Turbine Engine Cycle Design

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Executive Summary

This project was the design of two new airbreathing engines, one for a commercial airliner and one for a high-performance aircraft. Each aircraft had specific thrust requirements and other design constraints (Figure 1) that needed to be met. The engines were designed by using a MATLAB simulation, simultaneously calculating each engine's performance values and optimizing engines for minimum thrust-specific fuel consumption (TSFC). Using the MATLAB simulation, four engine cycles described below were chosen, from all the ramjets, turbojets, turbofans (as well as with differing components in the presence of an afterburner or the separation of nozzles vs. a single combined nozzle) possible.

Through general experimentation it was found that turbofans far outperformed turbojets and ramjets, so every engine designed in this project is a turbofan with air bleeding. The major design choices extend to the presence of an afterburner, as well as the separation or combination of the exit nozzle.

In the first flight condition, a high specific thrust is required at low (zero) Mach number – hence, it was found that a turbofan with separated nozzles, which produce high thrust at low TSFC cost when Mach number is low, was the most desirable engine cycle (See Table 1.A). In the second flight condition, the commercial airliner is climbing, with nonzero Mach number and high specific thrust requirement. It was found that a turbofan with combined nozzles and an afterburner was most desirable, as the afterburner produces a boost to thrust that would otherwise require a significant increase in TSFC to replicate. Finally, the third and fourth flight conditions are the cruise steps of the commercial/high-performance aircraft respectively, with the largest difference between the two being that the high-performance aircraft cruises at supersonic speed – for both of these, due to low Mach number, a combined nozzle with no afterburner was preferred by the simulation.

Another goal of the project was to determine performance of the previously determined four engine cycles across all flight conditions. Using the simulation, it was found that separated nozzles were highly costly in terms of fuel at higher Mach numbers, while a combined nozzle, while being much less fuel-demanding, does not produce enough thrust. With these two observations, the final designs for the two airbreathing engines could be put forward, marking also the third and final goal of the project.

In this case, it was determined that the ideal engine cycle would be a turbofan with combined nozzle (nozzle mixer, bleeding included) and an afterburner. The assumption is that the aircraft spends the most time cruising, rather than taking off (or climbing, in the commercial airliner's case). With this in mind, the MATLAB simulation was used to optimize the cruising step, but with higher-than-required specific thrust to ensure the aircraft could produce more than enough thrust during the takeoff step. Finally, the results are shown below:

Aircraft, Step	$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$
Commercial, Takeoff	5.1458	49.7168
Commercial, Climb	3.8394	66.6349
Commercial, Cruise	3.0499	83.8843
Performance, Takeoff	5.3694	57.1388
Performance, Cruise	3.0494	100.6092

Introduction

The purpose of this project is to design and then optimize two airbreathing engines, one for each of the two aircraft described below.

Vehicle	Flight Condition	Altitude km//kft	Ta K//R	Pa kPa//psia	M	Required Specific Thrust kN·s/kg // lb_f·s/lb_m
Commercial Airliner	Max Takeoff MTO Thrust (Static)	0	298//519	101.3//14.7	0	3.05//311
	Max Climb MCL Thrust	4.57//15.0	258//465	57.2//8.30	0.45	2.04//208
	Max Cruise MCR Thrust	10.7//35.0	219//394	23.8//3.45	0.88	0.936//95.4
High Performance Aircraft	MTO Thrust	0	298//519	101.3//14.7	0	3.05//311
	MCR Supersonic Thrust	15.2//50.0	216//389	11.6//1.68	1.3	1.35//138

Figure 1 : Design Conditions given by problem description

The project has three main goals. The first is to design four different cycles, one for each flight condition, that produces the exact required specific thrust while minimizing TSFC with respect to other possible cycles. The second goal is to examine the cycles from the first goal in terms of their performance on the other three flight conditions. The third and final goal is to suggest a single engine cycle, not restricted to those already studied, that might best suit the commercial airliner and the high-performance aircraft.

The components able to be selected/used in engine cycles are shown in Figure 1.

- diffuser (**d**)
- bypass fan (**f**)
- compressor (**c**)
- fuel pump (**p**)
- main combustor/burner (**b**)
- turbine (**t**): runs compressor and fuel pump
- fan turbine (**ft**): to run the fan
- afterburner (**ab**)
- core nozzle (**n**)
- fan nozzle (**fn**)
- combined nozzle (**cn**) [replaces the separate core and fan nozzles]

Figure 2: General components of an engine, for the purposes of this study

Approach

The method of approach used for the purposes of this study was rather straightforward. First, a MATLAB function using the Equations in Appendix B was created, named getValue. In this case, a set of inputs, namely, $f, f_{ab}, b, Pr_C, \beta, and\ Pr_f$ are taken as design parameters, and the method getValue returns the performance values of the engine cycle. The equations in Appendix B, which are a comprehensive list of relationships regarding stagnation properties and power required/produced across an engine's components, drive this method by allowing ST, TSFC, and other performance values (also included in Appendix B) to be calculated. The method getValue contains a block of code for setting atmospheric conditions, allowing the user to modify those conditions in order to test performance at the flight conditions given.

From here, a second MATLAB method, named optimize, was written using the language's inbuilt fmincon function. This method iterates through a range of user-defined values, inputting each set of values while holding ST constant into getValue and obtaining the TSFC, which it then compares and minimizes. In conjunction with getValue, it is possible to set a range of restrictions and define an atmospheric condition, and the optimize function will return the optimized engine cycle (defined by its design parameters).

The importance of getValue and optimize is emphasized by the manner in which getValue is set up, where an afterburner can be added or removed by changing the value of a variable that controls whether the afterburner part of the code will be executed. Similarly, the another user-defined variable executes the code for separate nozzles or for a combined nozzle (with nozzle mixer), another important design choice.

With the combination of these two powerful pieces of code, simulations can be run to determine the return values (outputs) of different engine compositions. Comparing TSFC across engine compositions results in a) arrival at a set of optimized engine parameters, and b) arrival at a consensus best engine design, component-wise, for that flight condition.

In reference to the third goal, it became clear that cycles that require low TSFC are incapable of delivering the thrust required for takeoff. As a result, a compromise was struck, prioritizing TSFC over required ST in that ST was allowed to exceed its required value. Thus, optimize was used on a getValue function with the atmospheric conditions of the cruise flight condition but the specific thrust requirement of the takeoff flight condition. This was called the "best" engine cycle, as it is highly fuel-efficient at the cost of exceeding ST. However, it was reasoned that an overabundance of ST is manageable through other means, such as perhaps aerodynamically tweaking the aircraft to produce greater drag at cruise conditions.

Results

To fulfill the first and second goals of the project, four different engine cycles are required. For the first goal, the engine cycles must provide the target Specific Thrust while maintaining a relatively low TSFC for each flight condition. For the purposes of this section, the “general” cycle (see Appendix A) is considered the base case, with possible modifications being made in the following areas:

1. Choice of afterburner (present, or not present)
2. Choice of combined or separate nozzles for turbofans
3. Choice of fan or no fan (turbojet or turbofan)
4. Bleeding compressor air to cool turbine (or not)

In the simulation, it was found that in no flight condition are the fan and bleed not beneficial to the optimization of the engines, so therefore the cycles described below are all turbofans with a bleed-air system by default.

1. Commercial and High-Performance Aircraft – Takeoff

   The engine cycle, now referred to as Engine Cycle 1, chosen for this flight condition includes separate nozzles with no afterburner. The idea behind this is simple – separating core and bypasses effectively increases the produced thrust when the flight velocity is low (in this case, it is zero). An afterburner has a similar effect, but also dramatically increases TSFC, so it is left out.

f	f_{ab}	b	Pr_c	Pr_f	β
0.0234	0	0.0076	16.7917	1.5974	10.5194

Table 1.A – Simulation Outputs for Cycle 1

$ST\ (kN*\frac{s}{kg})$	$TSFC(\frac{kg}{N*s})$	$u_{ef}, u_{ec}(\frac{m}{s})$	$\eta_{th}, \eta_o, \eta_p$	$w_c, w_f, w_p\ (\frac{kJ}{kg})$	$w_t(\frac{kJ}{kg})$	$T_{ef}, T_{ec}(K)$, $p_e(kPa)$
3.05	81.5997	289.6	14.66% 0 0	487.320 549.490 0.733	488.06	303.7 303.7 101.3

Table 1.B – Simulation Outputs for Cycle 1

T_{01}	p_{01}	T_{02}	p_{02}	T_{03}	p_{03}	T_{04}	p_{04}	$T_{05,1}$	$p_{05,1}$
298	101.3	345.2	161.8	809.0	2717	1646	2609	1259	755.4

Table 1.C – Component Stagnation Pressures, Temperatures for Cycle 1 (kPa, K)

$T_{05,m}$	$p_{05,m}$	T_{06}	p_{06}	T_{07}	p_{07}	T_e	p_e	T_{ef}	T_{ec}
1256	757.3	2300	101.3	N/A	N/A	2300	101.3	N/A	N/A

Table 1.D – Component Stagnation Pressures, Temperatures for Cycle 1 (kPa, K)

2. Commercial Aircraft – Climb

Engine Cycle 2 is a turbofan with an afterburner and a combined nozzle. The flight condition is defined by a nonzero Mach number, with a slight decrease in required thrust in comparison to the first flight condition. While separated nozzles are more fuel-efficient at boosting thrust when the Mach number is low, here the Mach number is sufficiently high to warrant the addition of an afterburner with a combined nozzle, which achieves a similar result in terms of boosting thrust as separated nozzles with no afterburner, but is much more fuel(cost) efficient when the Mach number is not zero.

f	f_{ab}	b	Pr_c	Pr_f	β
0.0268	0.0344	0.0	1.001	1.6	1.2857

Table 2.A – Simulation Outputs for Cycle 2

$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	$u_{ef}, u_{ec}(\frac{m}{s})$	$\eta_{th}, \eta_o, \eta_p$	$w_c, w_f, w_p\ (\frac{kJ}{kg})$	$w_t(\frac{kJ}{kg})$	$T_{ef}, T_{ec}(K)$, $p_e(kPa)$
2.04	108.0005	1027.8	0% 11.13% 24.39%	0.007 98.58 .119	.126	745.6691 745.6691 57.2

Table 2.B – Simulation Outputs for Cycle 2

T_{01}	p_{01}	T_{02}	p_{02}	T_{03}	p_{03}	T_{04}	p_{04}	$T_{05,1}$	$p_{05,1}$
268.449	65.0134	311.13	104.02	311.14	104.03	1341	99.867	1341	99.83

Table 2.C – Component Stagnation Pressures, Temperatures for Cycle 2 (kPa, K)

$T_{05,m}$	$p_{05,m}$	$T_{05,2}$	$p_{05,2}$	T_{06}	p_{06}	T_{07}	p_{07}	T_{ef}	T_{ec}
1340.8	99.84	1258.6	75.59	2300	73.32	1210.5	439.23	N/A	745.6691

Table 2.D – Component Stagnation Pressures, Temperatures for Cycle 2 (kPa, K)

3. Commercial Aircraft – Cruise

The engine cycle optimized for flight condition 3, the cruising flight condition, is a turbofan with a combined nozzle and no afterburner. The thrust requirement for this flight condition is the lowest among them, but the freestream Mach number is high. The thrust requirement is satisfied by a combined nozzle, needing no "boosts" in the form of an afterburner or separated nozzles, so thus the cycle (this cycle) with the highest possible TSFC and lowest ST at high Mach numbers is used.

f	f_{ab}	b	Pr_c	Pr_f	β
0.0082	0	0.1	31.1808	0.0175	1.2000

Table 2.A – Simulation Outputs for Cycle 2

$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	$u_{ef}, u_{ec}(\frac{m}{s})$	$\eta_{th}, \eta_o, \eta_p$	$w_c, w_f, w_p\ (\frac{kJ}{kg})$	$w_t(\frac{kJ}{kg})$	$T_{ef}, T_{ec}(K)$, $p_e(kPa)$
0.96	221.7484	1118.4	--- 9.77% 38.44%	513.56 15.32 374.4433	513.94	1748.3 1748.3 23.8

Table 2.B – Simulation Outputs for Cycle 2

T_{01}	p_{01}	T_{02}	p_{02}	T_{03}	p_{03}	T_{04}	p_{04}	$T_{05,1}$	$p_{05,1}$
252.9817	37.937	267.82	45.525	756.5579	1419.5	1086.6	1362.7	580.03	100.0

Table 2.C – Component Stagnation Pressures, Temperatures for Cycle 2 (kPa, K)

$T_{05,m}$	$p_{05,m}$	$T_{05,2}$	$p_{05,2}$	T_{06}	p_{06}	T_{07}	p_{07}	T_{ef}	T_{ec}
597.54	101.25	582.82	91.895	2300	91.895	2266	752.37	N/A	1748.3

Table 2.D – Component Stagnation Pressures, Temperatures for Cycle 2 (kPa, K)

4. High Performance Aircraft – Cruise
   This engine cycle is the sole supersonic flight condition, but the specific thrust requirement is actually relatively low, at only 1.35 (less than half that of the takeoff condition). The Mach number, however, is very high, so separating core and bypass nozzles is out of the question. Since the Mach number is low, an afterburner is not needed and just represents more fuel consumption, so Cycle 4 is fundamentally the same as Cycle 3 component-wise.

f	f_{ab}	b	Pr_c	Pr_f	β
0.0260	0	0.0	1	0.454	1.6

Table 2.A – Simulation Outputs for Cycle 2

$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	$u_{ef}, u_{ec}(\frac{m}{s})$	$\eta_{th}, \eta_o, \eta_p$	$w_c, w_f, w_p\ (\frac{kJ}{kg})$	$w_t(\frac{kJ}{kg})$	$T_{ef}, T_{ec}(K)$, $p_e(kPa)$
1.35	159.775	1270.0	--- 19.89% 46.56%	1.42*10^(-5) 6.753 .1142	.1142	1038.9 1038.9 116.0

Table 2.B – Simulation Outputs for Cycle 2

T_{01}	p_{01}	T_{02}	p_{02}	T_{03}	p_{03}	T_{04}	p_{04}	$T_{05,1}$	$p_{05,1}$
289.0090	29.482	334.9637	47.172	334.9637	47.172	1331.6	45.285	1331.5	45.271

Table 2.C – Component Stagnation Pressures, Temperatures for Cycle 2 (kPa, K)

$T_{05,m}$	$p_{05,m}$	$T_{05,2}$	$p_{05,2}$	T_{06}	p_{06}	T_{07}	p_{07}	T_{ef}	T_{ec}
1331.5	45.271	1275.0	37.43	2300	3.7432	1710.7	106.58	N/A	1038.9

Table 2.D – Component Stagnation Pressures, Temperatures for Cycle 2 (kPa, K)

The second goal of the project involves obtaining outputs (ST, TSFC) for the above described four engine cycles across all four flight conditions.

Vehicle	Flight Condition	Altitude km//kft	Ta K//R	Pa kPa//psia	M	Required Specific Thrust kN·s/kg // $lb_f s/lb_m$
Commercial Airliner	Max Takeoff MTO Thrust (Static)	0	298//519	101.3//14.7	0	3.05//311
	Max Climb MCL Thrust	4.57//15.0	258//465	57.2//8.30	0.45	2.04//208
	Max Cruise MCR Thrust	10.7//35.0	219//394	23.8//3.45	0.88	0.936//95.4
High Performance Aircraft	MTO Thrust	0	298//519	101.3//14.7	0	3.05//311
	MCR Supersonic Thrust	15.2//50.0	216//389	11.6//1.68	1.3	1.35//138

Table 6: Standard Flight Conditions

1. Cycle 1 (See Table 1.A for other parameters):

Condition	$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	f	f_{ab}
Commercial/Performance MTO	3.05	81.5997	0.0234	0
Commercial MCL	3.2827	501.3556	0.4572	0
Commercial MCR	2.4914	663.8735	0.4594	0
Performance MCR	3.4008	483.17	0.4564	0

Table 7: Outputs for Cycle 1 across Flight Conditions

The performance of the cycle is severely compromised at other flight conditions, as the TSFC increases by an entire order of magnitude. This is expected, as by the nature of this cycle (separated nozzles), its performance at nonzero Mach numbers should come at a heavy cost. In no situation is the cycle unable to produce more than the required specific thrust, however, the high TSFC implies that this is not holistically a very efficient cycle.

2. Cycle 2 (See Table 2.A for other parameters):

Condition	$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	f	f_{ab}
Commercial/Performance MTO	3.0180	1611.2	0.3507	1.0000
Commercial MCL	2.04	108.005	0.0268	0.0344
Commercial MCR	0.9227	545.9841	0.1215	0.0185
Performance MCR	1.3100	540.0416	0.1340	0.0626

Table 8: Outputs for Cycle 2 across Flight Conditions

Cycle 2 fails to meet the specific thrust requirements for the other three flight conditions other than the one for which it was designed. Similarly, the TSFC is on the fourth order of 10 for the first condition, where the aircraft is taking off. That is, the cycle is poor at producing a lot of thrust at zero Mach number, and although it is significantly less poor in the other two conditions (545.9841 and 540.0416 TSFC respectively), the cycle is still only maximized for the commercial aircraft's climb thrust condition.

3. Cycle 3 (See Table 3.A for other parameters):

Condition	$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	f	f_{ab}
Commercial/Performance MTO	2.6451	123.6453	0.0413	0
Commercial MCL	2.2673	87.0754	0.0053	0
Commercial MCR	2.04	221.7484	0.0082	0
Performance MCR	1.3493	181.8101	0.0186	0

Table 9: Outputs for Cycle 3 across Flight Conditions

The third cycle performs much better than its counterparts TSFC-wise, with no value exceeding 230 kg/kN*s. However, Cycle 3 does not meet the specific thrust requirements of the flight conditions for which it was not designed. It should be noted here that a combined nozzle + no afterburner is the lowest fuel-cost cycle available to us – it should therefore be expected that TSFCs are STs are similarly low across the four conditions.

4. Cycle 4 (See Table 4.A for other parameters)

Condition	$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	f	f_{ab}
Commercial/Performance MTO	2.7651	159.9946	0.0890	0
Commercial MCL	1.9403	158.6727	0.0516	0
Commercial MCR	0.96	153.3975	0.0070	0
Performance MCR	1.35	159.775	0.0260	0

Table 10: Outputs for Cycle 4 across Flight Conditions

Cycle 4 is similar to Cycle 3, except with a different set of parameters. So, the behavior across the four conditions is similar, with the Cycle failing to produce enough thrust but maintaining a relatively equal TSFC no matter what conditions. Thus, it is safe to conclude that the strength of a cycle where the nozzle is combined (with a nozzle mixer) and contains no afterburner is that it has relatively the same thrust-specific fuel consumption even if conditions vary.

The final goal of the project is to suggest a single engine cycle of each aircraft.

1. Commercial Aircraft:

It is important to mention that, while the separated nozzle engine cycle introduced in Cycle 1 is the most efficient at the takeoff flight conditions, the engine cycle becomes more and more inefficient as Mach number increases, as evidenced in Table 7.

Therefore, the problem with the commercial aircraft is one of satisfying both the 3.05 ST requirement in the takeoff step while minimizing TSFC on the remaining two steps (climb and cruise), which we can assume will be more important in the scope of fuel consumption because the aircraft will be cruising for significantly longer than it is taking off. In terms of engineering design, there is a clear hierarchy to what is most important when presenting an overall cycle for the commercial aircraft:

1) Meet/exceeds specific thrust requirements of the takeoff stage.
2) Meets/exceeds specific thrust requirements on the remaining two stages
3) Minimizes TSFC on the longest step, which is the cruise (TCR) step
4) Minimizes TSFC as much as possible on the remaining two steps

With this in mind, to achieve 1) without large TSFC requires the use of some thrust-enhancing component, either a core and bypass nozzle system or an afterburner. From Table 7 we know that separated nozzles are not a feasible option due to high TSFC elsewhere. Thus, it is the engine cycle will certainly be defined by a nozzle mixer and combined nozzle, along with an afterburner.

Tables 11, 12, and 13.A, B describe the proposed cycle for the commercial aircraft. At flight conditions for cruise, the aircraft reaches the specific thrust requirement in the takeoff step while achieving a very low TSFC. In doing so, the design guarantees that the aircraft achieves at least the specific thrust requirement at the takeoff stage. While having much having cruise thrust than required might endanger the passengers, it is possible through considerations of aerodynamics to produce enough drag to prevent over-acceleration of the aircraft, thus potentially nullifying that concern.

f	f_{ab}	b	Pr_c	Pr_f	β
0.0282	0.0429	0.1	46.9729	1.6	6.4679

Table 11 - Commercial Aircraft Engine Cycle design parameters

	$ST\ (kN * \frac{s}{kg})$	$TSFC(\frac{kg}{N * s})$	$u_{ef}, u_{ec}(\frac{m}{s})$	$\eta_{th}, \eta_o, \eta_p$	$w_c, w_f, w_p\ (\frac{kJ}{kg})$	$w_t(\frac{kJ}{kg})$	$T_{ef}, T_{ec}(K)$, $p_e(kPa)$
Takeoff	5.1458	49.7168	682.5677	--- 0% 0%	797.31 357.54 192.8	799.24	--- 424.8590 101.3
Climb	3.8394	66.6349	713.0704	--- 18.04% 30.36%	718.24 322.09 1.2847	719.53	--- 373.7736 57.2
Cruise	3.0499	83.8843	759.1339	--- 25.82% 41.67%	676.69 303.45 .804	677.5	--- 325.0960 23.8

Table 12 - Commercial Aircraft Engine Cycle design outputs

	T_{01}	p_{01}	T_{02}	p_{02}	T_{03}	p_{03}	T_{04}	p_{04}	$T_{05,1}$	$p_{05,1}$
Takeoff	289	101.3	345.3856	162.080	1104.1	761.34	2140.6	730.88	1484.5	122.13
Climb	268.4490	65.013	311.1356	104.02	994.6574	488.62	2054.9	469.07	1460.8	893.24
Cruise	252.9187	37.937	293.158	60.699	937.1146	285.12	2010	273.71	1488.6	560.29

Table 13A – Component Properties, Commercial Aircraft (kPa, K)

	$T_{05,m}$	$p_{05,m}$	$T_{05,2}$	$p_{05,2}$	T_{06}	p_{06}	T_{07}	p_{07}	T_{ef}	T_{ec}
Takeoff	1447.5	124.04	1154.5	451.44	2468.8	437.90	647.0651	516.56	N/A	424.8590
Climb	1415.5	916.21	1150.3	364.14	2465.7	353.22	617.423	398.29	N/A	373.7736
Cruise	1398.9	578.55	1148.4	241.09	2464.3	233.86	601.5980	258.98	N/A	325.0960

Table 13.B – Component Properties, Commercial Aircraft (kPa, K)

The efficiencies are not ideal, as shown in Table 12. However, in the above statement we prioritized decreasing TSFC while meeting/exceeding all three specific thrust requirements, and this cycle does so. Similarly, having specific thrust greater than the required value is preferred to not meeting the required value.

Most importantly, the TSFC values are all sub-100, with fuel consumption during takeoff falling as low as 50 kg/kN*s.

2. High Performance Aircraft

The high-performance aircraft differs from the commercial aircraft on the surface level due to having no climb step while simultaneously having a supersonic cruise step. However, the concepts remain the same – the supersonic condition simply varies the values, albeit significantly. For the same reasons as above, the following order of priority must be preserved.

1) Meet/exceeds specific thrust requirements of the takeoff stage
2) Meets/exceeds specific thrust requirements while cruising
3) Minimizes TSFC on the longest step, which is the cruise (TCR) step
4) Minimizes TSFC as much as possible while taking off

For the very same reason, the ideal cycle is a combined nozzle (with nozzle mixer), featuring an afterburner to provide the required boost in thrust. As with the previous aircraft, an optimization using the atmospheric conditions of the cruising step and the specific thrust requirement of the takeoff step will be used, as, in the case of a high-performance aircraft, having an excess of thrust capability may not necessarily be as dangerous or undesirable as with the commercial aircraft.

Tables 15, 16, and 17A and 17B describe the proposed engine cycle for the high-performance aircraft.

f	f_{ab}	b	Pr_c	Pr_f	β
0.0261	0.0591	0.1	52.1667	5.4356	1.6

Table 15 – High-Performance Aircraft Engine Cycle design parameters

	$ST\ (kN*\frac{s}{kg})$	$TSFC(\frac{kg}{N*s})$	$u_{ef}, u_{ec}(\frac{m}{s})$	$\eta_{th}, \eta_o, \eta_p$	$w_c, w_f, w_p\ (\frac{kJ}{kg})$	$w_t(\frac{kJ}{kg})$	$T_{ef}, T_{ec}(K)$, $p_e(kPa)$
Takeoff	5.3694	57.1388	823.4199	--- 0% 0%	834.63 308.12 2.5514	837.18	--- 456.5118 101.3
Cruise	3.0494	100.6092	936.9632	--- 31.58% 49.06%	809.45 298.82 .856	810.30	--- 353.4210 11.6

Table 16 – High Performance Engine Cycle design outputs

	T_{01}	p_{01}	T_{02}	p_{02}	T_{03}	p_{03}	T_{04}	p_{04}	$T_{05,1}$	$p_{05,1}$
Takeoff	289	101.3	345.3856	162.080	1139.7	8455.2	2096.2	8117	1405.6	1156.5
Cruise	289.0080	29.482	334.9637	47.172	1105.3	246.08	2068.6	2362.4	1398.9	352.07

Table 17.A – Component Properties, High-Performance Aircraft (K, kPa)

	$T_{05,m}$	$p_{05,m}$	$T_{05,2}$	$p_{05,2}$	T_{06}	p_{06}	T_{07}	p_{07}	T_{ef}	T_{ec}
Takeoff	1379.6	1165.7	1124	470.95	2922.2	456.82	774.2317	81.937	N/A	456.5118
Cruise	1370.3	355.56	1122.0	147.06	2920.9	142.65	765.3281	253.88	N/A	353.4210

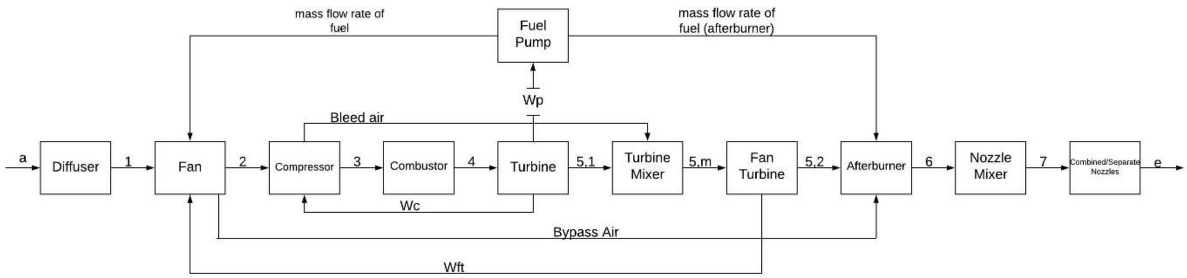
Table 17.B – Component Properties, High-Performance Aircraft (kPa, K)

This cycle is essentially the same as that of the commercial aircraft, except with supersonic considerations. As such, it has many of the same flaws. Like stated before, the excess thrust can be alleviated by increasing drag elsewhere, such that net thrust is still relatively ideal. However, that idea might be to some merit on a commercial aircraft, but not so much so on a high-performance aircraft, where having more thrust than is required may be beneficial.

Like the previous cycle, the cycle for High-Performance Aircraft also prioritizes TSPC, sacrificing accuracy of specific thrust and efficiency in the process. The overall and propulsive efficiencies are 31.58% and 49.06% - not necessarily poor, but certainly not as efficient as possible. Both engine cycles are fundamentally flawed in that they produce more thrust than is required, however, in consideration especially of TSFC, accurate specific thrust is not the highest priority.

Appendices

Appendix A – Engine Diagram:



Appendix B – Equations:

Polytropic Efficiencies

1. $\eta_i = \frac{((Pr_i)^{\frac{\gamma-1}{\gamma}}-1)}{(\text{Pr})^{\frac{\gamma-1}{\gamma\eta_{pi}}}}$ (compressor)
2. $\eta_i = \frac{Tr_i - 1}{Tr^{1/\eta_{pi}}-1}$ (turbine)

Diffuser

1. $\dot{m}_1 = \dot{m}_a(1+\beta)$
2. $T_{01} = T_a(1+\frac{\gamma-1}{2}M^2)$
3. $p_{01} = p_a(1+\eta_a\frac{\gamma-1}{2}M^2)$ (subsonic)
4. $p_{01} = p_a\left(1+\eta_a\frac{\gamma-1}{2}M^2\right)r_d$ (supersonic)

Fan

1. $\dot{m}_a(1+\beta) = \dot{m}_a(1+\beta)$
2. $T_{02} = T_{01}(1+\left(Pr_f * \frac{\gamma-1}{\gamma\eta_{pi}} - 1\right))$
3. $p_{02} = Pr_f * p_{01}$
4. $\frac{\dot{W}_f}{\dot{m}_a} = c_{p,fan}(T_{02}-T_{01})(1+\beta)$

Compressor

1. $\dot{m}_2 = \dot{m}_1(1-b)$
2. $\frac{\dot{W}_c}{\dot{m}_a} = (T_{03}-T_{02})(\frac{c_p}{R})(\bar{R})(MW)$

3. $p_{03} = Pr_c * p_{02}$
4. $T_{03} = T_{02}(Pr_c)^{R/\eta_{pi}c_P}$

Combustor

1. $\dot{m}_a(1 - b + f) = \dot{m}_4$
2. $T_{04} = \frac{(1-b)T_{03}}{1-b+f} + \frac{\eta_b f \Delta h_R}{\frac{c_p}{R}(1-b+f)(\bar{R})(MW)}$
3. $p_{04} = Pr_b * p_{03}$
4. $T_{max,b} = T_{max,0} + C_{b1}\left(\frac{b}{b_{\max}}\right)^{\frac{1}{2}}$
5. $f_{max} = \frac{(1-b)\left(T_{max,b}-T_{03}\right)}{\frac{\eta_b \Delta h_R}{c_{p,b}}-T_{max,b}}$

Fuel Pump

1. $f_1 = \dot{m}_a(f + f_{ab})$
2. $\frac{\dot{W}_{fp}}{\dot{m}_a} = \frac{(f+f_{ab})\left((p_{03}+\Delta p_{inj})-(p_a+\Delta p_{f,1})\right)}{\eta_p \rho_f}$
3. $p_{p,exit} = p_{03} + \Delta p_{inj}$
4. $\frac{\dot{W}_p}{\dot{m}_a} = (f + f_{ab})(p_{p,exit} - \left(p_a + \Delta p_{f,1}\right))$

Turbine

1. $\dot{m}_4 = \dot{m}_5 = \dot{m}_a(1 - b + f)$
2. $\dot{W}_T = \dot{W}_c + \dot{W}_p$
3. $T_{05,1} = T_{04} - \frac{\dot{W}_T}{(1-b+f)(\frac{c_p}{R})(\bar{R}MW)}$
4. $p_{05,1} = p_{04}Tr_i^{\frac{c_p}{R\eta_{pi}}}$

Turbine Mixer

1. $\sigma = \frac{1+f}{b}$
2. $p_{05,m} = p_{05,1}\left(\frac{T_{05,1}}{T_{03}}\right)^{\frac{c_p}{R\sigma}}\left(\frac{T_{05,m}}{T_{05,1}}\right)^{\frac{c_p}{R}}$
3. $T_{05,m} = \frac{bT_{03}+(1+f-b)T_{05,1}}{1+f}$
4. $\dot{m}_{5,m} = \dot{m}_a(1 + f)$

Fan Turbine

1. $T_{05,2} = T_{05,m} - \frac{\dot{W}_f}{(1+f)(c_{p,ft})}$
2. $p_{05,2} = p_{05,m} \left(\frac{T_{05,2}}{T_{05,m}}\right)^{\frac{c_{p,ft}}{R\eta_{pi,ft}}}$
3. $\frac{\dot{W}_{ft}}{\dot{m}_a} = \dot{W}_f$

Afterburner

1. $\dot{m}_6 = \dot{m}_{5,2} = \dot{m}_a(1+f)$
2. $T_{06} = \frac{\eta_{ab} f_{ab} \Delta h_R}{\frac{c_p}{R}(\bar{R} * MW)(1+f+f_{ab})} + \frac{(1+f)(T_{05,2})}{1+f+f_{ab}}$
3. $p_{06} = Pr_{ab}(p_{05,2})$
4. $f_{max,ab} = \frac{(1+f)(T_{max,ab} - T_{05,2})}{\frac{\eta_b \Delta h_R}{c_{p,ab}} - T_{max,ab}}$

Nozzle Mixer

1. $\sigma_1 = \frac{\beta}{1+f+f_{ab}}$
2. $T_{07} = \frac{T_{06} + \beta T_{02}}{\beta + 1}$
3. $p_{07} = Pr_{nm}(p_{02})(\frac{p_{06}}{p_{02}}^{\frac{1}{\sigma_1+1}} + \frac{T_{07}}{T_{02}}^{\frac{c_p}{R}} + \frac{T_{02}}{T_{06}}^{\frac{c_p}{R} * \frac{1}{\sigma_1+1}})$

Combined Nozzle

1. $u_{ec} = \left(2\eta_{cn} c_{p,cn} T_{06} \left(1 - \frac{p_a}{p_{06}}^{\frac{R}{c_{p,cn}}}\right)\right)^{\frac{1}{2}}$
2. $T_{ec} = T_{07}(1 - \eta_{cn}\left(1 - \left(\frac{p_a}{p_{07}}\right)^{\frac{R}{c_{p,cn}}}\right))$
3. $p_{ec} = p_a$

Core Nozzle

1. $u_e = \sqrt{2\eta_n c_{p,n} T_{06}(1 - \frac{p_a}{p_{06}}^{\frac{R}{c_{p,n}}})}$

2. $T_e = T_{06}(1 - \eta_n \left(1 - \left(\frac{p_a}{p_{06}}\right)^{\frac{R}{c_{p,n}}}\right))$

3. $p_e = p_a$

Fan Nozzle

1. $u_{ef} = \sqrt{2\eta_{fn} c_{p,fn} T_{02}(1 - \frac{p_e}{p_{02}}^{\frac{R}{c_{p,fn}}})}$

2. $T_{ef} = T_{02}(1 - \eta_{fn} \left(1 - \left(\frac{p_e}{p_{02}}\right)^{\frac{R}{c_{p,fn}}}\right))$

3. $p_{ef} = p_a$

Performance

1. $ST = \frac{\tau}{\dot{m}_a} = (1 + f + f_{ab})u_e + \beta u_e - (1 + \beta)M\sqrt{\gamma_{air} R_{air} T_{amb}}$
2. $\Delta d = C_{\beta 1} M^2 \left(\frac{p_a}{p_{atm}}\right) \beta^{1.5}$
3. $ST_{effective} = ST - \Delta d$
4. $TSFC = \frac{f + f_{ab}}{ST_{effective}}$
5. $\eta_p = \frac{\tau u}{\Delta \dot{KE}}$
6. $\eta_{th} = \frac{\frac{1}{2}\left((1+f+f_{ab})u_e^2 + \beta u_{ef}^2 - (1+\beta)u_a^2\right)}{(f+f_{ab})\Delta h_R}$
7. $\eta_o = \frac{M\sqrt{\gamma_a R_a T_a}}{TSFC \Delta h_R}$