.174	1.506	1.476	1.403
$V_{j,core}$	m/s	196.8	198.3	202.7	257.4	258.8	264.5
T_{gross}	N	1148	1159	1186	1621	1674	1840
T_{net}	N	1148	964	804	1621	1278	1028
T_{gross}/T_{net}		1	1.202	1.475	1	1.310	1.790
$V_{j,core}$ / $V_{j,fan}$		0.620	0.614	0.608	1.183	1.152	1.074
T_{net}/ $T_{net,eng}$	%	1.01	1.02	1.00	1.18	1.24	1.26

For thrust/drag scaling in the wind tunnel at Mach 0.4 the net thrust should be 0.88 percent of the actual engine value, the model scale being 1:10 and the tunnel stagnation pressure 1 bar (0.88 times the full scale engine value assumed in table 2). For B = 5 the net thrust is 13 percent and for the B = 15 simulator 43 percent too high compared to the aerodynamic forces.

7. THE EFFECT OF THE LOCAL PRESSURE ON NOZZLE PERFORMANCE.

Is has been common practice to define the nozzle pressure ratio as the ratio of the total pressure in the nozzle exit plane to the wind tunnel free stream static pressure denoted here as p_{inf}. When the flow in the nozzle exit plane is subsonic, the ideal mass flow and ideal thrust is calculated by assuming that the static pressure in the exit plane p_e is equal to p_{inf}. In a calibration facility the actual mass flow and (gross) thrust are measured under simulated p_{t2}/ p_{inf} conditions, leading to discharge and velocity coefficients of the nozzle as function of the nozzle pressure ratio NPR_{inf}.

Due to external flow the pressure p_{loc} at the exit may become different from p_{inf}. A boattail usually leads to p_{loc} higher than p_{inf}. The nozzle then "feels" a lower pressure ratio (NPR_{loc}) and less mass flow will pass through the nozzle than according to the NPR_{inf}. This effect is called flow suppression and becomes more important with decreasing nozzle pressure ratio.

Likewise, the underwing pressures that are generated for instance by flap deflection may influence the local nozzle pressure ratio (again at subsonic exit flow conditions). Again, the effect on the mass flow is to change the apparent discharge coefficient compared to the value based on the assumption that the pressure p_e in the nozzle exit plane is equal to the free stream value p_{inf}.

The effect of p_e different from p_0 on the gross and net thrust can be derived from eq.(2).

$$\frac{T_{net}}{p_0\, A_e} = \left[1 + \gamma M_0^2 \left(1 - \frac{V_0}{V_e} \right) \right] \frac{p_e}{p_o} - 1 \qquad (2)$$

For $V_0 = 0$ the gross thrust T_{gross} results. It is assumed the fan pressure ratio remains unchanged. Due to a higher back pressure p_e / p_0 becomes accordingly higher but M_e and V_e decrease with a net result a lower mass flow, and a lower gross and net thrust.

In order to quantify these effects a realistic estimate is needed of the increase in back pressure compared to the free stream value at the engine nozzle exit plane, taking an under-wing installation as a typical example.

For a first estimate the lifting line theory provides a quick answer. It is assumed that the local lift coefficient c_ℓ is equal to 2.0 at Mach 0.2, resulting into a value 0.5 at Mach 0.4. Taking the position at half a chord length below the "lifting line" as representative for the location of the nozzle exit, the induced flow velocity is found to be equal to $V_0 c_\ell / 2\pi$. This leads to a local pressure that is about 1.5 percent above the free stream value in incompressible flow. This applies approximately to both Mach numbers as can be expected since the wing needs to generate the same lift force, whatever the value is of the flight velocity.

These effects will be more important at low nozzle pressure ratios and will therefore become more prominent with increasing bypass ratio. This will be illustrated by the following example using the fan nozzle pressure ratios calculated for three reference turbofan engines operating at take-off thrust at Mach 0.2 and 0.4, see table 2 for B = 5 and 15. Table 9 shows the effect of a 1.5 percent higher local exit pressure on the fan mass flow, and the gross and net thrust of the fan flow.

Table 9. Effect of 1.5 percent higher local exit pressure on fan nozzle performance for take-off conditions for unchanged fan flow total pressure

B_{des}		5	5	9	9	15	15
M_0		0.2	0.4	0.2	0.4	0.2	0.4
NPR_{inf}		1.738	1.850	1.496	1.591	1.327	1.412
NPR_{loc}		1.712	1.823	1.474	1.567	1.307	1.391
$M_{e,fan}$		0.911	0.967	0.765	0.828	0.631	0.703
$\Delta\ m_{fan}$	%	- 0.20	- 0.06	-0.72	-0.46	- 1.55	- 1.04
$\Delta\ T_{gross,fan}$	%	- 0.20	- 0.06	-0.71	-0.46	- 1.53	- 1.04
$\Delta\ T_{net,fan}$	%	- 0.19	- 0.07	-0.70	-0.46	- 1.52	- 1.00

These calculations show that for low bypass ratio engines the effect of a different local pressure near the nozzle exit on the mass flow and gross thrust is still rather small and comparable to the accuracies in nozzle discharge and velocity coefficients provided by the TPS calibration facilities. However, for VHBR and certainly for UHBR turbofans this effect can become quite significant and must be taken into account in the overall thrust minus drag bookkeeping procedures. It is of interest to note that the effects on the mass flow and the net and gross thrust are almost equal.

These effects are primarily a function of the nozzle pressure ratio and diminish rapidly as the flight speed and hence the ram pressure ratio builds up during take-off and climb-out. Figure 5 shows the effect of 1 percent lower nozzle pressure ratio on the mass flow for constant p_{tj} (note that in table 9 a typical value of 1.5 percent has been used).

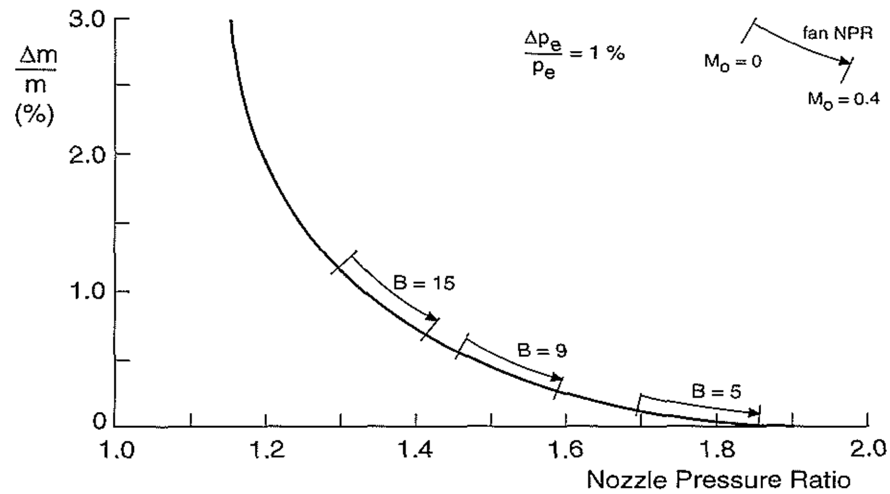

Figure 5: Variation of nozzle mass flow for 1 % exit pressure variation (with constant p_{tj}).

For low speed wind tunnel tests with VHBR and UHBR engine simulators it is strongly recommended to measure the static pressure in the nozzle exit and to use this pressure in combination with the total pressure upstream in the exhaust duct to define the nozzle pressure ratio NPR_{loc} and to use this value during nozzle calibration and wind tunnel testing to determine the gross and net thrust of the simulator.

If the free stream NPR is used, the estimated thrust of a UHBR simulator based on calibration tank data may differ more than 1 percent from the actual thrust at take-off conditions. A bookkeeping based on NPR_{inf} will interprete this as an increase in drag by 5 percent in a typical low-speed test [10]. Because the simulator thrust is not scaled in proportion to the aerodynamic forces, bookkeeping is required to distinguish between thrust and drag to arrive at the actual aircraft performance prediction. Misleading conclusions will result if variations in overall (balance) force are for some part attributed to drag variations when these are in fact caused by thrust variations.

To improve the present bookkeeping and test procedures further analysis is required (fan corrected speed or fan NPR as control parameter, choice of suitable control volumes, measurement of core cowl pressures, etc.). These procedures should be agreed upon by the research establishments that employ these TPS techniques in consultation with the airframe and engine manufacturers.

8. CONCLUSIONS.

- To compare the engine simulator requirements for turbofan engines with largely different bypass ratios, characteristics were defined for B = 5 (HBR), 9 (VHBR), 15 and 20 (UHBR) engines.

- For engine/airframe interference tests duplication of the fan nozzle pressure ratio and the nacelle contour including the core cowl are considered as the main simulation parameters to be observed. The simulator thrust is not a simulation parameter but its value may have implications for the attainable accuracies.

- The turbine mass flow becomes too small for VHBR and UHBR simulators to deliver the required power while duplicating core nozzle pressure ratio and core nozzle area of the actual engine. For the simulator either NPR_{core} or $A_{N,core}$ or both must be increased.

- For engine / airframe integration studies it is preferred to retain the core nozzle area and core cowl according to scale and to simply increase the turbine entry pressure to obtain the required mass flow. The resulting higher core nozzle pressure ratios are quite acceptable from a simulation point of view.

- For nozzle pressure ratios that are well below the critical value (1.9) the nozzle mass flow and gross thrust are influenced by pressure level variations in the exit plane. During take-off the actual thrust of an underwing mounted UHBR turbofan engine may well be 1 percent less than the value based on the assumption that the exit pressure is equal to the free stream value. This may be (mis)interpreted as 5 percent increase in drag by conventional bookkeeping.

- It is strongly recommended to measure the static pressure in the nozzle exit plane for wind tunnel tests on VHBR and UHBR engine/airframe integration at low speeds. The resulting (local) nozzle pressure ratio should be used as the correlation parameter for nozzle discharge and velocity coefficients rather than a NPR value based upon the free stream static pressure. Further study and agreement between the research institutes and the industry is needed on the appropriate thrust minus drag bookkeeping procedure.

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Appendix
Calculation model for turbofan performance characteristics.

On-design conditions.

For a given flight condition (Mach number, flight altitude) the thermodynamic cycle of a turbofan engine is determined by 4 independent parameters (apart from efficiencies, pressure losses and gas properties). For the present model the following free parameters are selected:

- the overall pressure ratio OPR = p_{t3} / p_{t2}
- the turbine inlet total temperature T_{t4}
- the temperature drop T_{t45} - T_{t5} of the low-pressure turbine
- the ratio $\sigma = NPR_{fan} / NPR_{core}$, i.e. the ratio of the fan to core NPR

It is assumed that the fan and core flow have separate nozzles. The power from the low pressure turbine is used for the fan. The fan exit pressure is equal to the compressor entry pressure. The power balance equation (assuming a mechanical efficiency of 100 %) yields:

$$c_{pg} (T_{t4} - T_{t5}) = c_p (T_{t3} - T_{t2}) + B\, c_p (T_{t3f} - T_{t2}) \tag{A1}$$

For the present calculations it is assumed that the specific heat values are c_p= 1004 J/kg/K for air and c_{pg} = 1147 J/kg/K for the gas behind the combustion chamber. The corresponding specific heat ratios are γ = 1.4 and γ_g = 4/3.

The first term on the right hand side follows from the selected OPR value, the total temperature T_{t2} (from the atmospheric temperature T_0 and the flight Mach number M_0) and for given and equal values for the polytropic efficiencies of the fan and the compressor $\eta_{fan} = \eta_{compr}$. Then for B = 0 the temperature drop of the high pressure turbine T_{t4} - T_{t45} can be calculated and, with a given value for the turbine polytropic efficiency, also the pressure ratio p_{t4} / p_{t45}.

In the next step a series of values T_{t4} - T_{t5} higher than T_{t4} - T_{t45} for B = 0 found for the previous step are chosen as input variable. The first term on the right side of eq.(A1) remains unchanged (OPR is constant) and values for B c_p (T_{t3f} - T_{t2}) result. This leaves one remaining degree of freedom to choose either a high bypass ratio B in combination with a low fan pressure ratio (small temperature increase across the fan) or vice versa.

This freedom is used by selection of $\sigma = NPR_{fan} / NPR_{core} = p_{t3f} / p_{t5}$ that defines the fan pressure ratio according to:

$$\Pi_{fan} = \frac{\sigma \ OPR \ \Pi_{core,\,loss}}{\Pi_{t,hp} \ \Pi_{t,lp}} \tag{A2}$$

The factor $\Pi_{core,loss}$ may be used to take into account pressure losses in the combustion chamber, the core nozzle and losses related to turbine blade cooling. The fan pressure ratio defines the value of T_{t3f} / T_{t2} (polytropic fan efficiency given) and the bypass ratio B follows for each input value of T_{t4} - T_{t5}.

It is remarked here that OPR is the product of the fan and the compressor pressure ratio. For different fan pressure ratios the compressor design has to change accordingly and also the high-pressure turbine. A design parameter study based on OPR = constant is therefore not equivalent to a fixed core engine model.

Jet velocities and the specific thrust (the net thrust divided by the total mass flow) follow according to standard textbooks. For the calculation of the specific fuel consumption TSFC (fuel mass flow divided by the net thrust) the following equation is used for the fuel/air ratio:

$$\frac{m_{fuel}}{m_{core}} = \frac{T_{t4} - T_{t3} - 17}{40417 - 8\,T_{t3}} \tag{A3}$$

with all temperatures in degrees Kelvin. This equation results from a curve fitting of fig. 2.15 from ref.11 and is applicable to T_{t4} values of at least 1500 K (given m_{fuel}/m_{core} gives T_{t4} with accuracy better than 4 deg at practical T_{t3} values and pressures).

For the present calculations the polytropic efficiencies for the fan, the compressor and the turbines were all given the same value of 0.88 and a core pressure loss $\Pi_{core,loss} = 0.95$ was assumed. Jet velocities were taken at fully expanded conditions, providing ideal thrust values.

A value $\sigma = 1.1$ was selected for all bypass ratios. This choice led to realistic values for the resulting fan pressure ratios.

Calculation of the net specific thrust in combination with a net ideal thrust requirement of 25 kN at Mach 0.8 and 35 kft leads to the dimensions of the core and fan nozzle exit areas A_N (assuming ideal convergent nozzles). Results are shown in table 1 in the main text.

Off-design conditions.

For calculation of the off-design behaviour the method of [2] was used. The method makes use of the fact that the corrected turbine mass flow $m_4 * (\sqrt{T_{t4}})/p_{t4}$ through the HP turbine remains constant when the turbine is operating under choked conditions. It is assumed that this is the case when the pressure ratio of the high pressure turbine $\Pi_{t,hp}$ is higher than 2.5. For all conditions considered here the high pressure turbine operates at choked conditions.

The value $\Pi_{t,hp}$ remains equal to the design value when the low turbine is choked ($\Pi_{t,lp} > 2.5$). This is the case here.

Next the low pressure turbine operation will be considered. When the core nozzle is choked ($NPR_{core} >$ 1.852) the value $\Pi_{t,lp}$ remains constant. When the core nozzle becomes subsonic the value for $\Pi_{t,lp}$ decreases in such a way that the resulting higher $p_{tj,core}$ and $T_{tj,core}$ in combination with the (fixed) core nozzle area allow the mass flow to pass (subsonically) through the core nozzle with ambient pressure in the exit plane (neglecting suppression from the external flow). This results into a decreasing value of $\Pi_{t,lp}$ with decreasing NPR_{core} (below 1.852).

The resulting power from the low pressure turbine is delivered to the fan to compress the bypass mass flow plus the core mass flow. The bypass mass flow is dictated by the fan nozzle area and the level of the fan delivery total pressure and temperature, neglecting duct losses.

Off-design calculations are performed for a given flight condition (Mach, altitude), turbine entry temperature T_{t4} and design turbine pressure ratios (at the design point the core nozzle is choked). At off-design conditions the core nozzle may become subsonic and the low pressure turbine pressure ratio will decrease below its design value. The fan pressure ratio is used as input variable that results into the power to be delivered by the low pressure turbine. This input variable is changed iteratively until the required low pressure turbine pressure ratio matches the actual low pressure turbine pressure ratio (equal to the design value or lower if NPR_{core} becomes subcritical). Results are shown in table 2 in the main text.

It is noted that this method will not provide realistic results when the low pressure turbine choking occurs at the exit guide vanes (EGV). For engine turbines with design pressure ratios of about 5 and one or two stages considered here choking will occur more upstream . However, turbines used for turbo powered simulators (TPS) may have to be designed for much higher pressure ratios and the increase in volume flow during the expansion process may lead to a design with choking at the exit guide vanes. In such a case change of the conditions downstream of the EGV will have no effect on the working point of the turbine.