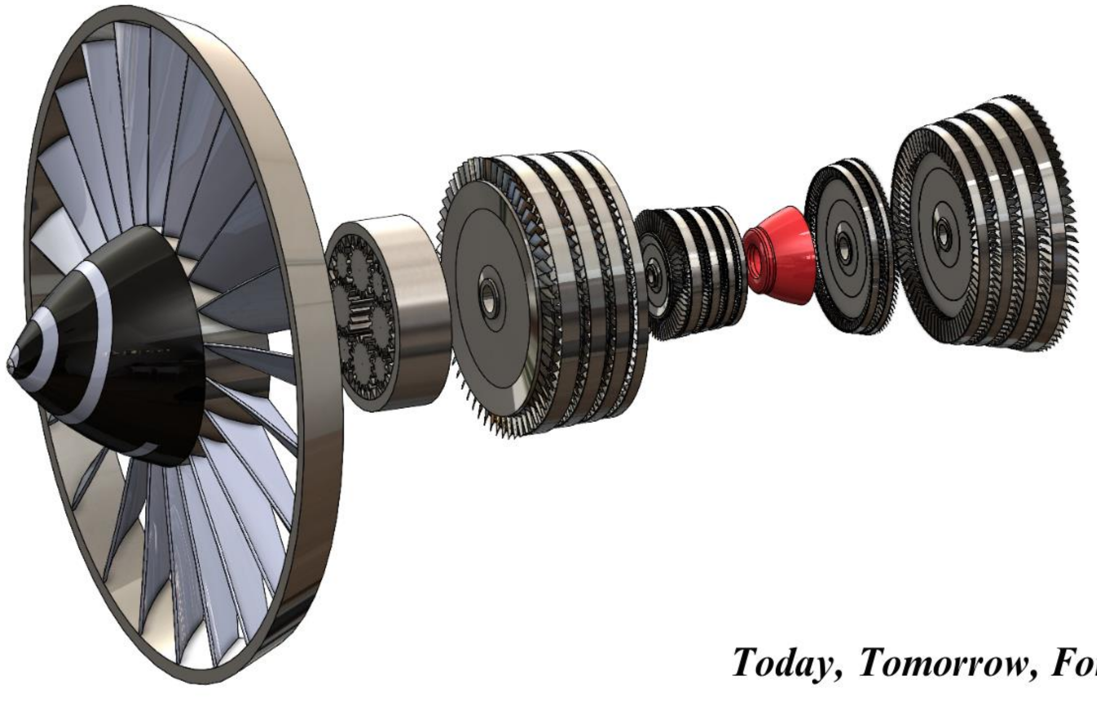
THE CENTURY

A Hybrid-Electric Propulsion System Using Fuselage Boundary Layer Ingestion for a Single Aisle Commercial Aircraf



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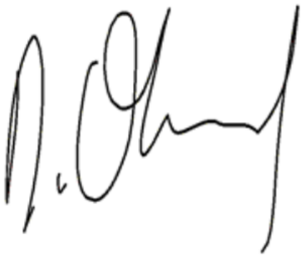

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NOMENCLATURE AND UNITS

Description		Unit
$\dot{m}$	*Mass flow rate*	*lb/s*
T_a	*The temperature of the air*	*R*
P_a	*The pressure of air*	*psi*
$T_{HPT,in}$	*High pressure turbine inlet temperature*	*R*
$T_{LPT,in}$	*Low pressure turbine inlet temperature*	*R*
$T_{LPT,in}$	*Low pressure turbine inlet pressure*	*psi*
TSFC	*Thrust Specific Fuel Consumption*	*lb/(lb.h)*
ρ	*Density*	*lb/in*^{3}
U	*Rotor Speed*	*ft/s*
$r_{hub\ t}$	*Turbine hub radius*	*in*
$r_{hub\ f}$	*Fan hub radius*	*in*
$r_{tip\ t}$	*Turbine tip radius*	*in*
$\dot{m}_h$	*Hot mass flow*	*lb/s*
$r_{tip\ f}$	*Fan tip radius*	*in*
ω	*Angular velocity*	*ft/s*
α_3	*Rotor Outlet Angle*	^{o}
γ	*The ratio of the specific heat coefficient*	
f	*Air fuel ratio*	
η_c	*Compressor Efficiency*	
ϕ	*Flow Coefficient*	
λ_n	*Stator loss coefficient*	
Ψ	*Work Coefficient*	
Λ	*Degree of reaction*	
η_t	*Turbine efficiency*	

η_f	*Fan efficiency*
η_m	*Mechanical efficiency*
η_j	*Hot and cold nozzle efficiency*

ABBREVIATIONS

BPR	***By-Pass Ratio***
FPR	***Fan pressure ratio***
LPT	***Low Pressure Turbine***
HPT	***High Pressure Turbine***
LPC	***Low Pressure Compressor***
HPC	***High Pressure Compressor***
OPR	***Overall pressure ratio***
IPC	***Intermediate pressure compressor***
TIT	***Turbine inlet temperature***

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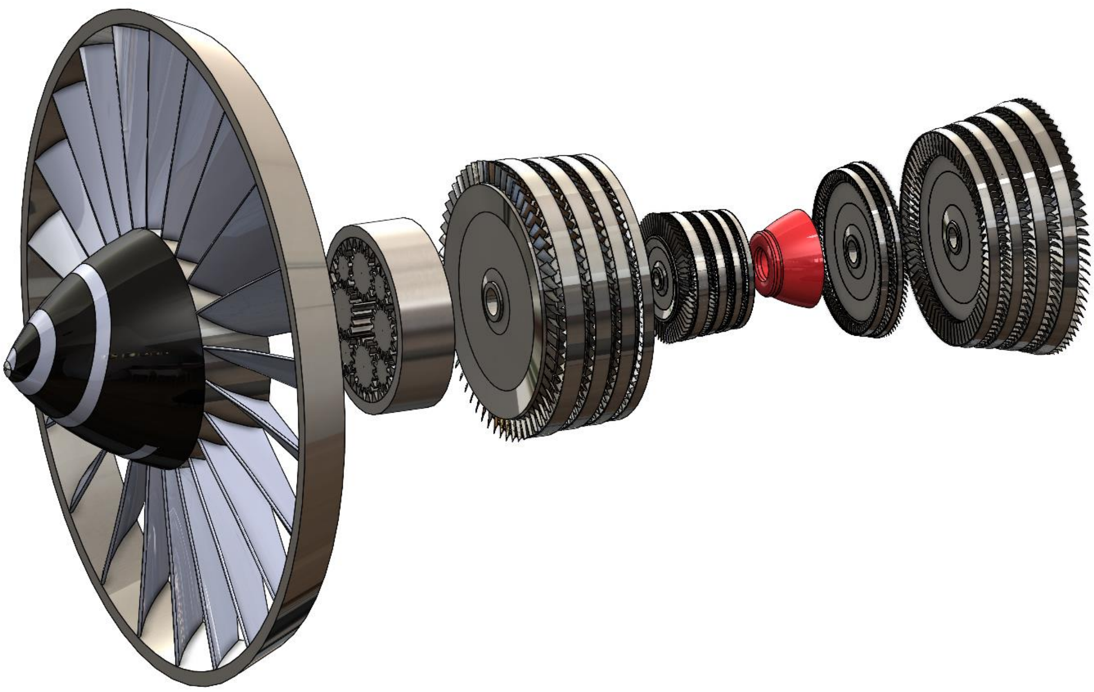


1 INTRODUCTION

In recent years, the depletion of fossil fuels and the search for alternative fuel systems has become one of the most important research and innovation topics [1]. Therefore, reducing fuel consumption in internal combustion engines is a crucial factor in achieving energy-efficient power systems and lowering carbon footprints [2]. Hybrid power systems, which combine an internal combustion engine and an electric motor, provide an excellent solution for reducing fuel consumption and emissions from fossil fuels [3]. Therefore, the conversion of internal combustion engines to hybrid systems has increased significantly in the automotive industry in the last decade. Furthermore, the marine industry has been on the way to hybrid propulsion transformation in ships to reduce emissions originating from fossil fuels [4]. Following this, the aviation industry has been working on hybrid-propelled planes to reduce emissions from gas turbines. STARC-ABL is the first passenger plane that has been worked on to be the first hybrid-propelled plane. The propulsion system of the STARC-ABL aircraft is based on a turbo-electric system, which uses electric motors powered by gas turbines mounted under the wings to generate thrust. The basic operating principle of the STARC-ABL aircraft is to reduce drag and take advantage of the slow airflow near the body of the aircraft. This slow airflow is sucked through an aft electric fan mounted on the tail, providing additional thrust, which means more thrust with less fuel consumption. However, the overall SFC decrease is very scant in this configuration. On the other hand, the boundary layer around the aircraft body is ingested by the electrically driven aft fan which hinders a lower level of drag exertion on the body. Thus, a more environment-friendly propulsion system will be achieved with a hybrid propulsion system. In this project, as we are The Century team, we redesigned and made a hybrid propulsion configuration for the STARC-ABL aircraft. CFM56-7B24 engine was used as a baseline engine whose bypass ratio (BPR), turbine inlet temperature (TIT), overall pressure ratio (OPR), and fan pressure ratio (FPR) were revised and optimized via parametric studies. All the designs of the hybrid engine propulsion system were performed through the GasTurb14 software. AxStream was used to design engine components and the aft fan with 1D and 2D thermodynamic/kinetic calculations. With this project, the baseline engine upgraded to new BPR, TIT, FPR, and OPR ratios, and engine TSFC decreased by 7.4% with a 11% thrust increase at the end of the base engine redesign. Hybrid electric propulsion increased the total thrust of the plane by 10% decreased the fuel consumption 20% with degree of hybridization (DOH) of 0.28 with almost similar propulsion system weight when compared to CFM56-7B24 engine.

2 METHODOLOGY

CFM56-7B24 turbofan engine was selected as a baseline engine to redesign and optimization. The engine specifications are given in Table 1[16].

Table 1 CFM56-7B24 engine specifications

PARAMETER	VALUE
Engine Type	Turbofan
Number of Compressor Stages (Fan, LP, HP)	1,3,9
Number of HP/LP Turbine stages	1,4
Combustor Type	Axial annular
Maximum Net Thrust at Sea Level (lbf)	24000lbf
Specific Fuel Consumption at Max. Power (lbm/hr/lbf)	0.37 lbm/hr/lbf
Overall Pressure Ratio at Max. Power	26
Bypass Ratio at Max. Power	5.3
Max. Envelope Diameter (in)	65 in
Max. Envelope Length (in)	98 in
Dry Weight Less Tailpipe (lbm)	5.234 lbm

According to the requested proposal high-pressure compressor (HPC) exit temperature (T3) and TIT (T4) was limited to 1620 R and 3150 R, respectively. Here, we designed four different engines by parametric studies based on different optimized BPR, OPR, FPR, MFR, and TIT values. During these studies engine dimensions, engine mass, thrust, and specific fuel consumption (SFC) were taken into consideration. We especially tried not to pass 65-inch diameter and 98-inch length in our engine designs. Aft and fore fans were designed as a single stage by using AxStream. 2D flow path designed and optimized via efficiency, power, and mass-flow rate under 500 iterations. Inlet and outlet thermodynamic and kinetic properties were achieved and presented in the result section. Similarly, compressors and turbines were also designed by using AxStream based on the GasTurb14 data. In this project, The Century team presented the optimal turbofan and electrical cycles based on technological advancements up to 2035. Engine designs were carried out to optimize power delivery, specific fuel consumption, and engineering costs.

3 DESIGN OF THE CFM-56 BASELINE ENGINE

In this project, CFM56-7B24 was selected as a base line engine and the new engines designed based on CFM56-7B24 parameters. Before starting a new engine design, we validated on and off designs of the CFM56-7B24 engine in Gasturb14. Fig. 2 shows baseline engine on and off design cycle calculation results. The trust of 24227lb and a TSFC of 0.3637 lb/(lb.h) was found for takeoff condition (see Fig. 1(a)) whereas these values were found to be 5585lb and 0.6864 lb/(lb.h) for cruise condition (see Fig. 1(b)). BPR and OPR 5.3 and 26 for the baseline engine. Similar isentropic efficiencies were taken with proposal request and the efficiencies of the turbines were calculated by Gasturb14. Thermodynamic, kinetic, and geometric results of the stations at takeoff condition were shown in Fig.2. The Mach number was found to be 0.81 at the exit of the hot nozzle and 0.9 for the cold nozzle. The Mach numbers were 1 for both nozzles at the cruise condition (see Fig. 3).

```
         W            T            P          WRstd
Station  lb/s         R           psia         lb/s
 amb                518,67      14,696
  2    751,000      518,67      14,549      758,586
 13    631,794      601,31      23,278      429,463
 21    119,206      576,73      20,369       90,693
 22    119,206      576,73      20,165       91,610
 24    119,206      692,01      36,498       55,441
 25    119,206      692,01      35,768       56,573
  3    116,822     1394,29     378,223        7,442
 31    106,094     1394,29     378,223
  4    108,541     2800,00     363,094       10,207
 41    113,309     2745,66     363,094       10,552
 43    113,309     2116,12      99,439
 44    119,270     2082,27      99,439
 45    121,058     2069,14      94,639       37,546
 49    121,058     1550,16      25,744
  5    121,654     1548,48      25,744      119,990
  8    121,654     1548,48      24,715      124,990
 18    631,794      601,32      22,813      438,228
Bleed    0,000     1394,29     378,222
---------------------------------------------------
Efficiency        isentr  polytr   RNI      P/P
 Outer LPC        0,9000  0,9064  0,990   1,600
 Inner LPC        0,9000  0,9047  0,990   1,400
 IP Compressor    0,9208  0,9271  1,210   1,810
 HP Compressor    0,9000  0,9260  1,727  10,574
 Burner           0,9995                  0,960
 HP Turbine       0,8846  0,8679  3,526   3,651
 LP Turbine       0,9218  0,9090  1,271   3,676
---------------------------------------------------
HP Spool mech Eff 0,9900  Nom Spd  14461 rpm
LP Spool mech Eff 0,9900  Nom Spd   5173 rpm
---------------------------------------------------
P22/P21=0,9900 P25/P24=0,9800 P45/P44=0,9517
---------------------------------------------------
hum [%]    war0      FHV      Fuel
  0,0    0,00000   18552,4   Generic

FN          =  24227,41 lb
TSFC        =    0,3637 lb/(lb*h)
WF          =   2,44743 lb/s
s NOX       =    0,8197

Core Eff    =    0,4506
Prop Eff    =    0,0000
BPR         =    5,3000
P2/P1       =    0,9900
P3/P2       =     26,00
P5/P2       =    1,7695
P16/P13     =    0,9800
P16/P6      =   0,92305
P16/P2      =   1,56800
P6/P5       =   0,96000
A8          =    382,05 in²
A18         =   1366,23 in²
XM8         =   0,90883
XM18        =   0,81826
WBld/W2     =   0,00000
CD8         =   0,97494
CD18        =   0,96397
PWX         =     150,0 hp
V18/V8,id=      0,57408
WBLD/W22 =      0,00000
Wreci/W25=      0,00000
Loading     =    100,00 %
WCHN/W25 =      0,04000
WCHR/W25 =      0,05000
WCLN/W25 =      0,01500
WCLR/W25 =      0,00500
WBLD/W25 =      0,00000
WLkBy/W25=      0,00000
WlkLP/W25=      0,00000
```

(a)

```
         W            T            P          WRstd
Station  lb/s         R           psia         lb/s
 amb                393,85       3,458
  2    306,307      444,38       5,220      798,209
 13    257,008      528,20       8,514      447,664
 21     49,299      503,34       7,416       96,238
 22     49,299      503,34       7,333       97,334
 24     49,299      622,52      13,699       57,941
 25     49,299      622,52      13,399       59,235
  3     48,313     1323,81     156,338        7,255
 31     43,876     1323,81     156,338
  4     44,941     2804,99     150,394       10,212
 41     46,913     2748,09     150,394       10,552
 43     46,913     2121,69      41,448
 44     49,378     2084,51      41,448
 45     50,118     2070,48      39,472       37,281
 49     50,118     1551,58      10,540
  5     50,364     1549,57      10,540      121,378
  8     50,364     1549,57      10,109      126,558
 18    257,008      528,20       8,329      457,608
Bleed    0,000     1323,81     156,337
---------------------------------------------------
Efficiency        isentr  polytr   RNI      P/P
 Outer LPC        0,7966  0,8101  0,426   1,631
 Inner LPC        0,7966  0,8064  0,426   1,421
 IP Compressor    0,8240  0,8387  0,517   1,868
 HP Compressor    0,8665  0,9025  0,734  11,667
 Burner           0,9981                  0,962
 HP Turbine       0,8848  0,8682  1,459   3,628
 LP Turbine       0,9114  0,8970  0,530   3,745
---------------------------------------------------
HP Spool mech Eff 0,9900  Speed      14461 rpm
LP Spool mech Eff 0,9900  Speed       5402 rpm
---------------------------------------------------
P22/P21=0,9887 P25/P24=0,9782 P45/P44=0,9523
---------------------------------------------------
hum [%]    war0      FHV      Fuel
  0,0    0,00000   18552,4   Generic

FN          =   5581,27 lb
TSFC        =    0,6869 lb/(lb*h)
WF          =   1,06486 lb/s
s NOX       =    0,4707
P5/P2       =    2,0191 EPR
Core Eff    =    0,5169
Prop Eff    =    0,7281
BPR         =    5,2132
P2/P1       =    0,9900
P3/P2       =     29,95
P5/P2       =    2,0191
P16/P13     =    0,9783
P16/P6      =   0,82398
P16/P2      =   1,59564
P6/P5       =   0,95907
A8          =    382,05 in²
A18         =   1366,23 in²
XM8         =   1,00000
XM18        =   1,00000
WBld/W2     =   0,00000
CD8         =   0,98000
CD18        =   0,97600
PWX         =     150,0 hp
V18/V8,id=      0,53110
WBLD/W22 =      0,00000
Wreci/W25=      0,00000
Loading     =    231,13 %
WCHN/W25 =      0,04000
WCHR/W25 =      0,05000
WCLN/W25 =      0,01500
WCLR/W25 =      0,00500
WBLD/W25 =      0,00000
WLkBy/W25=      0,00000
WlkLP/W25=      0,00000
```

(b)

Figure 1 Cycle calculation results of the CFM56-7B24 engine (a) takeoff condition (on design), (b) cruise condition (off design)

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	751	119,206	119,206	119,206	116,822	108,541	119,27	121,058	121,654	121,654	121,654	631,794	631,794	631,794
Total Temperature	R	518,67	576,727	692,012	692,012	1394,29	2800	2082,27	2069,14	1548,48	1548,48	1548,48	601,314	601,314	601,316
Static Temperature	R	485,923	549,369	670,685	665,237	1378,85	2795,91	2023,18	2030,26	1523,83	1497,56	1357,29	567,151	572,802	530,498
Total Pressure	psia	14,549	20,1649	36,4985	35,7685	378,223	363,094	99,4388	94,6388	25,7443	24,7146	24,7146	23,2784	22,8128	22,8128
Static Pressure	psia	11,5834	17,0011	32,6988	31,1399	362,606	360,754	88,0947	87,3824	24,1492	21,6312	14,696	18,9559	19,2349	14,696
Velocity	ft/s	626,834	574,435	507,185	568,289	448,08	249,192	923,772	749,128	580,689	834,533	1609,34	641,917	586,43	923,892
Area	in²	2681,44	357,763	257,2	239,078	52,8934	180,101	158,195	200,313	705,277	538,432	372,473	1571,09	1711,68	1317,01
Mach Number		0,58	0,5	0,4	0,45	0,25	0,1	0,432344	0,35	0,310571	0,45	0,908822	0,55	0,5	0,818261
Density	lb/ft³	0,06434	0,083527	0,131591	0,126344	0,709792	0,348263	0,117526	0,116169	0,042775	0,038986	0,029224	0,090211	0,090636	0,07477
Spec Heat @ T	BTU/(lb*R)	0,240085	0,240577	0,241909	0,241909	0,261151	0,30316	0,288843	0,28839	0,273873	0,273873	0,273873	0,240861	0,240861	0,240861
Spec Heat @ Ts	BTU/(lb*R)	0,239981	0,240261	0,241663	0,2416	0,260663	0,3031	0,287463	0,287484	0,273076	0,272227	0,267507	0,240467	0,240532	0,240123
Enthalpy @ T	BTU/lb	-4,31602	9,65096	37,439	37,439	213,459	625,494	411,161	407,201	260,584	260,584	260,584	15,5774	15,5774	15,5778
Enthalpy @ Ts	BTU/lb	-12,1681	3,05675	32,2984	30,9852	209,447	624,253	394,107	395,986	253,845	246,666	208,826	7,34287	8,70492	-1,48
Entropy Function @ T		-0,11924	0,252694	0,892664	0,892664	3,43967	6,44701	5,15292	5,12429	3,93607	3,93607	3,93607	0,399306	0,399306	0,399316
Entropy Function @ Ts		-0,34719	0,082028	0,782732	0,754088	3,3975	6,44055	5,03179	5,04452	3,8721	3,80281	3,41625	0,193897	0,228713	-0,040432
Exergy	BTU/lb	-0,357633	11,9898	38,1181	37,3992	206,709	510,279	295,91	291,207	140,548	139,095	139,095	17,8084	17,0895	17,0896
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,023069	0,02095	0,020634	0,020531	0,020531	0,020531	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Radius	in	9,93653	15,1955	14,8916	8,3161	8,45127	12,8945	12,8945	12,8945	13,5392	13,5392	8,32141	19,8009	21,9573	21,2106
Outer Radius	in	30,8588	18,5683	17,4244	12,0523	9,39979	14,9531	14,7181	15,1667	20,1942	18,8335	13,8151	29,8692	32,0463	29,7451
Axial Position	in	22,1757	22,1757	44,4795	56,9884	79,8534	91,1509	94,1783	95,442	107,228	126,412	142,471	42,8086	96,223	107,163

Figure 2 Thermodynamic, kinetic, and geometric results of the stations at takeoff condition

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	341,838	26,7575	26,7575	26,7575	26,2223	24,5037	26,9118	27,3132	27,447	27,447	27,447	315,081	315,081	315,081
Total Temperature	R	444,378	527,63	611,22	611,22	1384,87	3090	2296,38	2280,15	1665,56	1665,56	1665,56	493,412	493,412	493,412
Static Temperature	R	404,641	502,467	592,356	587,537	1369,53	3085,63	2212,48	2238,54	1600,25	1612,46	1428,12	465,216	469,877	411,036
Total Pressure	psia	5,27271	8,99466	14,2251	13,9406	207,5	199,2	58,1029	56,9409	13,4302	13,4302	13,4302	7,35799	7,21083	7,21083
Static Pressure	psia	3,80051	7,58247	12,7422	12,1343	198,929	197,926	49,5093	52,6082	11,4124	11,7658	7,23229	5,99019	6,07852	3,80814
Velocity	ft/s	690,495	549,472	476,997	534,462	446,653	260,909	1113,19	783,667	955,42	862,947	1811,35	581,643	531,402	994,181
Area	in²	2812,12	172,166	139,129	129,33	21,5637	78,1141	57,6378	79,1219	214,909	232,552	159,633	2244,55	2445,32	1825,04
Mach Number		0,69998	0,5	0,4	0,450004	0,250001	0,100001	0,500001	0,350001	0,5	0,450002	1	0,55	0,5	0,999987
Density	lb/ft³	0,02535	0,04073	0,05806	0,055743	0,392049	0,173133	0,060399	0,063432	0,019249	0,019695	0,013669	0,034753	0,034916	0,025006
Spec Heat @ T	BTU/(lb*R)	0,239848	0,240114	0,240976	0,240976	0,260853	0,310379	0,296092	0,295553	0,279674	0,279674	0,279674	0,240004	0,240004	0,240004
Spec Heat @ Ts	BTU/(lb*R)	0,239722	0,240033	0,240758	0,240702	0,260368	0,310326	0,294306	0,29467	0,277647	0,27805	0,271928	0,239915	0,239929	0,239742
Enthalpy @ T	BTU/lb	-22,1298	-2,1675	17,965	17,965	211,012	720,247	476,947	471,904	294,732	294,732	294,732	-10,3724	-10,3724	-10,3724
Enthalpy @ Ts	BTU/lb	-31,6577	-8,20104	13,4181	12,2566	207,025	718,887	452,183	459,631	276,49	279,851	229,165	-17,1331	-16,0156	-30,1244
Entropy Function @ T		-0,659571	-0,059374	0,456686	0,456686	3,414	6,94032	5,60587	5,57259	4,25471	4,25471	4,25471	-0,293731	-0,293731	-0,293731
Entropy Function @ Ts		-0,98698	-0,230166	0,346595	0,317909	3,37182	6,9339	5,44582	5,49345	4,0919	4,12241	3,63576	-0,499395	-0,464554	-0,932175
Exergy	BTU/lb	12,1144	30,2903	48,8642	48,3184	234,421	647,291	406,754	402,064	221,471	221,471	221,471	22,991	22,4451	22,4451
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,028954	0,026295	0,025898	0,025769	0,025769	0,025769	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3 Thermodynamic, kinetic, and geometric results of the stations at cruise condition

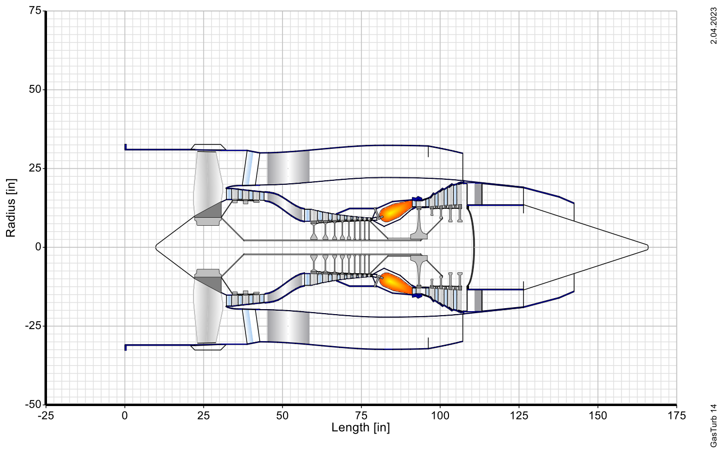


Figure 4 CFM56-7B24 Geometry

4 ENGINE SELECTION BASED ON PERFORMANCE CYCLE AND MISSION EVALUATION

4.1 PERFORMANCE CYCLE EVALUATIONS

An optimal cycle of the new CFM56-7B24 base engine was achieved via more than a million iterations and optimization of TIT, BPR, OPR, and mass flow rate (MFR) in the GasTurb14 software. BPR is one of the important design parameters for turbofan engines that affecting directly cold thrust and SFC. BPRs and their classifications used in turbofan engines were shown in Table 2[24]. The engines were designed on high and ultra-high BPR twin spools without a geared axial fan. The engine consists of a single-stage fan, three gear ratio of gearbox, four stages of low-pressure axial flow compressor, four stages of high-pressure axial flow compressor, a two-stage high-pressure axial turbine, and four stages of low-pressure axial turbine, cold and hot nozzles.

Table 2 Turbofan engine BPR ranges

TYPE OF TURBOFAN ENGINE	RANGE OF BPR
Low-Bypass	BPR<2
Medium-Bypass	2≤ BPR ≤5
High-Bypass	5≤ BPR ≤9
Ultra-High-Bypass	9≤ BPR

In this project, four engines were designed with the targets of achieving a minimum thrust of 24.200 lb, a specific fuel consumption (SFC) lower than 0.37 lb/lbf.h at the takeoff condition and 5500lb thrust and a lower SFC than 0.68 lb/lbf.h at the cruise condition for the baseline engine of CFM56-7B24, and a mass lower than 5234 lbm. To achieve these targets, the engines were designed with parametric studies that involved changing and optimizing the OPR, TIT, BPR, HPC exit temperature (T3), and MFR. During the iterations and optimizations, the maximum compressor exit temperature (T3) and turbine inlet temperature (T4) was assumed as 1620R and 3150R, respectively. The design parameters and results of the new engines were shown in Table 3.

Table 3 The engine design parameters for the base and the new engines

	ENGINE 1		ENGINE 2		ENGINE 3		ENGINE 4	
Mission	Take-Off	Cruise	Take-Off	Cruise	Take-Off	Cruise	Take-Off	Cruise
Thrust (lb)	25536	4283	24601	3953	30268	5418	31491	5711
TSFC (lb/(lb*h))	0.21	0.58	0.18	0.59	0.25	0.62	0.23	0.6
Mass Flow (lb/s)	867	341	983	434.4	1338	515	1485	649
T3(R)	1603	1384	1620	1562	1607	1389	1587	1586
T4(R)	3090	3090	2995	3070	3000	3000	3050	3112
V18/V8	0.63	0.41	0.75	0.4	0.43	0.37	0.65	0.37
BPR	11.77	11.77	14.98	15.73	12	12.14	15	16.11
OPR	39.35	39.35	38.4	48.71	39.58	38.9	37.88	46.82
FPR	1.7	1.7	1.26	1.24	1.68	1.66	1.6	1.47
LPC PR	1.58	1.58	1.61	1.91	4.0	3.93	4	5.35
HPC PR	14.88	14.88	19.25	21	6.0	6.15	6.1	6.06
LP Spool Speed	5051	5051	4461	5353	3476	3439	3362	4397
IPC Spool Speed	-	-	-	-	10428	10316	11766	15390
HP Spool Speed	20919	20923	18613	18613	23533	235357	22238	22238
Core Efficiency	0.49	0.57	0.46	0.55	0.49	0.57	0.49	0.57
Prop Efficiency	-	0.79	-	0.84	-	0.82	-	0.85

The main objectives focused on in Engine 1 were to reduce weight and shorten the length of the engine. In line with the objectives, the design process, the bypass ratio (BPR) was kept between 5 and 15 due to its effect on the engine diameter, and a value of 11.77 was deemed appropriate because of optimization studies. At the same time, other objectives were not neglected, and good progress was made in terms of fuel efficiency. In Engine 1, 43% less fuel consumption was achieved at take-off when compared to the baseline engine. The TIT value of 3090R was selected for T4 and 1603R for T3 at on design with 867lb/s mass flow rate. As a result of the optimization studies and iterations, the thrust value was increased by 5.52% to 25536 lb for takeoff. The thrust was increased by %4.35 with 5824lb whereas the decrease in SFC was %23.5 in cruise conditions. Performance cycle results for takeoff and cruise conditions of the Engine 1 were given in appendix 1. Engine 1 was not chosen as a potential candidate for the high-pressure compressor (HPC) with a higher-pressure ratio. This was because the desired pressure ratio of 14.88 for the HPC would require at least 13 stages, and in fact Engine 1's HPC did not have enough stages to achieve this pressure ratio. It is worth noting that in general, one stage of an axial compressor typically has a pressure ratio between 1.2 and 1.4 [24]. Besides, 13 stage of HPC would increase the engine length and weight. Similar to Engine 1 the main goal focused on in the Engine 2 was to maintain the T4 and T3 values at the maximum limits, hence T4 and T3 were found as 2995R and 1620R. The remaining parameters were optimized to provide the necessary thrust at the most optimum values with the least fuel consumption. In line with these goals, the optimum value for the higher BPR values was found to be 14.98 because of less fuel consumption. In addition, an OPR of 38.4 was preferred in engine 2 compared to the baseline engine. As a result of the optimization studies and iterations, the thrust of engine 2 was identical with the baseline engine with 24601 lb, and the fuel consumption has been reduced by 51.3% to 0.18 at the takeoff condition. The performance cycle results for takeoff and cruise conditions of the Engine 2 were shown in appendix 2. However, thrust of engine 2 decreased 16.9% with 4634 lb, whereas TSFC increase was 23.5% at the cruise condition. The engine 1 and 2 were ungeared engines and when we connected the electrical power unit, engines lost too much thrust because of the lower rotational speeds of LP spools. Therefore, we decided to increase rotational speed of the IP spool up to 10000 rpm by using gearbox. For these reasons, engine 3 and 4 were designed with BPRs of 12 and 15 with gear boxes which had a 3:1 and 3.5:1 gear ratio, respectively. Thus, the pressure ratios of LPC and HPC were decreased as well as stage number of the HPC that provide decrement in the engine weight and length. When we increased the intermediate pressure spool rotational speed, we *found that thrust increased to 30268 lb with BPR of 12. Besides TSFC was 0.25 with 32.4% decrement when compared to baseline engine. Furthermore, OPR of the engine was 39.58 which consisted of 1.68 FPR, 4 LPC PR, and 6 HPC PR. On the other hand, cruise thrust increased by 34.7% by using 11377 rpm IP spool rotational speed. However, MFR was increased from 751 lb/s to 1338 lb/s which resulted fan diameter increase. BPR of 15 was chosen for engine 4 with T3 and T4 temperatures of 1587R and 3050R, respectively. The optimum OPR was found to be 37.8 with IP spool rotational speed of 11766 rpm. These parameters provided extraordinary thrusts of 31491lb and 5711lb at the takeoff and cruise conditions. The performance cycle results for takeoff and cruise conditions of the Engine 4 were shown in appendix 3 Results showed that TSFC of engine was similar to engine 3.*

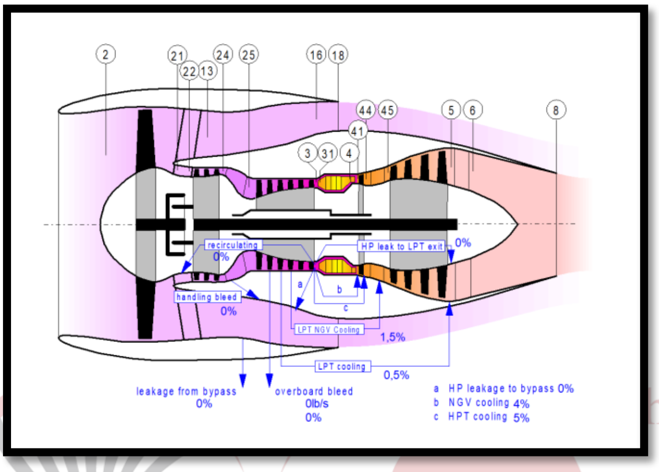


Figure 5 Turbofan engine station numbering and engine configuration

4.2 Mission Evaluation

A mission was planned to test hybrid propulsion system for designed engines in section 3.1. Therefore, a flight from Istanbul airport to San Diego International airport was planned to test the propulsion systems. The graph of the flight mission and fuel consumption were shown in Fig. 5.

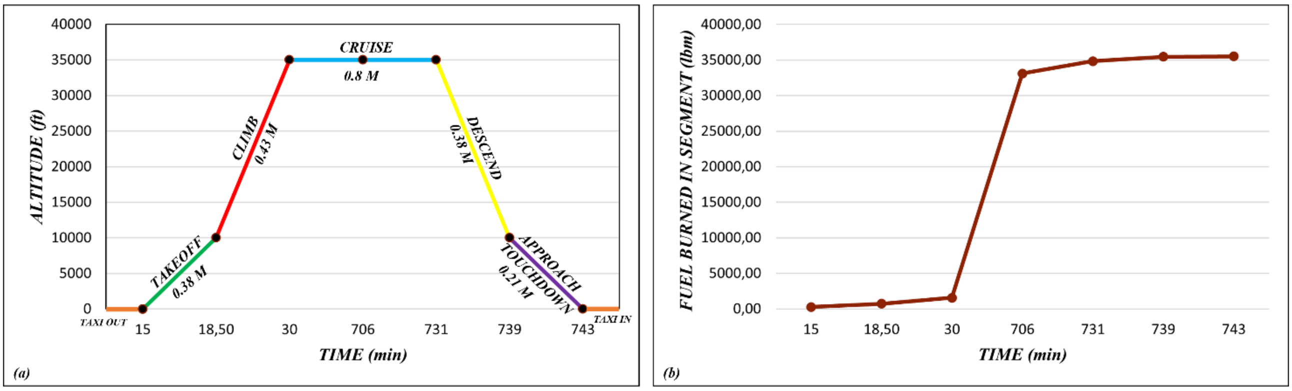


Figure 6 (a) Mission profile, (b) Fuel consumption of selected engine for mission profile

The total flight time 742.7 min including taxi out, takeoff, climb, cruise, descend, approach and taxi in. The mission flight data for baseline engine and four engines were given in Table 4-8. Cruise speed and altitude of the plane were 0.8 Mach and 35000 feet.

Table 4 Flight mission for CFM56-7B24

Segment	Altitude (ft)	Mach Number	Thrust (lbf)	TSFC (lbm/lbf*h)	Fuel Flow (lb/s)	Time(min)	Fuel Burned in Segment (lbm)
Taxi Out	0	0.015	3000	0.42	0.356	15	320.4
Take Off	0-10000	0.38	18000	0.53	2.666	3.5	559.8
Climb	10000-35000	0.43	10000	0.5	1.408	11.5	971.52
Cruise	35000	0.8	5000	0.65	0.910	676.2	36920.52
Descend	35000-10000	0.38	10000	0.48	1.341	24.5	1971.27
Approach & Touchdown	10000-0	0.21	14000	0.44	1.707	8	819.36
Taxi In	0	0.015	3000	0.42	0.356	4	85.44
Total						742.7	41648.31

Table 5 Flight mission for designed engine 1

Segment	Altitude (ft)	Mach Number	Thrust (lbf)	TSFC (lbm/lbf*h)	Fuel Flow (lb/s)	Time(min)	Fuel Burned in Segment (lbm)
Taxi Out	0	0.015	3000	0.29	0.246	15	221.4
Take Off	0-10000	0.38	18000	0.403	2.015	3.5	423.15
Climb	10000-35000	0.43	10000	0.41	1.140	11.5	786.6
Cruise	35000	0.8	5000	0.5	0.707	676.2	28684.4
Descend	35000-10000	0.38	10000	0.38	1.081	24.5	1589.07
Approach & Touchdown	10000-0	0.21	14000	0.32	1.246	8	598.08
Taxi In	0	0.015	3000	0.29	0.246	4	59.04
Total						742.7	32361.74

Table 6 Flight mission for designed engine 2

Segment	Altitude (ft)	Mach Number	Thrust (lbf)	TSFC (lbm/lbf*h)	Fuel Flow (lb/s)	Time(min)	Fuel Burned in Segment (lbm)
Taxi Out	0	0.015	3000	0.308	0.257	15	231.3
Take Off	0-10000	0.38	18000	0.404	2.023	3.5	424.83
Climb	10000-35000	0.43	10000	0.409	1.138	11.5	785.22
Cruise	35000	0.8	5000	0.519	0.721	676.2	29252.41
Descend	35000-10000	0.38	10000	0.386	1.073	24.5	1577.31
Approach & Touchdown	10000-0	0.21	14000	0.314	1.221	8	586.08
Taxi In	0	0.015	3000	0.308	0.257	4	61.68
Total						742.7	32918.83

Table 7 Flight mission for designed engine 3

Segment	Altitude (ft)	Mach Number	Thrust (lbf)	TSFC (lbm/lbf*h)	Fuel Flow (lb/s)	Time(min)	Fuel Burned in Segment (lbm)
Taxi Out	0	0.015	3000	0.3	0.256	15	230.4
Take Off	0-10000	0.38	18000	0.48	2.404	3.5	504.84
Climb	10000-35000	0.43	10000	0.47	1.306	11.5	901.14
Cruise	35000	0.8	5000	0.61	0.846	676.2	34323.912
Descend	35000-10000	0.38	10000	0.44	1.242	24.5	1825.74
Approach & Touchdown	10000-0	0.21	14000	0.38	1.498	8	719.04
Taxi In	0	0.015	3000	0.3	0.256	4	61.44
Total						742.7	38566.51

Table 8 Flight mission for designed engine 4

Segment	Altitude (ft)	Mach Number	Thrust (lbf)	TSFC (lbm/lbf*h)	Fuel Flow (lb/s)	Time(min)	Fuel Burned in Segment (lbm)
Taxi Out	0	0.015	3000	0.28	0.260	15	234
Take Off	0-10000	0.38	18000	0.39	2.13	3.5	447.3
Climb	10000-35000	0.43	10000	0.39	1.093	11.5	754.17
Cruise	35000	0.8	5000	0.546	0.826	676.2	33512.47
Descend	35000-10000	0.38	10000	0.34	1.105	24.5	1624.35
Approach & Touchdown	10000-0	0.21	14000	0.25	1.15	8	552
Taxi In	0	0.015	3000	0.28	0.260	4	62.4
Total						742.7	37186.69

According to the flight mission results CFM56-7B24 engine consumed the highest fuel with 41648lbm while the engines 1 and 2 had identical and the lowest fuel consumption during the mission. The fuel consumptions of geared engines 3 and 4 were higher than the non-geared engine of engine 1 and 2. Engine 4 carried out better fuel consumption with 37186.69 lbm than the engine 3 with 38566 lbm. Although ungeared engines showed better performance than the geared engines, we selected the engine 3 selected as our engine for hybrid propulsion system. Even though having 3.57% higher fuel consumption, the trade of reasons for selecting engine 3 instead of engine 4 were proper fan pressure ratio of 1.68 and lower mass flow rate which decreases the fan diameter, weight, and overall engine diameter. Additionally, engine 3 had 7.4% lower fuel consumption when compared to CFM56-7B24 engine. For these reasons, we selected and named the engine 3 as Century-250 in the project in light of the better performance results and reliability. The twin-spool turbofan engine with gear box selected whose station numbering, and engine configuration were shown in Fig. 4. As results of the parametric design studies, we decided to select engine 3 as our engine to carry out hybrid propulsion system.

5 DESIGN OF THE CENTURY-250 ENGINE

In this section, the design of the Century-250 engine was presented depending on parametric studies and optimizations. Then the component design was made, and performance results were compared with baseline engine CFM56-7B24. 0.8

Mach and 35.000ft is the standard design point for a passenger aircraft engine as they were selected for the cruise condition parameters. Turbofan engines are generally designed for takeoff conditions, so Century-250 engine is designed following this path. The Century-250 engine was designed as an ultra-high-bypass, twin-spool, axial turbofan engine. It consisted of 1 stage fan, 4 stage LPC, 4 stages HPC, 2 stage HPT, 4 stages LPT, and hot-cold nozzles. The geometry of Century-250 was shown in Fig. 6.

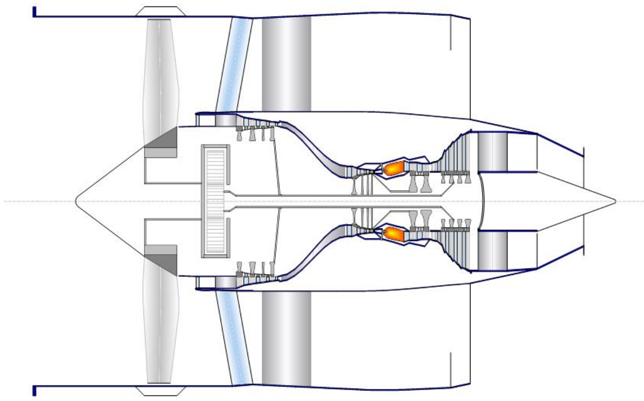


Figure 7 The Cenrtury-250 turbofan engine

5.1 PERFORMANCE CYCLE DESIGN AND ANALYSIS

Parametric cycle analyses of the reference engine were used in the preliminary design of the Century-250 engine. Our main design point was to provide electric power to flight and hybrid electric propulsion systems at 35.000ft and 0.8 Mach cruising conditions. Additionally, reducing fuel consumption, lowering engine weight, and reducing drag by decreasing the engine diameter were our main goals in the component designs. Before starting the design of the Century-250 engine, the requirements specified in the project request were noted and analyzed, and then the CFM56-7B24 engine was examined in the context of these requirements. The other engines presented in the project request, IAE V2500 and Pratt & Whitney PW1000G, were also analyzed in detail, with the four main parameters such as BPR, TIT, OPR, and SFC. On the other hand, it was aimed to achieve an ultra-high BPR value inspired by future technologies and to achieve this at high OPR values, as seen in similar engines. Thus, the design of the Century-250 engine was started with these goals and objectives and through GasTurb14 and AxStream software was used for this. In the design studies of the Century-250 engine, the BPR value was limited between 9 and 15, considering advanced technology. The other main parameter, OPR value, was found to be 26 in the CFM56-7B24 engine, 29.8 in the IAE V2500 engine [32], and 40 in Pratt & Whitney PW1000G engine [10]. In the studies conducted for the Century-250 engine, the OPR value was limited between 25 and 50.

The parametric section of the GasTurb14 software was used to find the best combination of the four main parameters of BPR, FPR, TIT, and OPR for reducing the specific fuel consumption (TSFC) of the Century-250 engine. Parametric studies were conducted to determine how TSFC value can be decreased. Fig. 7 shows the parametric study results evaluated by iterations. In Fig. 7 (a), optimum BPR, and TIT were searched for SFC and net thrust. Additionally, optimum OPR, FPR, and BPR were investigated for SFC in Fig. 7(b) whereas the optimum pressure ratio of HPC was searched against TIT, net thrust, and SFC (Fig. 7(c)). As a result of parametric and optimization studies, the BPR of 12 was found to be the most efficient value for the design. Moreover, the optimum OPR was found to be 39.58 with FPR, LPC, and HPC pressure ratios of 1.68 and 4, and 6, respectively. Besides T3 (HPC exit) and T4 (burner exit), temperatures were found to be 1607R and 3000R, respectively. All the parametric study results were given in Table 9 with the comparisons of baseline engine parameters and results. According to the results, the use of the Century-250 engine resulted in a 19.9% increase in the thrust of the CFM56-7B24 engine, while the specific fuel consumption (SFC)

of the baseline engine was decreased by 30.5% with the new engine at the takeoff condition. However, the thrust of Century-250 engine decreased by 2.9% when compared to baseline CFM56-7B24 engine.

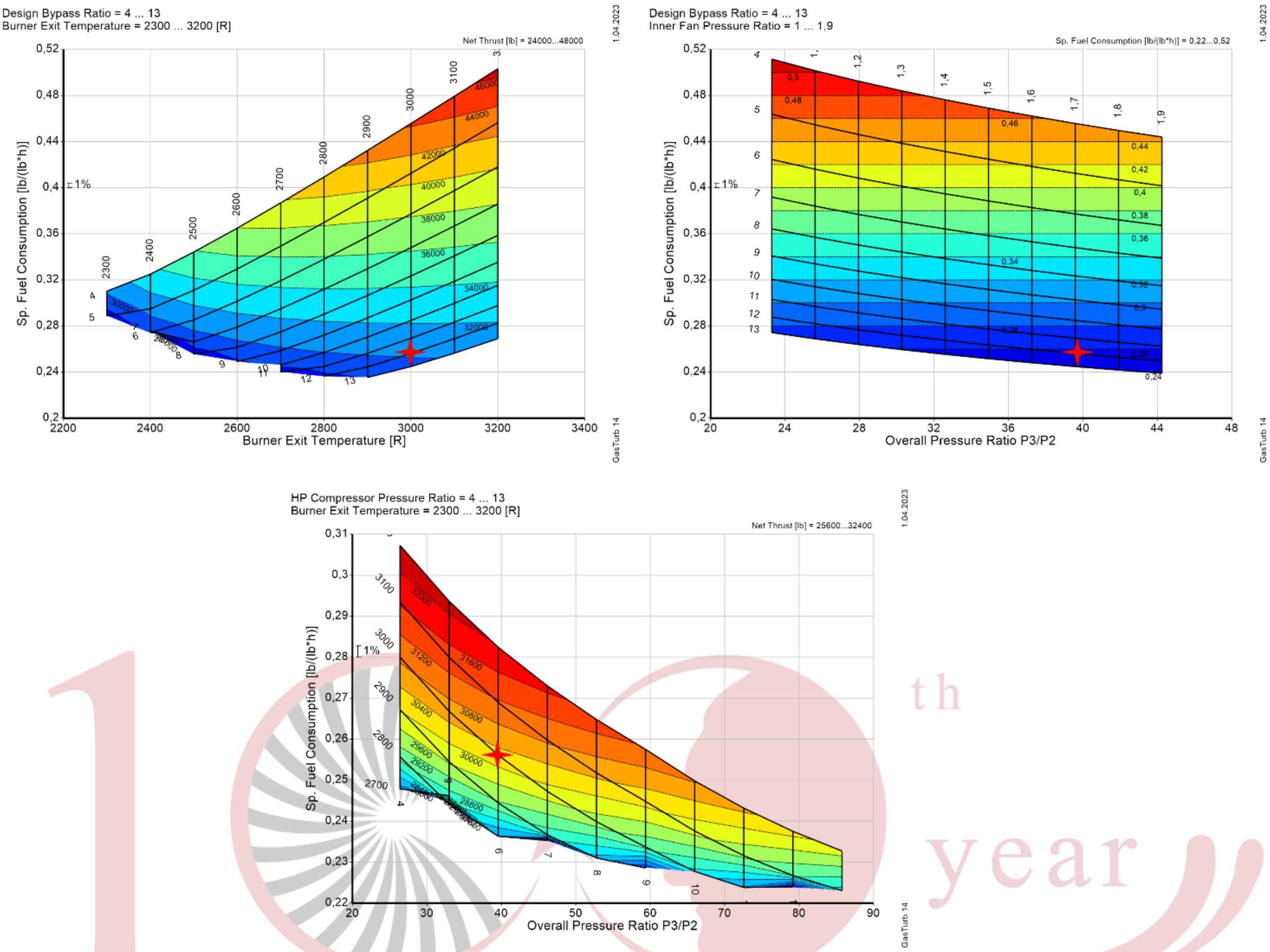


Figure 8 Parametric study results (a) BPR, TIT (T4) vs SFC, Thrust, (b) OPR vs SFC FPR, BPR (c) MFR vs SFC, BPR, OPR, Thrust

Table 9 shows the comparison of the baseline engine and the Century 250 design parameters and results of the cycle calculations.

Table 9 Baseline engine and the Century-250 design parameters and results

	CFM56-7B24		CENTURY-250	
Mission	**Take-Off**	**Cruise**	**Take-Off**	**Cruise**
Thrust (lb)	24227	5581	30268	5418
TSFC (lb/(lb*h))	0.36	0.68	0.25	0.62
Mass Flow (lb/s)	751	306	1338	515
T3(R)	1394	1323	1607	1389
T4(R)	2800	2805	3000	3000
V18/V8	0.57	0.53	0.43	0.37
BPR	5.3	5.21	12	12.14
OPR	26	29.95	39.58	38.9
FPR	1.4	1.4	1.68	1.66
LPC PR	1.81	1.86	4.0	3.93
HPC PR	10.57	11.66	6.0	6.15
LP Spool Speed	5173		3476	3439
IPC Spool Speed	-	-	10428	10316
HP Spool Speed	14461		23533	235357
Core Efficiency	0.45	0.51	0.49	0.57
Prop Efficiency	-	0.72	-	0.82

An increase in BPR also increased the mass flow rate of the engine from 751 lb/s to 1338 lb/s as well as cruise thrust increased from 306 lb/s to 674 lb/s. Furthermore, FPR of baseline engine increased from 1.4 to 1.68 with an OPR increase from 26 to 39.58. Optimized on design cycle of the Century-250 engine was illustrated in Fig. 8 (a). According to the on-design analyses, the rotational speed of HP, LP and IP spools were obtained as 23533 rpm, 3476 rpm, 10428 rpm, respectively.

```
               W          T          P        WRstd
Station  lb/s          R        psia         lb/s
 amb                518,67     14,696
  2    1338,479     518,67     14,549   1352,000
 13    1235,520     563,48     18,914   1000,610
 21     102,960     612,79     24,733     66,496
 22     102,960     612,79     24,486     67,167
 24     102,960     945,79     97,944     20,861
 25     102,960     945,79     95,985     21,287
  3     100,901    1607,23    575,910      4,532
 31      91,634    1607,23    575,910
  4      93,787    3000,00    552,873      5,996
405      97,906    2945,87    552,873
 41     100,480    2914,20    552,873      6,331
 43     100,480    2326,10    187,548
 44     103,054    2309,18    187,548
 45     104,770    2294,53    183,797     17,620
 49     104,770    1481,46     24,737
  5     105,113    1481,25     24,737    105,529
  8     105,113    1481,25     23,748    109,926
 18    1235,520     563,48     18,535   1021,031
Bleed     0,000    1607,23    575,909
-----------------------------------------------
Efficiency        isentr  polytr    RNI    P/P
 Outer LPC        0,9000  0,9037  0,990  1,300
 Inner LPC        0,9000  0,9072  0,990  1,700
 IP Compressor    0,8800  0,9005  1,367  4,000
 HP Compressor    0,8800  0,9042  3,192  6,000
 Burner           0,9995                 0,960
 HP Turbine       0,9200  0,9102  5,014  2,948
 LP Turbine       0,9200  0,8991  2,193  7,430
-----------------------------------------------
HP Spool mech Eff 0,9900  Nom Spd  23533 rpm
LP Spool mech Eff 0,9900  Nom Spd   3476 rpm
IPC & LPT                 Nom Spd  10428 rpm
-----------------------------------------------
P22/P21=0,9900 P25/P24=0,9800 P45/P44=0,9800
-----------------------------------------------
hum [%]     war0       FHV      Fuel
  0,0    0,00000   18552,4    Generic
```

```
FN         =  30268,34 lb
TSFC       =    0,2561 lb/(lb*h)
WF         =   2,15304 lb/s
s NOX      =    1,7824

Core Eff   =    0,4983
Prop Eff   =    0,0000
BPR        =   12,0000
P2/P1      =    0,9900
P3/P2      =     39,58
P5/P2      =    1,7003
NGV Out. 2 Stage HPT
P16/P13    =    0,9800
P16/P6     =   0,78051
P16/P2     =   1,27400
P6/P5      =   0,96000
A8         =    339,15 in²
A18        =   3804,10 in²
XM8        =   0,87041
XM18       =   0,58559
WBld/W2    =   0,00000
CD8        =   0,97262
CD18       =   0,94326
PWX        =     200,0 hp
V18/V8,id=     0,43487
WBLD/W22 =     0,00000
Wreci/W25=     0,00000
Loading    =    100,00 %
WCHN/W25 =     0,06500
WCHR/W25 =     0,02500
WCLN/W25 =     0,01667
WCLR/W25 =     0,00333
WBLD/W25 =     0,00000
Gear Rat =     3,00000
WLkBy/W25=     0,00000
WlkLP/W25=     0,00000
```

(a)

```
               W          T          P        WRstd
Station  lb/s          R        psia         lb/s
 amb                393,85      3,458
  2     515,804     444,38      5,220   1344,140
 13     476,577     482,17      6,749   1000,610
 21      39,227     524,01      8,787     65,942
 22      39,227     524,01      8,701     66,597
 24      39,227     805,83     34,212     21,003
 25      39,227     805,83     33,521     21,436
  3      38,442    1389,38    203,059      4,554
 31      34,912    1389,38    203,059
  4      35,851    2999,88    194,974      6,499
405      37,420    2938,42    194,974
 41      38,401    2902,44    194,974      6,847
 43      38,401    2391,01     76,568
 44      39,382    2368,07     76,568
 45      39,970    2351,92     75,035     16,670
 49      39,970    1675,54     15,262
  5      40,166    1673,45     15,262     69,470
  8      40,166    1673,45     14,652     72,364
 18     476,577     482,17      6,614   1021,026
Bleed     0,000    1389,38    203,058
-----------------------------------------------
Efficiency        isentr  polytr    RNI    P/P
 Outer LPC        0,8966  0,9003  0,426  1,293
 Inner LPC        0,8966  0,9039  0,426  1,683
 IP Compressor    0,8834  0,9032  0,585  3,932
 HP Compressor    0,8783  0,9034  1,349  6,058
 Burner           0,9995                 0,960
 HP Turbine       0,9200  0,9116  1,775  2,546
 LP Turbine       0,9104  0,8930  0,870  4,916
-----------------------------------------------
HP Spool mech Eff 0,9900  Speed     23537 rpm
LP Spool mech Eff 0,9900  Speed      3439 rpm
IPC & LPT                 Speed     10316 rpm
-----------------------------------------------
P22/P21=0,9902 P25/P24=0,9798 P45/P44=0,9800
-----------------------------------------------
hum [%]     war0       FHV      Fuel
  0,0    0,00000   18552,4    Generic
```

```
FN         =   5418,61 lb
TSFC       =    0,6241 lb/(lb*h)
WF         =   0,93942 lb/s
s NOX      =    0,6303
P5/P2      =    2,9238 EPR
Core Eff   =    0,5694
Prop Eff   =    0,8225
BPR        =   12,1492
P2/P1      =    0,9900
P3/P2      =     38,90
P5/P2      =    2,9238
NGV Out. 2 Stage HPT
P16/P13    =    0,9800
P16/P6     =   0,45139
P16/P2     =   1,26701
P6/P5      =   0,96001
A8         =    218,99 in²
A18        =   3049,80 in²
XM8        =   1,00000
XM18       =   1,00000
WBld/W2    =   0,00000
CD8        =   0,98000
CD18       =   0,97554
PWX        =     200,0 hp
V18/V8,id=     0,37519
WBLD/W22 =     0,00000
Wreci/W25=     0,00000
Loading    =    102,74 %
WCHN/W25 =     0,06500
WCHR/W25 =     0,02500
WCLN/W25 =     0,01500
WCLR/W25 =     0,00500
WBLD/W25 =     0,00000

WLkBy/W25=     0,00000
WlkLP/W25=     0,00000
```

Figure 9 Cycle results of the Century-250 (a) Take off condition, (b) Cruise condition

Off design, analyses were performed at 35000 ft altitude and 0.8 Mach flying speed which was shown in Fig. 4 (b). The thrust of the Century-250 was %34.7 higher when compared to the CFM56-7B24 engine in cruise conditions. Besides, the cruise TSFC of Century 250 was similar to CFM56-7B24 engine (see Table 9 and Fig. 8). Fig. 9 shows the thermodynamic, kinetic, and geometric station results of the Century 250 engine at the takeoff and cruise conditions. The exit Mach number was found to be 0.87 for hot nozzle and 0.59 for cold nozzle at the takeoff condition while they were obtained as 1 for all nozzles at cruise condition. The velocity of gas stream was 0.5 at both takeoff and cruise conditions which was lower than 0.75 at the LPT exit.

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	1338,48	102,96	102,96	102,96	100,901	93,7874	103,054	104,77	105,113	105,113	105,113	1235,52	1235,52	1235,52
Total Temperature	R	518,67	612,788	945,786	945,786	1607,23	3000	2309,18	2294,53	1481,25	1481,25	1481,25	563,48	563,48	563,48
Static Temperature	R	478,194	583,737	917,708	910,517	1589,94	2995,66	2223,96	2252,23	1421,03	1432,28	1310,47	531,408	536,73	527,382
Total Pressure	psia	14,549	24,4859	97,9438	95,9849	575,91	552,873	187,548	183,797	24,7372	23,7477	23,7477	18,9137	18,5354	18,5354
Static Pressure	psia	10,9521	20,6464	87,8182	83,645	552,306	549,319	159,76	169,785	20,9898	20,7789	14,6963	15,3998	15,6267	14,696
Velocity	ft/s	696,891	591,941	590,946	662,307	479,121	257,575	1117,29	786,89	904,583	817,135	1515,91	621,532	567,843	659,244
Area	in²	4474,06	262,369	97,1383	90,283	32,3445	105,938	68,5015	94,2279	419,71	473,057	329,87	3659,73	3987,13	3588,24
Mach Number		0,649999	0,5	0,4	0,45	0,25	0,1	0,5	0,35	0,5	0,45	0,87039	0,55	0,5	0,585588
Density	lb/ft³	0,061817	0,095464	0,258281	0,247951	0,937588	0,494938	0,193892	0,203472	0,039868	0,039157	0,030269	0,078217	0,078582	0,075212
Spec Heat @ T	BTU/(lb*R)	0,240085	0,240994	0,247364	0,247364	0,267525	0,306155	0,29393	0,293452	0,271845	0,271845	0,271845	0,240424	0,240424	0,240424
Spec Heat @ Ts	BTU/(lb*R)	0,239956	0,240658	0,246562	0,246357	0,267015	0,306098	0,292166	0,292578	0,269853	0,270242	0,266026	0,240126	0,240143	0,240113
Enthalpy @ T	BTU/lb	-4,31603	18,343	99,488	99,488	269,698	686,841	477,489	472,971	242,318	242,318	242,318	6,45803	6,45803	6,45803
Enthalpy @ Ts	BTU/lb	-14,0214	11,3407	92,5093	90,722	265,111	685,515	452,543	460,597	225,966	228,975	196,395	-1,26181	0,014292	-2,22703
Entropy Function @ T		-0,11924	0,465683	2,00516	2,00516	3,98682	6,75723	5,59451	5,56485	3,7608	3,7608	3,7608	0,171092	0,171092	0,171092
Entropy Function @ Ts		-0,40323	0,295124	1,89603	1,86755	3,94497	6,75078	5,43415	5,48556	3,59653	3,62726	3,28091	-0,034442	3,8816E-4	-0,061019
Exergy	BTU/lb	-0,357633	20,0117	95,7058	94,9869	258,44	575,55	369,102	364,92	127,099	125,646	125,646	9,4212	8,70231	8,70231
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,023496	0,021338	0,020981	0,020911	0,020911	0,020911	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Radius	in	11,868	14,9441	14,4557	5,11038	5,11805	7,74353	7,74353	7,74353	8,13071	8,13071	4,01571	18,4374	14,8059	14,8341
Outer Radius	in	39,5599	17,5168	15,4865	7,40635	6,05025	9,67902	9,04251	9,48451	14,1318	14,7203	11,1392	38,7926	38,5792	37,8277
Axial Position	in	19,78	19,78	45,8393	57,0769	73,7498	80,3581	87,014	87,7729	101,308	114,733	127,397	43,2058	97,4767	101,25

(a)

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	515,804	39,2269	39,2268	39,2268	38,4422	35,8512	39,3816	39,97	40,1662	40,1662	40,1662	476,577	476,577	476,577
Total Temperature	R	444,378	524,01	805,832	805,832	1389,38	2999,88	2368,07	2351,92	1673,45	1673,45	1673,45	482,172	482,172	482,172
Static Temperature	R	410,375	499,598	781,074	774,706	1374,07	2995,58	2281,59	2309,01	1607,77	1620,07	1434,49	454,625	459,178	401,677
Total Pressure	psia	5,21998	8,70068	34,2117	33,5206	203,059	194,974	76,5677	75,0354	15,2622	14,6519	14,6519	6,74872	6,61377	6,61377
Static Pressure	psia	3,95216	7,36443	30,6181	29,1387	194,716	193,723	65,2388	69,3247	12,9683	12,8355	7,88812	5,49446	5,57544	3,49298
Velocity	ft/s	638,738	541,203	549,824	616,493	446,163	257,373	1130,61	795,94	957,913	865,205	1815,89	574,91	525,253	982,761
Area	in²	4473,6	262,335	97,1009	90,2548	32,4393	114,918	64,9917	89,2349	277,344	312,614	214,604	3659,41	3986,72	2975,2
Mach Number		0,642984	0,493884	0,402426	0,453024	0,249338	0,10001	0,500217	0,350125	0,499992	0,449995	1	0,549914	0,499925	0,999923
Density	lb/ft³	0,025994	0,039786	0,105803	0,101519	0,382478	0,17455	0,077177	0,081037	0,021771	0,021384	0,014842	0,03262	0,032773	0,023471
Spec Heat @ T	BTU/(lb*R)	0,239848	0,240102	0,244056	0,244056	0,260996	0,308053	0,296622	0,296139	0,279164	0,279164	0,279164	0,239969	0,239969	0,239969
Spec Heat @ Ts	BTU/(lb*R)	0,23974	0,240024	0,24353	0,243395	0,260512	0,307995	0,294871	0,295267	0,277164	0,277567	0,271465	0,239881	0,239895	0,239712
Enthalpy @ T	BTU/lb	-22,1298	-3,0357	65,1295	65,1295	212,183	690,272	496,939	491,881	296,283	296,283	296,283	-13,0675	-13,0675	-13,0675
Enthalpy @ Ts	BTU/lb	-30,2829	-8,88901	59,0882	57,5343	208,205	688,948	471,394	479,221	277,945	281,323	230,386	-19,6727	-18,5809	-32,3684
Entropy Function @ T		-0,659571	-0,083442	1,43243	1,43243	3,42631	6,78814	5,72516	5,69278	4,26495	4,26495	4,26495	-0,374275	-0,374275	-0,374275
Entropy Function @ Ts		-0,937802	-0,250182	1,32146	1,29234	3,38435	6,7817	5,56504	5,61362	4,10207	4,13258	3,64573	-0,579888	-0,545058	-1,01268
Exergy	BTU/lb	11,8428	29,1745	93,3755	92,8241	234,675	620,847	430,979	426,249	226,199	225,096	225,096	20,1366	19,5909	19,5909
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,026908	0,024437	0,024069	0,023948	0,023948	0,023948	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0

(b)

Figure 10 Thermodynamic, kinetic, and geometric results of the stations (a) takeoff condition (b) cruise condition

6 ENGINE COMPONENT DESIGN

Engine component design was started with an air compression unit that consists of a fan, low-pressure compressor, and high-pressure compressors. These components also provide the overall pressure ratio (OPR) of the engine. Axial compressors were used due to higher levels of mass flow rate capacity and pressures.

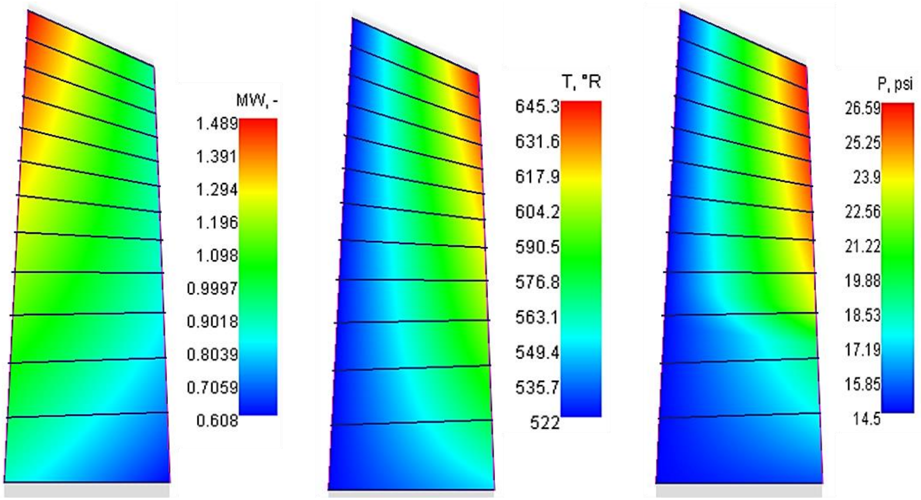
6.1 FAN DESIGN

Single stage axial fan was used in the Century-250 engine and design parameters were provided from GasTurb14 for the AxStream software in which fan design was performed (see Table 10). Design parameters were shown in Table 5. FPR was selected as 1.52 for a fan and the FPR has been reported to be in the range of 1.4 and 1.6 [17]. Inlet total pressure and temperature were 14.5 psi and 522 R, respectively. The outlet's total pressure and temperature were 21.82 psi and 958.6R, respectively. Additionally, MRF and rotational speed were found to be 958.6 lb/s and 4717 rpm, respectively. Moreover, fan tip and hub diameters were obtained as 67.68 and 25.24 inches, respectively.

Table 10 GasTurb14 data for fan design boundary conditions and geometric parameters

Fan Design			
Total Pressure $_{(inlet)}$ [psi]	14.54	Shaft Rotational Speed [RPM]	3476
Total Pressure $_{(outlet)}$ [psi]	24.48	Tip Diameter [inch]	79.12
Pressure Ratio	1.68	Hub Diameter [inch]	27.9
Total Temperature $_{(inlet)}$ [R]	518.67	Hub to Tip Ratio	0.35
Total Temperature $_{(outlet)}$ [R]	612.78	Blade Height [inch]	25.6
Mass Flow [lb/s]	1338.48	Number of Stage	1

The preliminary design was done in AxStream using 5000 iterations with the parameter given in Table 5. After the 1D calculations, 2D streamline calculations were performed to optimize the flow path of the fan. The 2D calculations were done to find the inlet total pressure for a given mass flow rate with 500 iterations. The relative Mach number, total pressure, and temperatures were evaluated and compared to Gasturb14 and literature findings (see Fig. 5).



(a) (b) (c)

Figure 11 Axial fan 2D streamline calculation result (a) relative Mach number, (b) Total temperature, (c) Total pressure

According to the 2D streamline calculations, the fan rotor blade tip relative Mach number was obtained as 1.48 which shouldn't exceed 1.5 (see Fig. 10 (a)). Fig. 10 (b) and (c) show the total temperature and pressure deviation in fan rotor blades where the 522R inlet temperature raised to 645.3R after the compression process. Additionally, the inlet pressure of 14.5 psi was increased to 26.59 psi in the fan rotor blades. The AxStream fan design results are illustrated in Table 5. It was observed that de Haller number of the fan was 0.86 which should be larger than 0.72 for lower loss and higher diffusion in the fan blades [8]. In addition, work and flow coefficients were found to be 0.94 and 1.18 which were consistent with the literature [3]. A good polyprotic efficiency of 87%was achieved at the end of the design process.

Table 5 Fan design results

Parameter	STAGE 1
Work Coefficient	0.94
Flow Coefficient	1.18
Stage Pressure Ratio	1.78
Number of Blades	22
Aspect Ratio	2.54
Blade Chord [inch]	9.71
Solidity	1.24
Stagger Angle [tan.deg]	21.27
Leading Edge Radius [inch]	0.09
Trailing Edge Radius [inch]	0.09
De-Haller Number	0.86
Polytrophic Efficiency [$\eta_{polytrophic}$]	0.87
Degree of Reaction at Hub	1

6.1.1 OFF-DESIGN ANALYSIS OF FAN

Off design of fan was performed by using GasTurb14 and a comparison of the on and off design performances of the axial fan were illustrated in the maps (see Fig. 11). According to the on-design analysis fan isentropic efficiency was found to be 0.93 while it was 0.88 for cruise conditions. The performance map showed that fan was far from the surge and choke margin (see the red line and blue-orange dots on the map). The calculated surge margins of on and off designs were also shown in Fig.11 where the fan surge margin was %30 and %25 at on-off design conditions, respectively. Design results showed that the fan could operate safely during takeoff and cruise conditions.

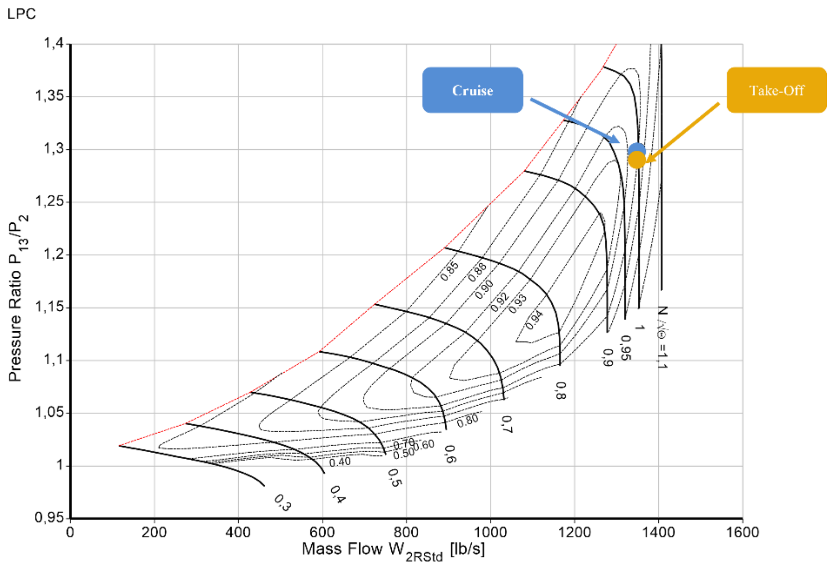


Figure 12 On and off design performance of the fan

6.1.2 FAN BLADE MATERIALS

Using composite materials as a fan blade is a good innovation and carbon fiber is one of the greatest applications whose density is lower than three times titanium alloys [Kosmatka, 2009]. Thus, large fan weight can be decreased using Carbon Fiber Reinforced Plastic composite (CFPR) as blade and fan case material. The density of the carbon fiber is 0.06 lb/in^3, Young's modulus and tensile stress are 37709 ksi and 507-725 MPa, respectively [Pandita, 2014]. Leading edge blade material was chosen as Ti6AlV4 alloys in the fan.

Figure 13 3-D CAD drawing of the fan

6.2 COMPRESSORS DESIGN

Axial and radial flow compressors are used in aviation engines. The axial compressors are selected when the higher-pressure ratios and mass flow rates required. In the Century 250 engine we designed 2 stages LPC and 10 stages HPC through the AxStream. Typical axial compressor design parameters were given in Table 7[19,36]. These parameters were taken consideration and results were compared to these parameters in the axial compressor designs.

Table 6 Typical axial compressor design parameters used in the literature

PARAMETER	Range of Values	Parameter	Range of Values
Flow Coefficient	$0.3 \leq \varphi \leq 0.9$	Tip Rotational Speed	$1480 \leq \omega r_t \leq 1640$ ft/s
HPC Max. Exit Temperature [R]	1700-1800	Hub/Tip Ratio at Inlet	0.6-0.75
Axial Mach Number	$0.3 \leq M_Z \leq 0.6$	De Haller Number	$W2 / W1 \geq 0.72$
HPC Pressure Ratio	$\Pi_C < 20$	Degree of Reaction at Hub	$0.15 \leq \Lambda$
Reynolds Number Based on Chord	$300{,}000 \leq Re_C$	LPC Pressure Ratio	1 Stage: $1.5 \leq PR \leq 2$ 2 Stage: $2 \leq PR \leq 3.5$ 3 Stage: $3.5 \leq PR \leq 4.5$
DCA Blade (Range)	$0.8 \leq M \leq 1.2$	Aspect Ratio Fan	$2 \leq AR \leq 5$
Loading Coefficient	$0.2 \leq \psi \leq 0.5$	Aspect Ratio Compressor	$1.0 \leq AR \leq 4.0$
Hub Rotational Speed	$\omega r_h \leq 1250$ ft/s	Taper Ratio	$0.8 \leq TR \leq 1$
Solidity	$1.0 \leq \sigma \leq 2.0$	Axial Gap Between Blade Rows	$0.23c_Z$ - $0.25c_Z$
Tip Relative Mach Number	(M_{1r}) tip ≤ 1.7	Pressure Ratio for OneStage	$1.5 \leq PR \leq 2.0$
Polytropic Efficiency	$0.88 \leq e_C \leq 0.92$	D-Factor	$0.5 \leq D \leq 0.6$

6.2.1 LOW PRESSURE COMPRESSOR (LPC) DESIGN

In the LPC design of the Century 250 engine, geometric data and boundary conditions were obtained from GasTurb14 and entered the AxStream (see Table 8). The air mass flow rate of the LPC was 59.96 lb/s and the stage number was 2 with the pressure ratio of 1.68. the total inlet temperature and pressures were found to be 592.6R and 21.8 psi, respectively.

Table 7 Geometric and boundary layer parameters of the LPC

Thermodynamic and Geometrical Properties			
Total Pressure $_{(inlet)}$ [psi]	24.48	Shaft Rotational Speed [RPM]	10428
Total Pressure $_{(outlet)}$ [psi]	97.94	1^{st} Stage Tip Diameter [inch]	36.61
Pressure Ratio	1.68	4^{th} Stage Tip Diameter [inch]	34.04
Total Temperature $_{(inlet)}$ [R]	612.78	1^{st} Stage Hub Diameter [inch]	32.35
Total Temperature $_{(outlet)}$ [R]	945.78	4^{th} Stage Hub Diameter [inch]	32.45
Mass Flow [lb/s]	102.96	1^{st} Stage Blade Height [inch]	2.13
Number Of Stage	4	4^{th} Stage Blade Height [inch]	0.79

There are three main flow annulus design which are constant tip, constant hub and mean line designs. To achieve the best compressor results and annulus area, mean line design was selected in the LPC design. After preliminary design in AxStream flow path optimize and revised via 2D streamline calculations by using 11 streamlines. Find outlet pressure for given mass flow rate boundary layer was used with 500 iterations in the AxStream design to achieve targeted polytropic efficiency. DCA blade profiles selected for LPC, and flow path optimized according to this type blading. The average polytropic efficiency was 87.5 for LPC after the optimizations. Fig. 7 shows relative Mach number, total temperature, and pressure changes through the annulus of LPC according to the 2D streamline calculations. It was observed that relative tip number at the inlet rotor tip was 1.18 and outlet Mach number was obtained as 0.5 which was consistent with the literature. Inlet total temperature was found to be 685R and the exit was 997R which were consistent with the GasTurb14 results. The total pressure ratio was calculated as 3.24 with the inlet and exit total pressures of 33.89 and 109.9 psi, respectively. The AxStream design results were shown in Table 8. De Haller numbers were not *lower than 0.72[24]. Furthermore, work and flow coefficients (loading factor) were found in range of values given in Table 7, respectively.*

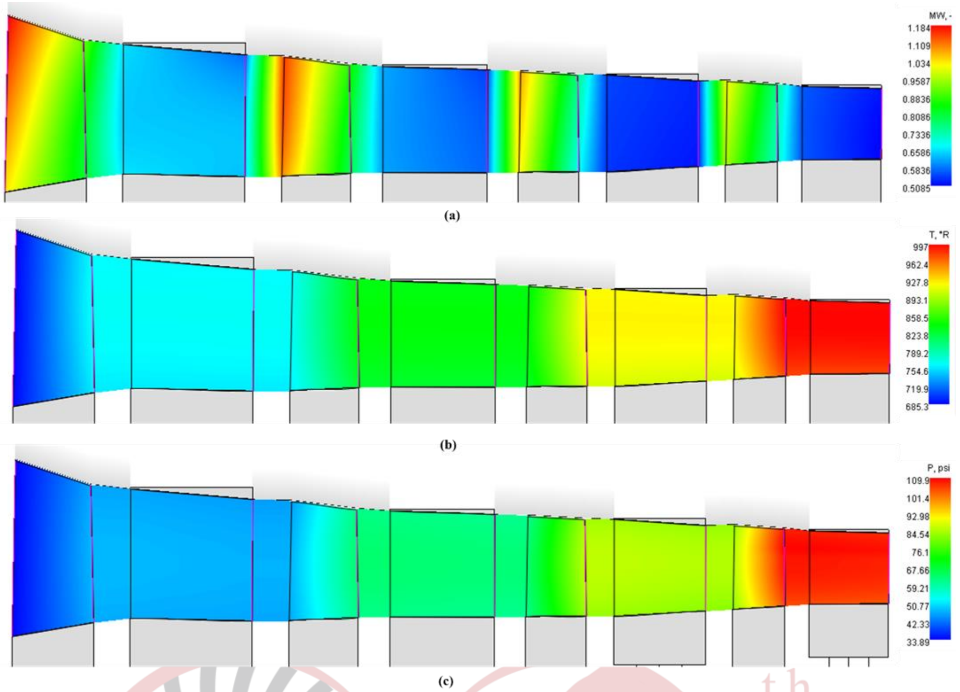


Figure 14 2D Streamline calculation results of the LPC, (a) Relative Mach number, (b) Total temperature, (c) Total pressure

Table 8 AxStream design results of the LPC

Parameter	STAGE 1		STAGE 4	
	Rotor	Stator	Rotor	Stator
Work Coefficient	0.33		0.3	
Flow Coefficient	0.63		0.6	
Stage Pressure Ratio	1.37		1.26	
Polytrophic Efficiency [η polytrophic]	0.84		0.88	
Degree of Reaction at Hub	1.05		0.92	
Number of Blades	30	30	46	46
Aspect Ratio	1.43	1.05	1.04	0.91
Blade Chord [inch]	1.62	1.62	1.06	1.06
Solidity	0.57	0.57	0.58	0.58
De-Haller Number	0.81	0.98	0.77	0.91

6.2.1.1 OFF-DESIGN ANALYSIS OF LPC

The comparison of the on and off design performance can be seen in Fig. 8. The isentropic efficiency was 0.83 at the takeoff and it was 0.88 for the cruise condition. Moreover, design points were not closer to surge or choke regions.

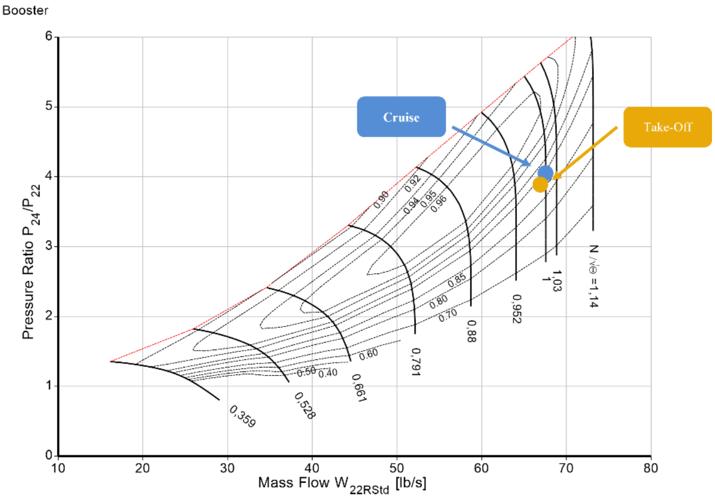


Figure 15 Performance map of the LPC at the cruise and take off conditions

6.2.1.2 LPC MATERIAL

LPC blade and disk material was selected Ti6242 alloys which have the density of 0.164 lb/m^3, Young's modulus of 16500 ksi and a tensile stress of 101 ksi.

Figure 16 3-D CAD drawing of the LPC

6.2.2 HIGH PRESSURE COMPRESSOR (HPC) DESIGN

The boundary conditions and geometric data evaluated from the GasTurb14 for AxStream was shown in Table 9.

Table 9 Boundary condition and geometric data used in HPC design

Thermodynamic and Geometrical Properties			
Total Pressure $_{(inlet)}$ [psi]	95.98	Shaft Rotational Speed [RPM]	20755
Total Pressure $_{(outlet)}$ [psi]	575.91	1st Stage Tip Diameter [inch]	14.55
Pressure Ratio	6	4th Stage Tip Diameter [inch]	13.25
Total Temperature $_{(inlet)}$ [R]	945.78	1st Stage Hub Diameter [inch]	10.77
Total Temperature $_{(outlet)}$ [R]	1607.23	4th Stage Hub Diameter [inch]	12.19
Mass Flow [lb/s]	102.96	1st Stage Blade Height [inch]	1.9
Number Of Stage	4	4th Stage Blade Height [inch]	0.53

HPC was designed as 4 stages and annulus of the HPC was optimized according to efficiency, inlet/ outlet temperatures and pressures via streamline calculations. Similar to LPC DCA blade profile was selected for HPC and

2D streamline calculations were done using 9 streamlines. Fig. 9 shows relative Mach number, total temperature, and pressure changes through the annulus of HPC. When looking at the relative Mach numbers, it was detected that tip Mach number was 0.9 and it did not exceed the 1.5. At the exit of the HPC it decreased to 0.28 which presented good speed before the diffusor. Inlet total temperature was 997R, whereas it was 1688

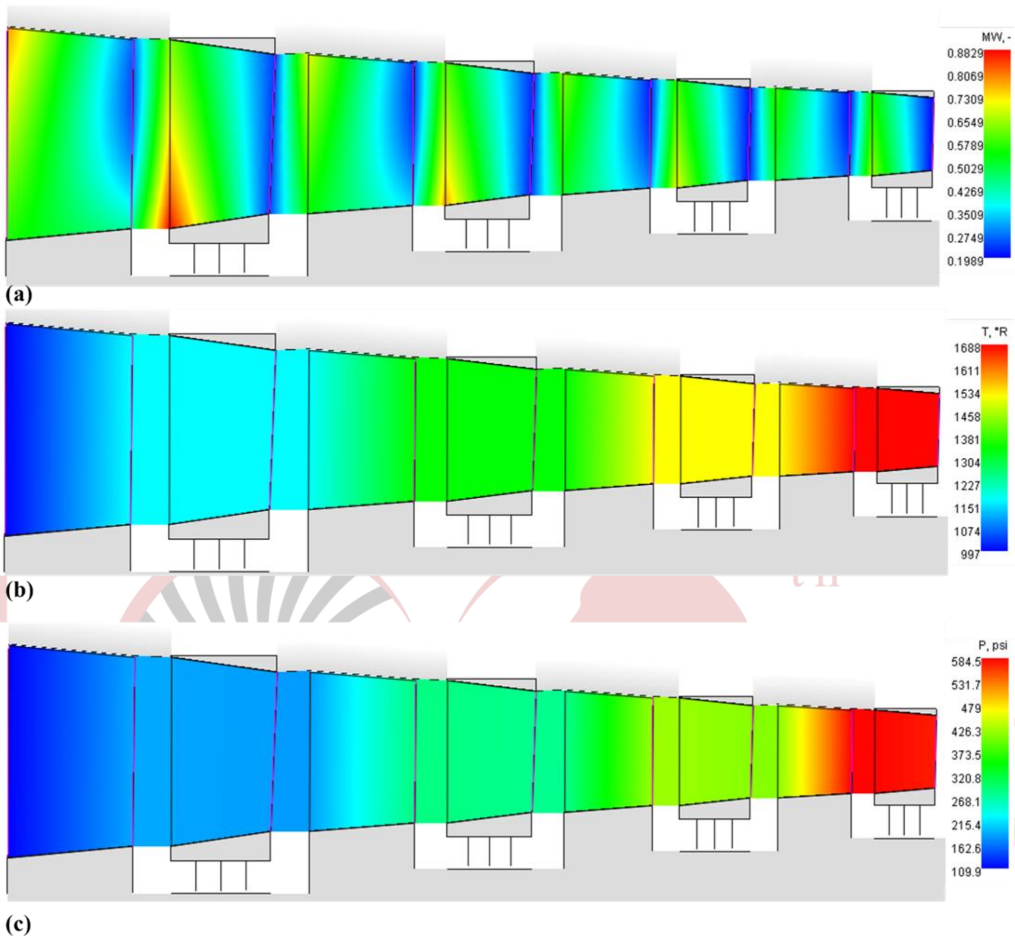


Figure 17 2D Streamline calculation results of the HPC (a) Relative Mach, (b)Total Temperature and (c)Total Pressure

The total temperature at the HPC inlet was 997R and increased to 1680K at the HPC exit. Moreover, total inlet pressure was found to be 109.9 psi whereas it decreased to 584.5 psi at the HPC exit. The design results of the HPC were shown in Table 10. The first and the last stages work coefficients were 1.05 and 0.4. In addition, flow coefficients were found to be 0.73 and 1.07 for the first and last stages. The stage pressure ratio was 1.92 at the first stage and it decreases to 1.03 at the last stage. The findings were consistent with the reported literature specifications.

Table 10 Design results of the HPC

Parameter	*STAGE 1*		*STAGE 4*	
	Rotor	*Stator*	*Rotor*	*Stator*
Work Coefficient	*1.05*		*0.4*	
Flow Coefficient	*0.73*		*1.07*	
Stage Pressure Ratio	*1.91*		*1.03*	
Polytrophic Efficiency [η polytrophic]	*0.82*		*0.78*	
Degree of Reaction at Hub	*0.39*		*0.8*	
Number of Blades	*62*	*70*	*91*	*96*
Aspect Ratio	*1.9*	*1.41*	*1.07*	*1.02*
Blade Chord [inch]	*1.16*	*1.02*	*0.63*	*0.6*
Solidity	*1.9*	*1.9*	*1.61*	*1.6*
De-Haller Number	*0.72*	*0.68*	*0.87*	*0.95*

6.2.2.1 OFF-DESIGN PERFORMANCE OF HPC

The performance map of HPC showed that HPC can operate safely not only at cruise condition but also at takeoff condition. Furthermore, isentropic efficiencies of cruise and takeoff conditions were 0.88 (see Fig. 17).

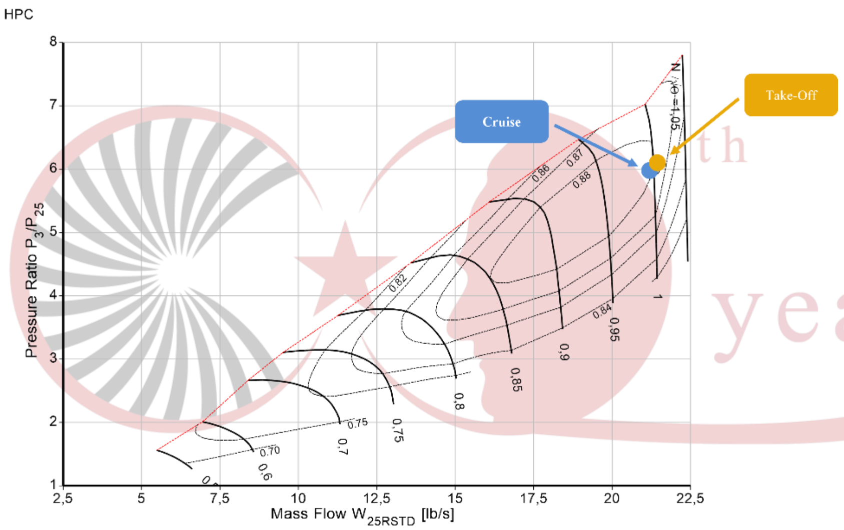


Figure 18 Performance map of HPC at cruise and take off conditions

According to the performance map, it can be observed that HPC operates far from the surge and choke lines.

6.2.2.2 HPC MATERIALS

The first seven stages blade material was selected as Ti6242 (Ti6Al2Sn4Zr2Mo), and the last three stages were selected as Hastelloy-X. Ti6242 material was used as HPC disk material. The density of Ti6242 was 0.164 lb/in^3 whereas elastic modulus and tensile stress were found to be 16680 ksi, and 17400 ksi respect. CAD drawing of the HPC can be seen in Fig. 18.

Figure 19 3-D CAD drawing of the HPC

6.3 COMBUSTION CHAMBERS

Combustion chamber were annular type for Century 250 engine.

6.3.1 Combustion Chambers Material

Ceramic matrix composite (CMC) material was used to manufacture combustion chamber with Zr alloy ceramic coatings. The density of CMC was 0.0722 lb/inc^3, elastic modulus and tensile stress were obtained as 154.5ksi and 790 ksi, respectively.

6.4 TURBINE DESIGNS

THE CENTURY had 2 stages of HPT and 4 stages of LPT. Similar concept was used to design turbines of the turbofan engines in AxStream software. Table 11 shows the turbine design criteria's which have been reported in the literature. We remarked not to exceed 45 ×10^9 in^2×rpm^2 in the turbine designs and Zweifiel coefficients, loading factors, flow coefficients and reaction numbers were taken in consideration in the turbine designs. Additionally, the AN^2 can be used to check the turbine blade stresses, which is shown in Equation 1. AN^2 rule is a design limit for a turbine material at maximum temperature. Its typical values for traditional turbines are in 0.5− 10 × 10^{10} in^2×RPM^2 rang [33].

$$AN^2 = \Omega_{shaft}^2 \times A \times 30\,\pi \qquad (1)$$

Table 15 Turbine design parameters

Parameter	Range Of Values	Parameter	Range Of Values
AN^2 [in^2 × rpm^2]	HPT: 4-5 × 10^{10} LPT: <6 ×10^7	Zweifel Coefficient	$0.75 < \xi < 1.15$
Turbine Inlet Temperature	$R \leq 3150$	Degree of Reaction at Hub	0.15<°R
Exit Mach Number	0.4<M<0.5	Hub to Tip Ratio at Inlet	0.5-0.85
Exit Swirl Angle	0°-20°	Aspect Ratio	2.5-3.5
Mach Number Between Stages	0.85<M<1.2	Loading Coefficient	$0.8 < \psi < 2.5$
Flow Coefficient	$0.5 \leq \phi \leq 1.5$		

6.4.1 HIGH PRESSURE TURBINE (HPT) DESIGN

The CENTURY 250 HPT was designed in AxStream through the data that obtained from the GasTurb14. The boundary conditions and geometric data used in HPT design in AxStream are shown in Table 16.

Table 16 Thermodynamic and geometrical data for HPT design.

Thermodynamic and Geometrical Properties			
Total Pressure $_{(inlet)}$ [psi]	*552.87*	*1st Stage Tip Diameter [inch]*	*16.62*
Total Pressure $_{(outlet)}$ [psi]	*187.54*	*2nd Stage Tip Diameter [inch]*	*15.89*
Pressure Ratio	*2.94*	*1st Stage Hub Diameter [inch]*	*13.06*
Total Temperature $_{(inlet)}$ [R]	*3000*	*2nd Stage Hub Diameter [inch]*	*12.68*
Total Temperature $_{(outlet)}$ [R]	*2309.18*	*1st Stage Blade Height [inch]*	*1.78*
Mass Flow [lb/s]	*93.78*	*2nd Stage Blade Height [inch]*	*1.6*
Shaft Rotational Speed [RPM]	*23533*	*Number of Stage*	*2*

2D streamline calculations were performed with the 9 streamline and 500 iterations were done using the find inlet total pressure for given mass flow rate. The annulus and flow path were optimized to obtain higher efficiency than 0.85 and inlet/exit pressure and temperatures in AxStream. Fig. 17 shows 2D flow path, pressure, and Mach number in the HPT. The inlet and exit total pressures were found to be 516.3 psi and 179 psi whereas inlet/exit total temperatures were determined as 3000R/2312R. Moreover, the relative Mach number of the HPT rotor tip exit was 0.94 which was lower than 1.

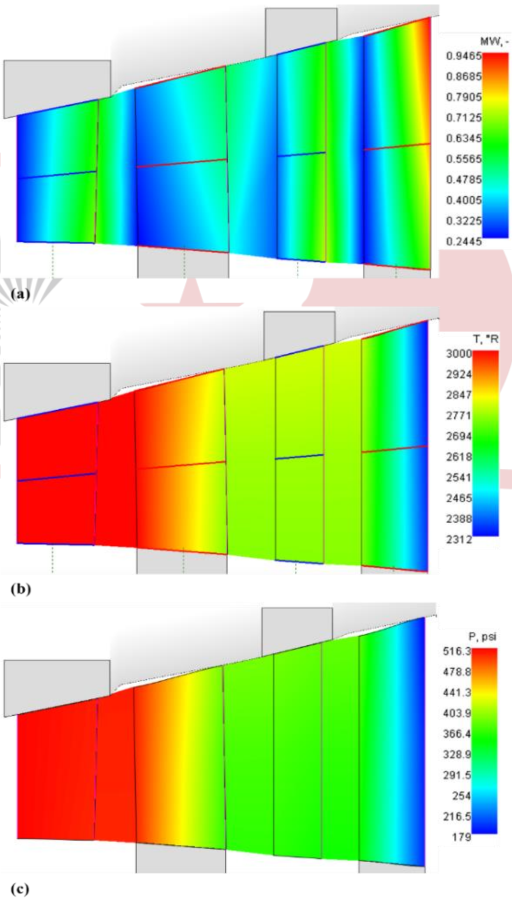


Figure 20 HPT 2D Flow path calculation result (a) Mach number, (b) Total temperature, (c) Total pressure

Fig. 16 shows the velocity triangles of the HPT.

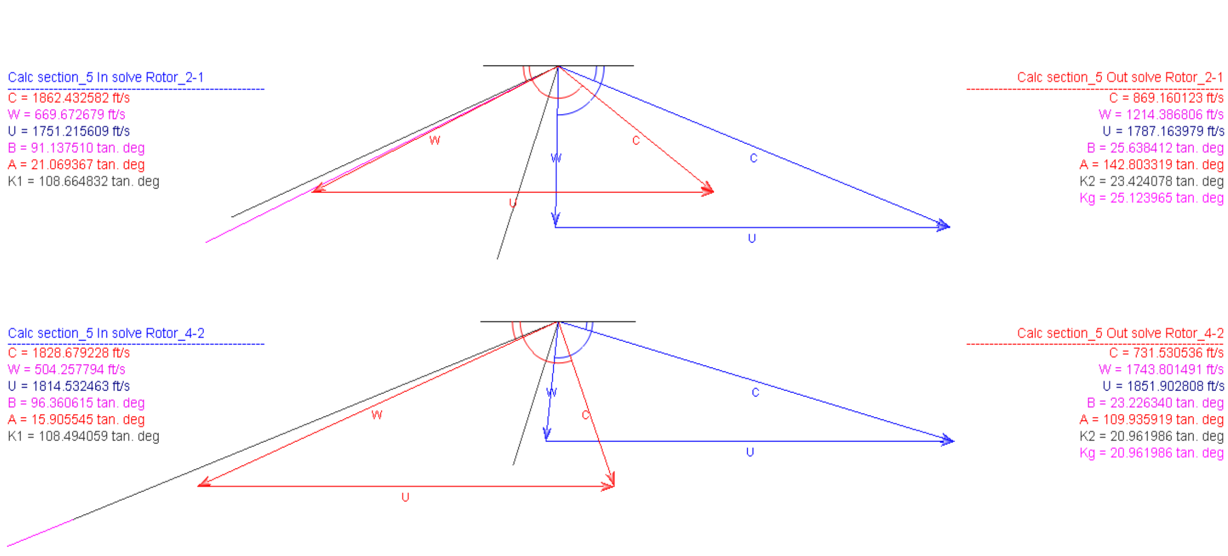


Figure 21 Hub section HPT velocity triangles from AxStream

6.4.1.1 HPT RESULTS

The design results of the HPT were shown in Table 17. It was found that stage loading was in the range of 1.4 and 2.4 and the flow coefficient was 0.7/0.6 which was in the range of 0.6 and 0.9.

Table 17 HPT design results from AxStream

Parameter	STAGE 1		STAGE 2	
	Stator	Rotor	Stator	Rotor
Flow Coefficient	0.7		0.62	
Work Coefficient	1.43		1.8	
Stage Pressure Ratio	1.38		1.98	
Number of Blades	97	83	80	86
Aspect Ratio	1.36	1.58	2.06	2.39
Blade Chord [inch]	0.74	0.82	0.75	0.74
Solidity	1.41	1.45	1.15	1.23
Stagger Angle [tan.deg]	46.72	45.34	65.65	55.22
Leading Edge Radius [in]	0.03	0.02	0.04	0.02
Trailing Edge Radius [in]	0.003	0.004	0.003	0.003
Zweifel Coefficient	0.79	0.75	0.73	0.80
Degree of Reaction at Hub	-	0.36	-	0.39
AN^2 [$in^2 \times rpm^2 \times 10^6$]	39869			

The 3D CAD drawing of the HPT was given in Fig. 21.

Figure 22 3-D CAD drawing of the HPT

6.4.1.2 OFF-DESIGN PERFORMANCE OF HPT

HPT off design performance map was obtained from GasTurb14 and showed in Fig. 22.

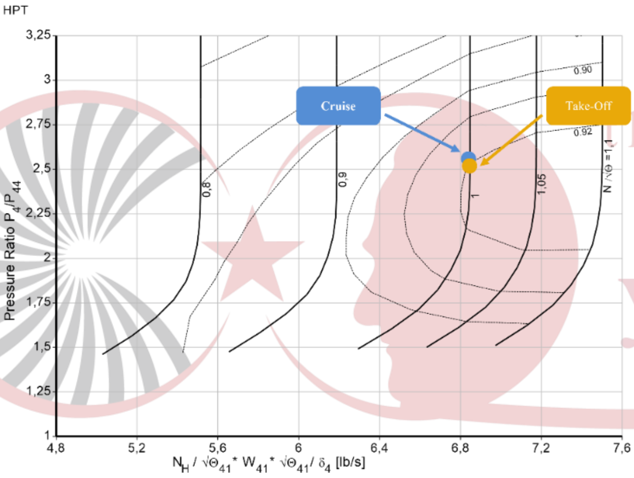


Figure 23 HPT off design performance map

6.4.1.3 HPT MATERIALS

The TMS238 (Ni-based super alloy) was selected as a blade material and composite coatings were used to increase thermal strength of the blades as shown Fig. 20. The HPT disk was also thought to be manufactured from the TMS238.

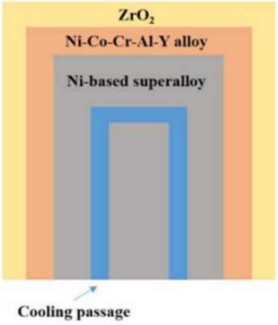


Figure 24 HPT blade material and coatings

6.4.2 LOW PRESSURE TURBINE (LPT) DESIGN

Table 11 shows the data obtained from the GasTurb14 for LPT design.

Table 11 Thermodynamic and geometrical design parameters of the LPT

Thermodynamic and Geometrical Properties			
Total Pressure $_{(inlet)}$ [psi]	183.8	Shaft Rotational Speed [RPM]	10428
Total Pressure $_{(outlet)}$ [psi]	24.7	1st Stage Tip Diameter [inch]	19.18
Pressure Ratio	7.44	4th Stage Tip Diameter [inch]	23.74
Total Temperature $_{(inlet)}$ [R]	2294.5	1st Stage Hub Diameter [inch]	13.68
Total Temperature $_{(outlet)}$ [R]	1481.2	4th Stage Hub Diameter [inch]	13.54
Mass Flow [lb/s]	104.7	1st Stage Blade Height [inch]	2.75
Number of Stage	4	4th Stage Blade Height [inch]	5.1

LPT consisted of 4 axial stages and AxStream streamline calculation module was used to optimize 2D flow path by 9 streamlines. Similar boundary conditions and calculation models with HPT were used in 2D streamline calculations of LPT. Fig. 20 shows LPT flow path optimized in AxStream with Mach number, total temperature, and pressure changes.

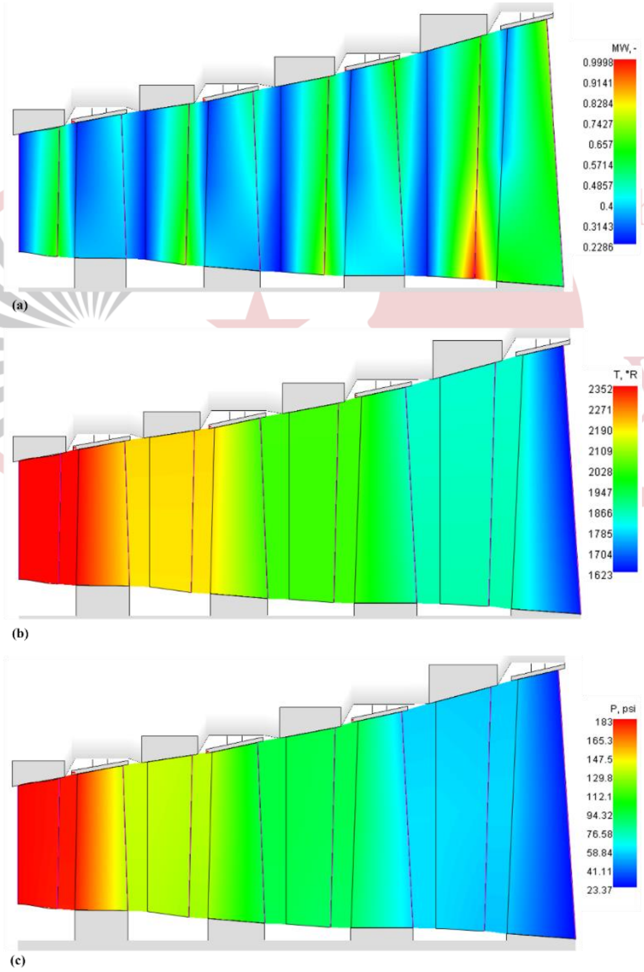


Figure 25 LPT 2D streamline calculation result (a) Relative mach, (b) Total temperature, (c) Total pressure

Velocity triangles of the LPT are illustrated in Fig. 25.

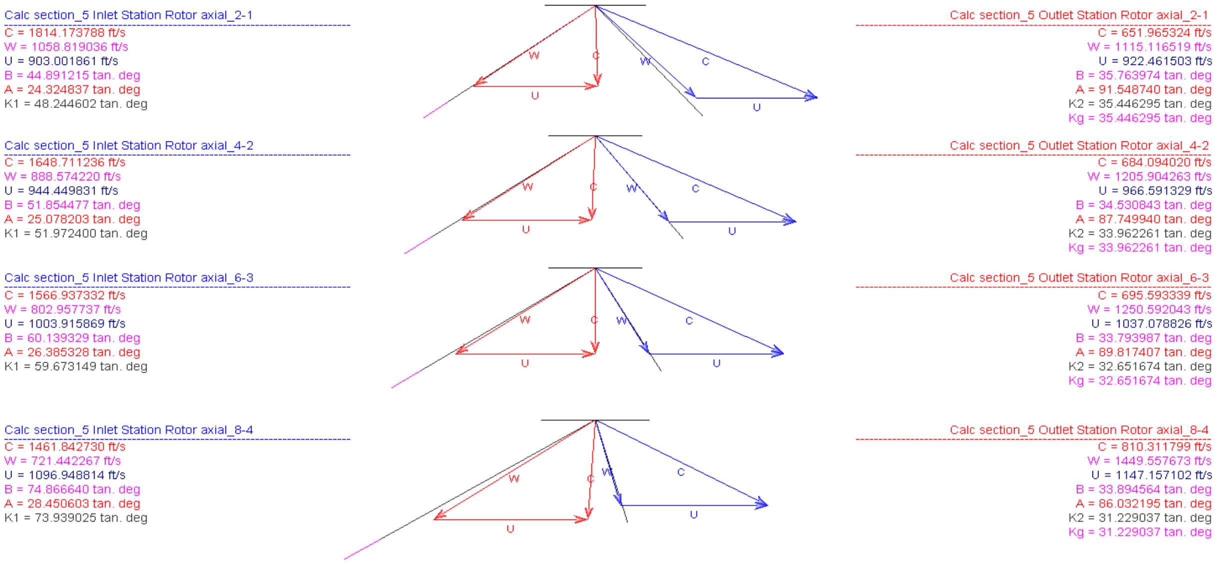


Figure 26 LPT velocity triangles from AxStream

6.4.2.1 LPT RESULTS

LPT design results are presented in Table 12 showing the first and the last stages results. When the results were investigated, it was found that they were in the range of literature.

Table 12 LPT design results

Parameter	*STAGE 1*		*STAGE 4*	
	Stator	*Rotor*	*Stator*	*Rotor*
Flow Coefficient	*0.6*		*0.67*	
Work Coefficient	*1.11*		*1.32*	
Stage Pressure Ratio	*1.3*		*1.64*	
Degree of Reaction at Hub	*0.15*		*0.28*	
Number of Blades	*74*	*88*	*66*	*78*
Aspect Ratio	*2.26*	*2.8*	*3.27*	*3.99*
Blade Chord [in]	*1.12*	*1*	*1.44*	*1.3*
Solidity	*1.31*	*1.39*	*1.42*	*1.5*
Stagger Angle [tan.deg]	*46.53*	*19.8*	*46.59*	*34.26*
Leading Edge Radius [in]	*0.05*	*0.04*	*0.03*	*0.05*
Trailing Edge Radius [in]	*0.005*	*0.004*	*0.005*	*0.005*
Zweifel Coefficient	*0.85*	*1.05*	*0.79*	*0.97*
AN2 [$in^2 \times rpm^2 \times 10^6$]	*38869*			

3D CAD drawing of the LPT is presented in Fig. 26.

Figure 27 3-D CAD drawing of the LPT

6.4.2.2 OFF-DESIGN PERFORMANCE OF LPT

Off-design performance map of the LPT was presented in Fig. 24 including take off condition.

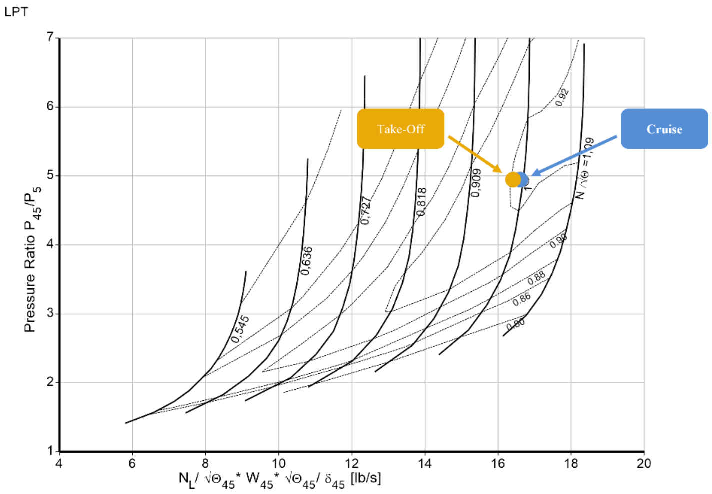


Figure 28 LPT off design performance map

6.4.2.3 LPT MATERIALS

The blade material of the LPT was selected as TMS 238 having the density of 570.24 lb/ft^3 and the disk material was similar to blades.

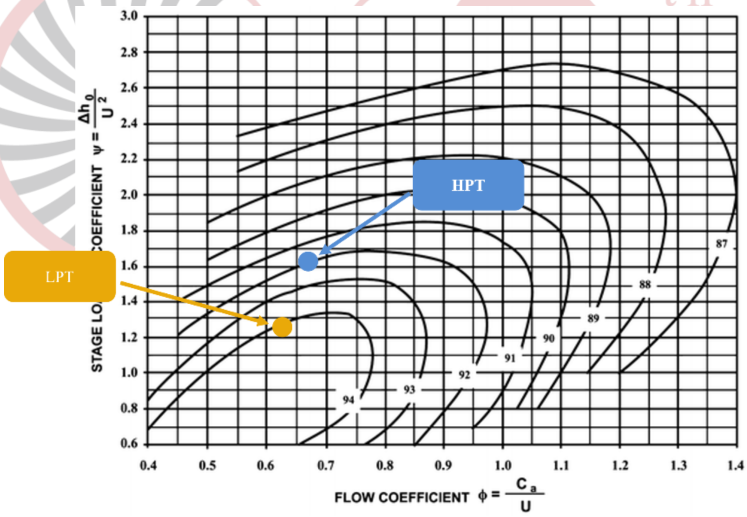


Figure 29 HPT and LPT smith charts

6.5 COLD AND HOT NOZZLE DESIGN

Critical pressure for hot nozzle can be calculated from the Eq.2

$$\frac{P_{06}}{P_c} = \left(\frac{1}{1-(1/\eta_n)\times(\gamma-1)/(\gamma+1)}\right)^{\gamma/(\gamma-1)} \tag{2}$$

If the nozzle was unchoked $P_8 = P_a$, then the speed of the gases leaving the nozzle given with Eq. 3.

$$V_8 = \sqrt{2 \times C_{ph} \times T_{07} \times \eta_{nt} \times \left[1 - \left(\frac{P_a}{P_{07}}\right)^{(\gamma-1)/\gamma}\right]} \tag{3}$$

Critical pressure can be calculated by using the Eq.4.

$$\frac{P_{016}}{P_c} = \left(\frac{1}{1-(1/\eta_n)\times(\gamma-1)/(\gamma+1)}\right)^{\gamma/(\gamma-1)} \tag{4}$$

If the nozzle is unchoked $P_{18} = P_a$, then the speed of the gases leaving the nozzle is given with Eq.5

$$V_{18} = \sqrt{\frac{2\times\gamma_c\times R\times T_{08}\times \eta_{fn}}{(\gamma_c-1)}\left[1-(P_a/P_{016})^{\frac{\gamma_c-1}{\gamma_c}}\right]} \tag{5}$$

The nozzle radius can be calculated at inlet (ri) or exit (re) from the Eq. 6.

$$r = \sqrt{\frac{\dot{m}}{\pi\times\rho\times V}} \tag{6}$$

The axial length of the nozzle can be calculated by using Eq.6 in where θ can be taken in the range of $\theta = 11 - 15°$.

$$L = \frac{r_i - r_e}{tan\theta} \tag{7}$$

Nozzle material was selected as Inconel 625 whose density is 527 lb/ft^3.

6.6 AFT FAN DESIGN

Designed aft fan 2D streamline calculations was shown in Fig. 25. According to the results tip Mach number of the fan was found to be 1.74 which was higher than literature. However, it was though that this fan will be manufactured a new generation material which is strength for higher stress levels. Inlet and outlet total temperatures and pressures can also be seen in Fig. 25 (b) and (c).

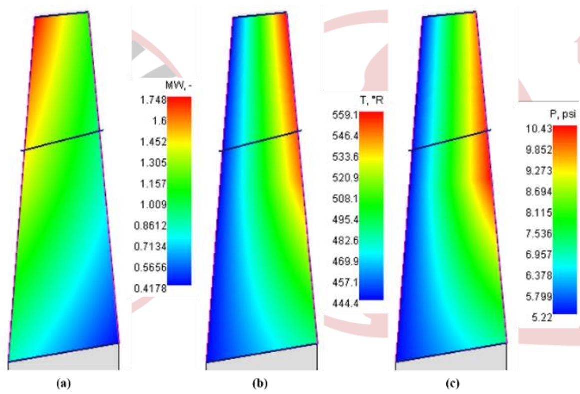


Figure 30 AFT fan 2D streamline calculation result (a) Relative mach, (b) Total temperature, (c) Total pressure

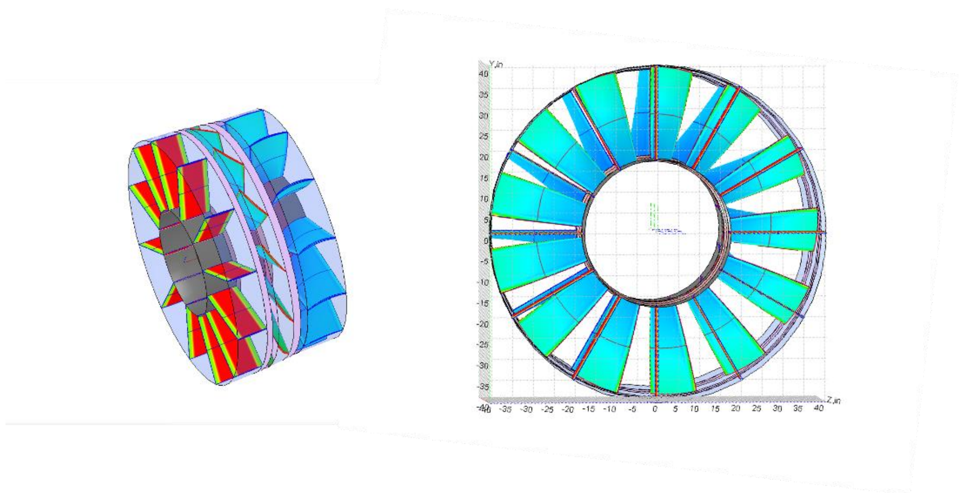


Figure 31 AFT Fan geometry and dimensions from AxStream

7 ENGINE WEIGHT AND GEARBOX WEIGHT CALCULATIONS

Fan rotational speed is recommended nearly one-third of the LPT speed for example (3476/10428 rpm). The LPT rotational speed was 10428 rpm and carried out a gear box usage to reduce fan rotational speed. The gear ratio sun and *the planet gears (z_s) were estimated by equation 8, while the optimum number of planets (N_{rpl}) was calculated by equation 192. The gear ratio was assumed as 3.0 which resulted approximately 3476 rpm fan rotational speed.*

$$Nr_{pl} = \frac{16.3677}{2.8 \times sin^{-1}\left(\frac{z-1}{z+1}\right) \times 1.1736} \qquad (8)$$

$$Nr_{pl} = \frac{16.3677}{2.8 \times sin^{-1}\left(\frac{3-1}{3+1}\right) \times 1.1736} \qquad Nr_{pl} = 8.8470$$

$$2 \times {z_s}^3 + {z_s}^2 = \frac{0.4 \times {z_s}^2 + 1}{Nr_{pl}} \qquad z_s = 0.27421$$

The weight of the gear box was found by using Eq. 9.

$$W_{gear} = 0.5 \times \frac{W}{K \times \omega} \times \left(\frac{1}{Nr_{pl}} + \frac{1}{Nr_{pl} \times z_s} + z_s + {z_s}^2 + \frac{0.4 \times z^2}{Nr_{pl} \times z_s} + \frac{0.4 \times z^2}{Nr_{pl}}\right) \qquad (9)$$

$$W_{gear} = 648.6 \text{ lbm}$$

The weight of the Century 250 engine was obtained as 1886.21 lbm without gearbox mass and mass factor added (see Fig. 29). Addition of gearbox mass, net mass was calculated as 2534.81 lbm. When the net mass factor is applied, the total mass of the engine found as 3295.25 lbm. Furthermore, the hybrid propulsion weight was found as 1730.6 lbm, hence the total mass of the hybrid propulsion system was evlauted as 5025.2 lbm. Engine length and dimesions can be seen in Fig. 31. It is found that our engine without electrical system configuration is 37% lighter compared with CFM56-7B24. When the electrical system is taken into consideration, the overall mass of the hybrid-electric propulsion system from the sum of two turbofan engines mass and the electrical system mass, turned out to be 8321 lbm, whereas two CFM56-7B24 engines weight is 10468 lbm. That means our propulsion system is 20% lighter than two CFM56-7B24.

Front LP Shaft Cone Length	in	0,939005
Middle LP Shaft Length	in	43,8321
Middle LP Shaft Radius	in	1,34402
Rear LP Shaft Cone Length	in	2,56719
HP Shaft Cone Length	in	3,91416
HP Shaft Length	in	3,58926
HP Shaft Radius	in	2,02918
Engine Length	in	119,418
Max Engine Diameter	in	87,6661
Nacelle Length (Bypass only)	in	91,8678
LP Shaft Mass	lbm	46,3164
HP Shaft Mass	lbm	8,51944
Gear Box Mass	lbm	0
Net Mass	lbm	1886,21
Total Mass	lbm	1886,21
LP Spool Inertia	lb*in²	65177,6
HP Spool Inertia	lb*in²	2886,94

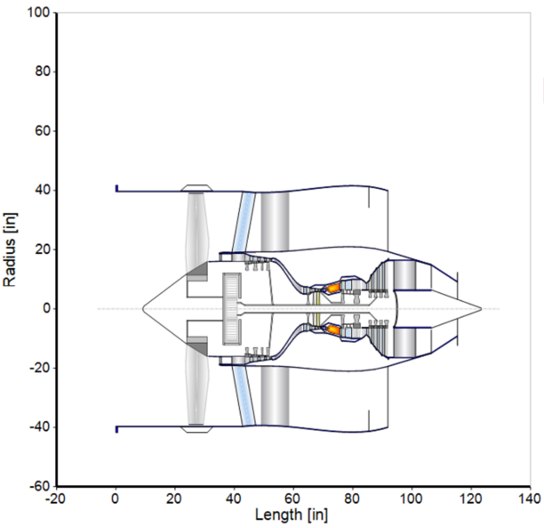


Figure 32 Engine weight and dimensions

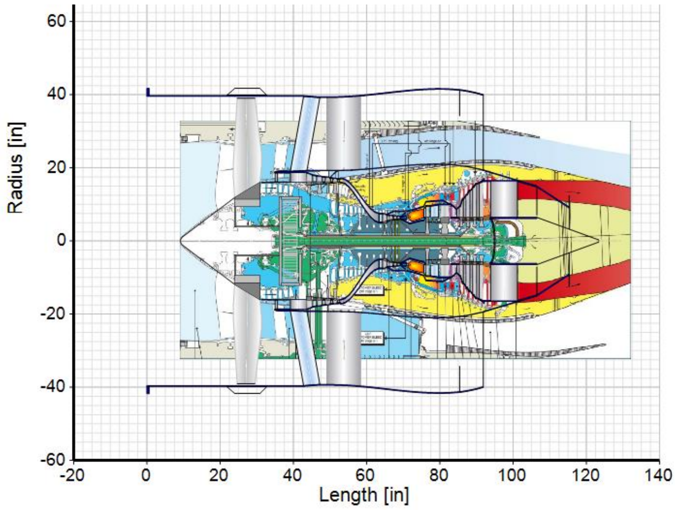


Figure 33 Engine cross section with CFM56-7B24

8 HYBRID PROPULSION SYSTEM DESIGN

Aft fan was designed to ingest boundary air layer and provide additional thrust for plane during the flight. Aft fan was propelled by an electric motor which was powered through the two generators. All two generators also powered by the two primary turbo fan engines which mounted below the wings. The aim of the using aft fan was to ingest boundary layer which formed around the plane body, thus the drag force exerted on the plane body was decreased. Here, we connected the generators to HP spool in our design which resulted in thrust decrease. Fig. 25 shows the designed hybrid propulsion in GasTurb14 software. Aft fan rotational speed was 3500 rpm and needs to 3500 HP at running condition.

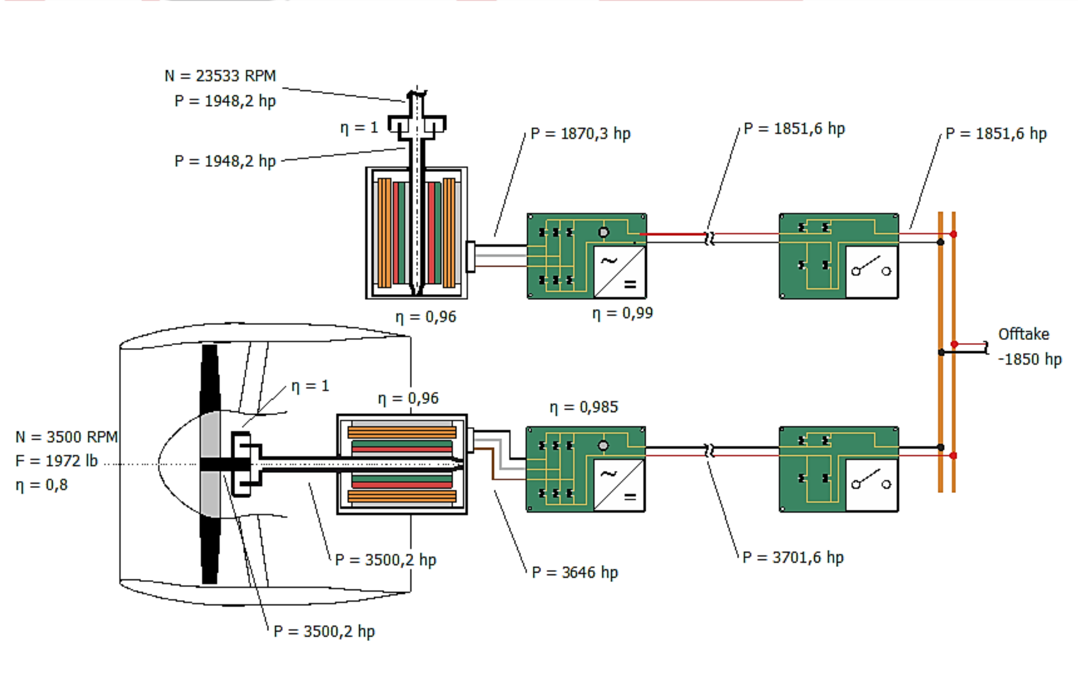


Figure 34 Operation of the hybrid-electric propulsive system

```
Fan Net Thrust          = 1971,78 lb       Fan Pressure Ratio     =  1,25
Fan Gross Thrust        = 9817,82 lb       Fan Corr. Flow         = 844,90 lb/s
Fan Isentr. Efficiency =  0,92
Fan Prop. Efficiency    =  0,89

-----------------------------------------------------------------------

                        Power Output   Losses     Efficiency      Mass
                            hp           hp                        lb

Overall System            3500,20      298,00       0,903        1730,6
-----------------
Fan Gear Box              3500,20        0,00       1,000         575,4
Electric Motor            3500,20      145,84       0,960         345,3

El. System                3646,04       74,23       0,980         585,7
 - Inverter               3646,04       55,52       0,985          95,9
 - Cable to Fan           3701,57        0,00       1,000         371,0
 - SSPC to Fan            3701,57        0,00       1,000          15,8
 - SSPC to Generator      1851,57        0,00       1,000           7,9
 - Cable to Generator     1851,57        0,00       1,000          46,4
 - Rectifier              1851,57       18,70       0,990          48,7

Generator                 1870,27       77,93       0,960         224,2
Generator Gear Box        1948,20        0,00       1,000           0,0

At the DC Bus an electric Power of 1850 hp is fed into the electric system.
```

Figure 35 Specifications of the hybrid-electric propulsion system

Aft fan provided 1971.7 lb thrust with a pressure ratio of 1.25 and mass flow rate of 844.9 lb/s. the fan isentropic efficiency was determined as 0.92 (see Fig. 28). The non-hybrid and hybrid propulsion cycle results can be seen in Fig. 28. If we compared to results, we could fine the thrust loss was 370 lb when the electric propulsion connected to the engines.

```
            W          T          P         WRstd
Station   lb/s         R         psia        lb/s
 amb                 393,85      3,458
  2     515,805      444,38      5,220     1344,142
 13     476,578      482,17      6,749     1000,610
 21      39,227      524,01      8,787       65,942
 22      39,227      524,01      8,701       66,597
 24      39,227      805,83     34,212       21,003
 25      39,227      805,83     33,521       21,436
  3      38,442     1389,38    203,060        4,554
 31      34,912     1389,38    203,060
  4      35,851     2999,89    194,976        6,499
405      37,420     2938,43    194,976
 41      38,401     2902,44    194,976        6,847
 43      38,401     2391,02     76,568
 44      39,382     2368,08     76,568
 45      39,970     2351,93     75,036       16,670
 49      39,970     1675,54     15,262
  5      40,166     1673,45     15,262       69,470
  8      40,166     1673,45     14,652       72,364
 18     476,578      482,17      6,614     1021,026
Bleed     0,000     1389,38    203,060
--------------------------------------------------
Efficiency        isentr  polytr    RNI      P/P
 Outer LPC        0,8966  0,9003   0,426    1,293
 Inner LPC        0,8966  0,9039   0,426    1,683
 IP Compressor    0,8834  0,9032   0,585    3,932
 HP Compressor    0,8783  0,9034   1,349    6,058
 Burner           0,9995                    0,960
 HP Turbine       0,9200  0,9116   1,775    2,546
 LP Turbine       0,9104  0,8930   0,870    4,916
--------------------------------------------------
HP Spool mech Eff 0,9900   Speed     23537 rpm
LP Spool mech Eff 0,9900   Speed      3439 rpm
IPC & LPT                  Speed     10316 rpm
--------------------------------------------------
P22/P21=0,9902 P25/P24=0,9798 P45/P44=0,9800
--------------------------------------------------
hum [%]     war0       FHV      Fuel
   0,0    0,00000    18552,4    Generic

FN         =   5418,65 lb
TSFC       =    0,6241 lb/(lb*h)
WF         =   0,93943 lb/s
s NOX      =    0,6303
P5/P2      =    2,9238 EPR
Core Eff   =    0,5694
Prop Eff   =    0,8225
BPR        =   12,1492
P2/P1      =    0,9900
P3/P2      =     38,90
P5/P2      =    2,9238
NGV Out. 2 Stage HPT
P16/P13    =    0,9800
P16/P6     =   0,45139
P16/P2     =   1,26701
P6/P5      =   0,96001
A8         =    218,99 in²
A18        =   3049,80 in²
XM8        =   1,00000
XM18       =   1,00000
WBld/W2    =   0,00000
CD8        =   0,98000
CD18       =   0,97554
PWX        =     200,0 hp
V18/V8,id=     0,37519
WBLD/W22 =     0,00000
Wreci/W25=     0,00000
Loading    =    102,74 %
WCHN/W25 =     0,06500
WCHR/W25 =     0,02500
WCLN/W25 =     0,01500
WCLR/W25 =     0,00500
WBLD/W25 =     0,00000

WLkBy/W25=     0,00000
WlkLP/W25=     0,00000
```

(a)

```
            W          T          P         WRstd
Station   lb/s         R         psia        lb/s
 amb                 393,85      3,458
  2     516,375      444,38      5,220     1345,627
 13     477,020      482,40      6,756     1000,628
 21      39,355      524,46      8,805       66,049
 22      39,355      524,46      8,718       66,707
 24      39,355      807,51     34,400       20,978
 25      39,355      807,51     33,707       21,410
  3      38,568     1391,64    204,095        4,549
 31      35,026     1391,64    204,095
  4      35,975     3010,97    195,986        6,499
405      37,549     2949,17    195,986
 41      38,533     2912,99    195,986        6,847
 43      38,533     2285,86     60,885
 44      39,517     2265,23     60,885
 45      40,107     2250,37     59,667       20,576
 49      40,107     1565,16     10,982
  5      40,304     1563,56     10,982       93,643
  8      40,304     1563,56     10,543       97,544
 18     477,020      482,40      6,621     1021,045
Bleed     0,000     1391,64    204,095
--------------------------------------------------
Efficiency        isentr  polytr    RNI      P/P
 Outer LPC        0,8953  0,8991   0,426    1,294
 Inner LPC        0,8953  0,9028   0,426    1,687
 IP Compressor    0,8830  0,9029   0,585    3,946
 HP Compressor    0,8787  0,9038   1,353    6,055
 Burner           0,9995                    0,960
 HP Turbine       0,9198  0,9091   1,777    3,219
 LP Turbine       0,9103  0,8914   0,728    5,433
--------------------------------------------------
HP Spool mech Eff 0,9900   Speed     23537 rpm
LP Spool mech Eff 0,9900   Speed      3446 rpm
IPC & LPT                  Speed     10338 rpm
--------------------------------------------------
P22/P21=0,9901 P25/P24=0,9798 P45/P44=0,9800
--------------------------------------------------
hum [%]     war0       FHV      Fuel
   0,0    0,00000    18552,4    Generic

Electric propulsion system (1850 hp) connected to HP Spool.

FN         =   5048,34 lb
TSFC       =    0,6765 lb/(lb*h)
WF         =   0,94871 lb/s
s NOX      =    0,6356
P5/P2      =    2,1038 EPR
Core Eff   =    0,5635
Prop Eff   =    0,8328
BPR        =   12,1211
P2/P1      =    0,9900
P3/P2      =     39,10
P5/P2      =    2,1038
NGV Out. 2 Stage HPT
P16/P13    =    0,9800
P16/P6     =   0,62805
P16/P2     =   1,26847
P6/P5      =   0,96002
A8         =    294,63 in²
A18        =   3049,80 in²
XM8        =   1,00000
XM18       =   1,00000
WBld/W2    =   0,00000
CD8        =   0,98000
CD18       =   0,97556
PWX        =     200,0 hp
V18/V8,id=     0,43386
WBLD/W22 =     0,00000
Wreci/W25=     0,00000
Loading    =    101,71 %
WCHN/W25 =     0,06500
WCHR/W25 =     0,02500
WCLN/W25 =     0,01500
WCLR/W25 =     0,00500
WBLD/W25 =     0,00000

WLkBy/W25=     0,00000
WlkLP/W25=     0,00000
```

(b)

Fig. 28 Cruise cycle calculation results, (a) non-hybrid propulsion, (b) hybrid propulsion

The thrust comparison of non-hybrid and hybrid propulsion system are illustrated in Table 30. The two-engine provided total thrust of 10837lb while hybrid-electric propulsion provided 12068.3 lb thrust. This means that hybrid-electric propulsion had 10.2% thrust increase at the cruise condition.

Table 13 Net thrust comparison of the baseline and hybrid electric propulsion

	Net Thrust (lbf)	
	Baseline	Hybrid-Electric
Primary Engine 1	5418.6	5048.3
Primary Engine 2	5418.6	5048.3
Electric Fan	-	1971.7
Total Thrust (lbf)	10837	12068.3

TSFC comparison of the baseline and hybrid-electric showed almost identical fuel consumption. This shows that by using the hybrid-electric propulsion boundary layer ingested and drag force exerted on plane body decreased. However, hybrid-electric propulsion increased the net thrust 10% and when drag force reduction taken consideration fuel consumption will decrease. The aft fan is useful for planes and the loss of energy from the engines is provided more with the help of the aft fan. Even though it causes an increase in mass when added, it allows to catch the flow separation that occurs around the plane body and thanks to the slow air flow around the body, the aircraft can fly at the same speed with less thrust at the same altitude. This constitutes fuel reduction at the cruise condition.

Degree of hybridization (DOH) was calculated by Eq. 10. The DOH number of 0.28 showed that hybridization level was 28% which was a good agreement in the project. This means that %28 of the total thrust was obtained from the electrical aft fan.

$$DoH = \frac{Power\ Extraction}{(Power\ Extraction + Propulsive\ Power)}$$

$$Propulsive\ Power = Net\ Thrust \times Flight\ Velocity$$

$$Propulsive\ Power = 1971{,}8\ lb + 5048 * 2\ lb = 12067{,}8 \times 0.8$$

$$Power\ Extraction = 1948\ hp \times 2$$

$$DoH = 0{,}287 = \%28.7$$

9 MISSION AND PROPULSION COMPARISON

Non hybrid propulsion system fuel consumption was calculated as 38566.51 lbm and illustrated in Table 7 in section 4.2. The hybrid propulsion mission fuel consumption is shown in Table 14 where the fuel consumption decreased to 30370.96 lb. The cruise thrust of the hybrid electric propulsion was determined via calculation of the net thrust of the two baseline engines and addition of aft fan thrust which corresponded to 10000 lb net thrust of the system. As a result, 21.2% fuel saving was achieved when the hybrid propulsion is used. Although hybrid propulsion carried out 1730 lb additional weight to propulsion system, the fuel saving and thrust increase tolerated this weight increase.

Table 14 Flight mission for designed Century-250 with hybrid electric propulsion system

Segment	Altitude (ft)	Mach Number	Thrust (lbf)	TSFC (lbm/lbf*h)	Fuel Flow (lb/s)	Time(min)	Fuel Burned in Segment (lbm)
Taxi Out	0	0.015	3000	0.3	0.256	15	230.4
Take Off	0-10000	0.38	18000	0.48	2.404	3.5	504.84
Climb	10000-35000	0.43	10000	0.47	1.306	11.5	901.14
Cruise	35000	0.8	4032	0.76	0.765	676.2	26128.368
Descend	35000-10000	0.38	10000	0.44	1.242	24.5	1825.74
Approach & Touchdown	10000-0	0.21	14000	0.38	1.498	8	719.04
Taxi In	0	0.015	3000	0.3	0.256	4	61.44
Total						742.7	30370.96

10 CONCLUSIONS

In this project, a hybrid propulsion was designed with the new turbofan engines having ultra-high bypass ratio of 12. The engines were designed with iterative studies by changing T4 and T3 temperatures, OPR, and BPRs to obtain best hybrid propulsion system. The results showed that increasing the BPR of baseline engine from 5.3 to 12 decreased the specific fuel consumption significantly not only at takeoff condition but also at cruise condition. Hybrid electric propulsion increased the total thrust of the plane by 12.1% and ingested the boundary layer apart this thrust increase. The weight of the engines was also decreased from 5585 lbm to 3295lbm, however, the diameter of the engine fan increased from 65 inches to 80 inches. On the other hand, total weight of the hybrid propulsion was obtained as 5025lbm. The diameter increase was traded of with fuel saving and thrust increase with weight reduction. Moreover, DOH calculation showed that 28% hybridization was achieved in this project and this ratio carried out very good fuel saving. It is believed that if this ratio increased up to 50%, it would bring out ultimate fuel consumption to the air planes which resulted decrease in carbon foot print. In conclusion, hybrid propulsion provides restricted thrust increase with extremely fuel saving according to the mission results from the viewpoint of propulsion system, however, it is known that boundary layer ingestion will provide decrement in the fuel consumption and additional thrust. This issue can be investigated via computational fluid dynamics (CFD) analysis and results can be discussed detailly.

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12 APPENDIXES

```
             W          T          P        WRstd
Station   lb/s          R       psia         lb/s       FN          =  25536,09 lb
 amb                 523,97     14,696                  TSFC        =    0,2172 lb/(lb*h)
  2     867,579      522,00     14,504      881,892     WF          =   1,54069 lb/s
 13     799,669      579,41     20,240      613,687     s NOX       =    1,7549
 21      67,910      619,39     24,992       43,639
 22      67,910      619,39     24,742       44,079     Core Eff =       0,4968
 24      67,910      717,44     39,130       29,997     Prop Eff =       0,0000
 25      67,910      717,44     38,347       30,609     BPR         =   11,7754
  3      66,552     1603,03    570,776        3,012     P2/P1       =    1,0000
 31      60,440     1603,03    570,776                  P3/P2       =     39,35
  4      61,981     3090,00    547,945        4,057     P5/P2       =    1,3664
 41      64,697     3032,63    547,945        4,196     P16/P13     =    0,9800
 43      64,697     2238,72    129,434                  P16/P6      =   1,00087
 44      68,092     2209,04    129,434                  P16/P2      =   1,36758
 45      69,111     2196,16    126,845       16,476     P6/P5       =   1,00000
 49      69,111     1461,05     19,818                  A8          =    301,32 in²
  5      69,451     1460,52     19,818       86,422     A18         =   2148,05 in²
  8      69,451     1460,52     19,818       86,422     XM8         =   0,67992
 18     799,669      579,41     19,835      626,212     XM18        =   0,66889
Bleed     0,000     1603,03    570,774                  WBld/W2     =   0,00000
-------------------------------------------------       CD8         =   0,94229
Efficiency         isentr  polytr    RNI      P/P       CD18        =   0,95063
 Outer LPC         0,9066  0,9109  0,979    1,395       PWX         =     200,0 hp
 Inner LPC         0,8992  0,9066  0,979    1,723       V18/V8,id=      0,62931
 IP Compressor     0,8808  0,8882  1,363    1,582       WBLD/W22 =      0,00000
 HP Compressor     0,8785  0,9131  1,773   14,885       Wreci/W25=      0,00000
 Burner            0,9995                   0,960       Loading     =    100,00 %
 HP Turbine        0,9333  0,9219  4,743    4,233       WCHN/W25 =      0,04000
 LP Turbine        0,9218  0,9030  1,591    6,401       WCHR/W25 =      0,05000
-------------------------------------------------       WCLN/W25 =      0,01500
HP Spool mech Eff 0,9900   Nom Spd    20919 rpm         WCLR/W25 =      0,00500
LP Spool mech Eff 0,9900   Nom Spd     5051 rpm         WBLD/W25 =      0,00000
-------------------------------------------------       WLkBy/W25=      0,00000
P22/P21=0,9900 P25/P24=0,9800 P45/P44=0,9800            WlkLP/W25=      0,00000
-------------------------------------------------
hum [%]      war0        FHV      Fuel
   0,0    0,00000    18413,0      Generic
```

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	867,579	67,91	67,91	67,91	66,5518	61,9806	68,0925	69,1111	69,4507	69,4507	69,4507	799,669	799,669	799,669
Total Temperature	R	522	619,391	717,438	717,438	1603,03	3090	2209,04	2196,16	1460,52	1460,52	1460,52	579,405	579,405	579,406
Static Temperature	R	475,336	590,031	695,338	689,691	1585,78	3085,59	2127,22	2155,7	1400,85	1411,91	1353,33	546,475	551,922	531,946
Total Pressure	psia	14,5038	24,7419	39,1295	38,3469	570,776	547,945	129,434	126,845	19,8178	19,8178	19,8178	20,2398	19,835	19,835
Static Pressure	psia	10,4553	20,8626	35,0577	33,3868	547,38	544,434	110,23	117,163	16,8165	17,3413	14,6959	16,4803	16,7231	14,696
Velocity	ft/s	748,26	595,089	516,303	578,507	478,532	261,137	1093,44	770,301	898,174	811,342	1201,75	630,229	575,755	756,261
Area	in²	2812,37	172,19	139,185	129,376	21,4958	71,7667	64,1152	88,0697	343,649	371,828	283,932	2244,75	2445,59	2041,99
Mach Number		0,7	0,5	0,4	0,45	0,25	0,1	0,5	0,35	0,5	0,45	0,679915	0,55	0,5	0,668886
Density	lb/ft³	0,059367	0,095435	0,136082	0,130657	0,931662	0,47624	0,139864	0,146698	0,032401	0,033151	0,02931	0,081397	0,081781	0,074567
Spec Heat @ T	BTU/(lb*R)	0,240096	0,24107	0,242203	0,242203	0,267401	0,308429	0,292726	0,29229	0,271851	0,271851	0,271851	0,240608	0,240608	0,240608
Spec Heat @ Ts	BTU/(lb*R)	0,239947	0,240731	0,241947	0,241882	0,266893	0,308376	0,290926	0,291434	0,269816	0,270202	0,268159	0,240228	0,240291	0,240127
Enthalpy @ T	BTU/lb	-3,51762	19,9346	43,5676	43,5676	268,583	716,557	449,27	445,28	237,148	237,148	237,148	10,2965	10,2965	10,2966
Enthalpy @ Ts	BTU/lb	-14,7065	12,8577	38,2405	36,8796	264,007	715,194	425,377	433,422	221,027	223,993	208,287	2,35916	3,672	-1,13277
Entropy Function @ T		-0,096874	0,503322	1,01938	1,01938	3,97669	6,90795	5,41777	5,3904	3,71208	3,71208	3,71208	0,268965	0,268965	0,268968
Entropy Function @ Ts		-0,424177	0,332782	0,909498	0,880866	3,93484	6,90152	5,25716	5,311	3,54786	3,57859	3,41307	0,063478	0,098307	-0,030904
Exergy	BTU/lb	-0,472263	20,6035	42,1631	41,4369	257,214	598,35	332,759	329,027	114,494	114,494	114,494	12,1702	11,4439	11,4439
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,025491	0,02315	0,022801	0,022687	0,022687	0,022687	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Radius	in	10,1762	13,5319	13,7246	6,29022	6,44812	7,33534	7,33534	7,33534	7,33534	7,33534	3,99235	16,1579	15,2595	15,2899
Outer Radius	in	31,6032	15,4247	15,2535	8,98602	6,96056	8,75507	8,61485	9,04658	12,7747	13,1211	10,576	31,2347	31,8011	30,2907
Axial Position	in	16,4969	16,4969	27,5537	36,4747	49,1875	55,1855	56,4633	58,2971	64,2294	76,6209	85,8057	34,4032	57,0485	64,1996

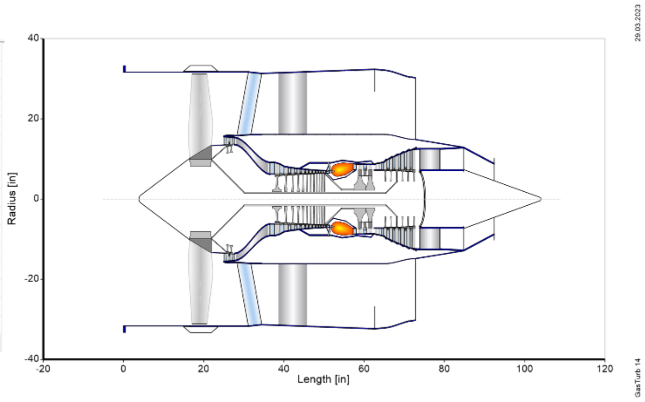
Engine 1 Take off cycle results.

```
          W           T          P         WRstd
Station  lb/s         R         psia        lb/s          FN          =    4283,59 lb
 amb                393,85      3,458                     TSFC        =     0,5795 lb/(lb*h)
  2    341,841      444,38      5,273     881,898         WF          =    0,68952 lb/s
 13    315,083      493,41      7,358     613,790         s NOX       =     0,6276
 21     26,758      527,63      9,086      43,653         P5/P2       =     2,5471 EPR
 22     26,758      527,63      8,995      44,094         Core Eff =         0,5714
 24     26,758      611,23     14,226      30,008         Prop Eff =         0,7953
 25     26,758      611,23     13,941      30,620         BPR         =    11,7753
  3     26,223     1384,88    207,504       3,035         P2/P1       =     1,0000
 31     23,815     1384,88    207,504                     P3/P2       =      39,35
  4     24,504     3090,01    199,204       4,412         P5/P2       =     2,5471
 41     25,574     3025,37    199,204       4,557         P16/P13     =     0,9800
 43     25,574     2340,32     58,104                     P16/P6      =    0,53693
 44     26,912     2296,39     58,104                     P16/P2      =    1,36759
 45     27,314     2280,16     56,942      14,780         P6/P5       =    1,00000
 49     27,314     1667,86     13,430                     A8          =     164,23 in²
  5     27,447     1665,56     13,430      53,821         A18         =    1869,92 in²
  8     27,447     1665,56     13,430      53,821         XM8         =    1,00000
 18    315,083      493,41      7,211     626,317         XM18        =    1,00000
Bleed    0,000     1384,88    207,504                     WBld/W2     =    0,00000
---------------------------------------------------       CD8         =    0,97200
Efficiency        isentr  polytr    RNI     P/P           CD18        =    0,97600
 Outer LPC        0,9066  0,9109  0,431   1,395           PWX         =      200,0 hp
 Inner LPC        0,8992  0,9066  0,431   1,723           V18/V8,id=       0,41308
 IP Compressor    0,8808  0,8882  0,600   1,582           WBLD/W22 =       0,00000
 HP Compressor    0,8777  0,9131  0,780  14,884           Wreci/W25=       0,00000
 Burner           0,9995                  0,960           Loading     =     100,00 %
 HP Turbine       0,9316  0,9219  1,727   3,428           WCHN/W25 =       0,04000
 LP Turbine       0,9218  0,9080  0,684   4,240           WCHR/W25 =       0,05000
---------------------------------------------------       WCLN/W25 =       0,01500
HP Spool mech Eff 0,9900  Speed      20923 rpm            WCLR/W25 =       0,00500
LP Spool mech Eff 0,9900  Speed       5051 rpm            WBLD/W25 =       0,00000
---------------------------------------------------       WLkBy/W25=       0,00000
P22/P21=0,9900 P25/P24=0,9800 P45/P44=0,9800              WlkLP/W25=       0,00000
---------------------------------------------------
hum [%]     war0       FHV     Fuel
   0,0   0,00000   18413,0    Generic
```

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	341,838	26,7575	26,7575	26,7575	26,2223	24,5037	26,9118	27,3132	27,447	27,447	27,447	315,081	315,081	315,081
Total Temperature	R	444,378	527,63	611,22	611,22	1384,87	3090	2296,38	2280,15	1665,56	1665,56	1665,56	493,412	493,412	493,412
Static Temperature	R	404,641	502,467	592,356	587,537	1369,53	3085,63	2212,48	2238,54	1600,25	1612,46	1428,12	465,216	469,877	411,036
Total Pressure	psia	5,27271	8,99466	14,2251	13,9406	207,5	199,2	58,1029	56,9409	13,4302	13,4302	13,4302	7,35799	7,21083	7,21083
Static Pressure	psia	3,80051	7,58247	12,7422	12,1343	198,929	197,926	49,5093	52,6082	11,4124	11,7658	7,23229	5,99019	6,07852	3,80814
Velocity	ft/s	690,495	549,472	476,997	534,462	446,653	260,909	1113,19	783,667	955,42	862,947	1811,35	581,643	531,402	994,181
Area	in²	2812,12	172,166	139,129	129,33	21,5637	78,1141	57,6378	79,1219	214,909	232,552	159,633	2244,55	2445,32	1825,04
Mach Number		0,69998	0,5	0,4	0,450004	0,250001	0,100001	0,500001	0,350001	0,5	0,450002	1	0,55	0,5	0,999987
Density	lb/ft³	0,02535	0,04073	0,05806	0,055743	0,392049	0,173133	0,060399	0,063432	0,019249	0,019695	0,013669	0,034753	0,034916	0,025006
Spec Heat @ T	BTU/(lb*R)	0,239848	0,240114	0,240976	0,240976	0,260853	0,310379	0,296092	0,295553	0,279674	0,279674	0,279674	0,240004	0,240004	0,240004
Spec Heat @ Ts	BTU/(lb*R)	0,239722	0,240033	0,240758	0,240702	0,260368	0,310326	0,294306	0,29467	0,277647	0,27805	0,271928	0,239915	0,239929	0,239742
Enthalpy @ T	BTU/lb	-22,1298	-2,1675	17,965	17,965	211,012	720,247	476,947	471,904	294,732	294,732	294,732	-10,3724	-10,3724	-10,3724
Enthalpy @ Ts	BTU/lb	-31,6577	-8,20104	13,4181	12,2566	207,025	718,887	452,183	459,631	276,49	279,851	229,165	-17,1331	-16,0156	-30,1244
Entropy Function @ T		-0,659571	-0,059374	0,456686	0,456686	3,414	6,94032	5,60587	5,57259	4,25471	4,25471	4,25471	-0,293731	-0,293731	-0,293731
Entropy Function @ Ts		-0,98698	-0,230166	0,346595	0,317909	3,37182	6,9339	5,44582	5,49345	4,0919	4,12241	3,63576	-0,499395	-0,464554	-0,932175
Exergy	BTU/lb	12,1144	30,2903	48,8642	48,3184	234,421	647,291	406,754	402,064	221,471	221,471	221,471	22,991	22,4451	22,4451
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,028954	0,026295	0,025898	0,025769	0,025769	0,025769	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0

Engine 1 Cruise cycle results.

Front LP Shaft Cone Length	in	8,09598
Middle LP Shaft Length	in	36,023
Middle LP Shaft Radius	in	1,81197
Rear LP Shaft Cone Length	in	2,59312
HP Shaft Cone Length	in	4,23602
HP Shaft Length	in	3,48742
HP Shaft Radius	in	2,21256
Engine Length	in	102,383
Max Engine Diameter	in	70,123
Nacelle Length (Bypass only)	in	72,8435
LP Shaft Mass	lbm	44,3773
HP Shaft Mass	lbm	9,71364
Gear Box Mass	lbm	0
Net Mass	lbm	1753,98
Total Mass	lbm	2280,17
LP Spool Inertia	lb*in²	87981,3
HP Spool Inertia	lb*in²	8943,51



Engine 1 Geometry

Appendix 2

```
             W            T           P        WRstd
Station   lb/s           R         psia        lb/s
 amb                 523,97      14,696
  2      983,441     522,00      14,504     999,666
 13      921,923     563,27      18,619     758,299
 21       61,518     566,35      18,520      51,011
 22       61,518     566,35      18,334      51,527
 24       61,518     659,93      29,515      34,551
 25       61,518     659,93      28,925      35,256
  3       60,288    1619,57     556,952       2,811
 31       54,751    1619,57     556,952
  4       56,032    2995,14     534,674       3,701
405       58,493    2941,64     534,674
 41       60,031    2910,34     534,674       3,908
 43       60,031    2061,18      97,418
 44       61,569    2050,74      97,418
 45       62,594    2038,54      95,069      19,182
 49       62,594    1391,57      17,099
  5       62,799    1391,41      17,099      88,404
  8       62,799    1391,41      17,099      88,404
 18      921,923     563,27      18,247     773,774
Bleed      0,000    1619,57     556,952
-------------------------------------------------
Efficiency         isentr  polytr   RNI     P/P
 Outer LPC         0,9344  0,9367  0,979   1,284
 Inner LPC         0,8500  0,8551  0,979   1,277
 IP Compressor     0,8788  0,8866  1,124   1,610
 HP Compressor     0,8545  0,8989  1,478  19,255
 Burner            0,9995                  0,960
 HP Turbine        0,8965  0,8760  4,856   5,488
 LP Turbine        0,9203  0,9026  1,299   5,560
-------------------------------------------------
HP Spool mech Eff 0,9900  Nom Spd  18613 rpm
LP Spool mech Eff 0,9900  Nom Spd   4461 rpm
-------------------------------------------------
P22/P21=0,9900 P25/P24=0,9800 P45/P44=0,9759
-------------------------------------------------
hum [%]     war0       FHV      Fuel
  0,0    0,00000   18413,0    Generic

FN          =  24601,31 lb
TSFC        =    0,1875 lb/(lb*h)
WF          =   1,28105 lb/s
s NOX       =    1,8219

Core Eff =      0,4634
Prop Eff =      0,0000
BPR         =  14,9862
P2/P1       =   1,0000
P3/P2       =    38,40
P5/P2       =   1,1789
NGV Out. 2 Stage HPT
P16/P13     =   0,9800
P16/P6      =  1,06717
P16/P2      =  1,25809
P6/P5       =  1,00000
A8          =   390,06 in²
A18         =  2954,47 in²
XM8         =  0,47894
XM18        =  0,56483
WBld/W2     =  0,00000
CD8         =  0,92852
CD18        =  0,94149
PWX         =    200,0 hp
V18/V8,id=     0,75632
WBLD/W22 =     0,00000
Wreci/W25=     0,00000
Loading     =   100,00 %
WCHN/W25 =     0,06500
WCHR/W25 =     0,02500
WCLN/W25 =     0,01667
WCLR/W25 =     0,00333
WBLD/W25 =     0,00000
WLkBy/W25=     0,00000
WlkLP/W25=     0,00000
```

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	983,441	61,5181	61,5181	61,5181	60,2877	56,0322	61,5688	62,5941	62,7991	62,7991	62,7991	921,923	921,923	921,923
Total Temperature	R	522	566,353	659,934	659,934	1619,57	2995,14	2050,74	2038,54	1391,41	1391,41	1391,41	563,274	563,274	563,274
Static Temperature	R	475,336	539,481	639,584	636,528	1602,15	2990,81	1989,84	2000,23	1376,83	1344,39	1338,37	531,212	536,532	529,558
Total Pressure	psia	14,5038	18,3344	29,515	28,9247	556,952	534,674	97,418	95,0693	17,0985	17,0985	17,0985	18,6194	18,247	18,247
Static Pressure	psia	10,4553	15,4573	26,4407	25,4797	534,136	531,237	85,8069	87,7755	16,411	14,9551	14,696	15,1602	15,3835	14,696
Velocity	ft/s	748,26	569,293	495,429	531,327	480,843	257,38	938,057	743,801	441,719	793,237	842,466	621,418	567,739	637,182
Area	in²	3187,95	201,215	160,249	154,317	20,0645	65,3892	81,203	102,312	636,353	379,692	362,177	2773,47	3021,58	2781,62
Mach Number		0,7	0,5	0,4	0,43	0,25	0,1	0,442538	0,35	0,247795	0,45	0,478937	0,55	0,5	0,56483
Density	lb/ft³	0,059367	0,077334	0,11158	0,108041	0,89983	0,479422	0,116392	0,118444	0,032172	0,030025	0,029637	0,077028	0,077388	0,074903
Spec Heat @ T	BTU/(lb*R)	0,240096	0,240457	0,241538	0,241538	0,267889	0,306036	0,288244	0,287796	0,268795	0,268795	0,268795	0,240422	0,240422	0,240422
Spec Heat @ Ts	BTU/(lb*R)	0,239947	0,240151	0,241303	0,241268	0,267375	0,305979	0,28682	0,286901	0,26829	0,267168	0,26696	0,240125	0,240142	0,24012
Enthalpy @ T	BTU/lb	-3,51762	7,15061	29,7068	29,7068	272,972	685,255	402,221	398,51	218,021	218,021	218,021	6,40826	6,40826	6,40826
Enthalpy @ Ts	BTU/lb	-14,7065	0,673935	24,8018	24,0652	268,351	683,931	384,637	387,455	214,122	205,447	203,837	-1,30874	-0,033111	-1,70523
Entropy Function @ T		-0,096874	0,188954	0,725979	0,725979	4,01641	6,74911	5,09062	5,06326	3,51409	3,51409	3,51409	0,169805	0,169805	0,169805
Entropy Function @ Ts		-0,424177	0,018257	0,615984	0,599165	3,97458	6,74266	4,9637	4,98344	3,47305	3,38015	3,36268	-0,035729	-8,9946E-4	-0,046626
Exergy	BTU/lb	-0,472263	8,34613	28,713	27,9867	259,294	571,877	287,256	283,651	97,1784	97,1784	97,1784	8,84676	8,12052	8,12052
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,023398	0,021249	0,020894	0,020824	0,020824	0,020824	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Radius	in	10,018	13,4975	13,7369	7,27146	7,45749	8,63499	8,63499	8,63499	8,63499	8,63499	5,07334	15,4681	20,4225	19,9374
Outer Radius	in	33,3934	15,6918	15,4826	10,0992	7,87677	9,76612	10,0205	10,3504	16,6469	13,9794	12,2433	33,4976	37,1332	36,5778
Axial Position	in	16,6967	16,6967	29,9446	38,8736	51,3227	58,385	61,0997	63,2584	72,1784	88,3259	98,1115	36,5979	69,4769	72,1428

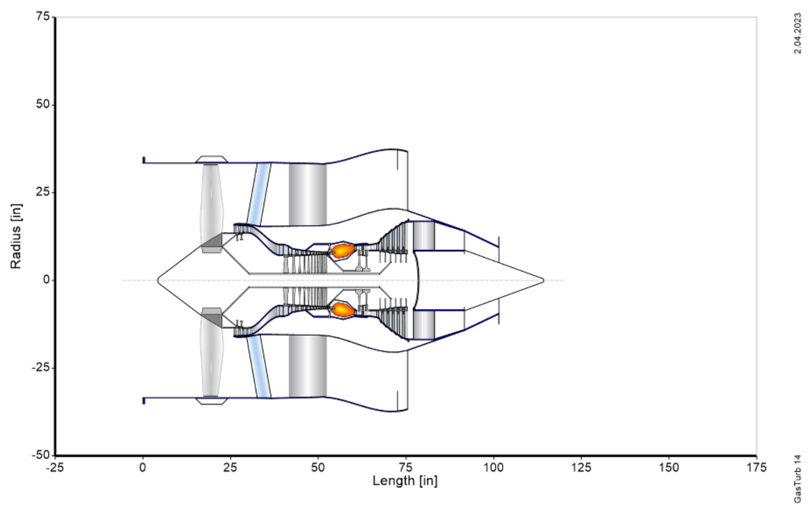
Engine 2 Take Off Cycle Results.

```
             W          T          P        WRstd
Station   lb/s          R       psia         lb/s        FN          =   3953,70 lb
 amb                393,85     3,458                     TSFC        =    0,5890 lb/(lb*h)
  2    434,405      444,38     5,273     1120,701        WF          =   0,64688 lb/s
 13    408,454      478,30     6,645      867,466        s NOX       =    1,1340
 21     25,952      480,04     6,612       55,494        P5/P2       =    2,2434 EPR
 22     25,952      480,04     6,533       56,159        Core Eff    =    0,5503
 24     27,659      604,40    12,479       35,162        Prop Eff    =    0,8449
 25     28,180      604,40    12,221       36,582        BPR         =   15,7390
  3     27,617     1562,01   256,837        2,742        P2/P1       =    1,0000
 31     25,080     1562,01   256,837                     P3/P2       =     48,71
  4     25,727     3070,12   247,060        3,723        P5/P2       =    2,2434
405     26,854     3011,96   247,060                     NGV Out. 2 Stage HPT
 41     27,559     2977,87   247,060        3,928        P16/P13     =    0,9738
 43     27,559     2134,64    46,929                     P16/P6      =   0,54706
 44     28,263     2121,19    46,929                     P16/P2      =   1,22728
 45     28,733     2107,12    45,867       18,556        P6/P5       =   1,00000
 49     28,733     1572,21    11,829                     A8          =    390,06 in²
  5     28,827     1571,32    11,829       62,336        A18         =   2954,47 in²
  8     28,827     1571,32    11,829       62,336        XM8         =   1,00000
 18    408,454      478,30     6,471      890,780        XM18        =   0,98981
Bleed    0,000     1562,01   256,836                     WBld/W2     =   0,00000
----------------------------------------------------     CD8         =   0,94356
Efficiency          isentr  polytr    RNI      P/P       CD18        =   0,97035
 Outer LPC          0,8962  0,8996  0,431    1,260       PWX         =     200,0 hp
 Inner LPC          0,8334  0,8386  0,431    1,254       V18/V8,id=      0,40649
 IP Compressor      0,7831  0,8019  0,487    1,910       WBLD/W22 =      0,00000
 HP Compressor      0,8258  0,8804  0,693   21,017       Wreci/W25=      0,00000
 Burner             0,9984                   0,962       Loading   =      205,27 %
 HP Turbine         0,8940  0,8738  2,184    5,265       WCHN/W25 =      0,06500
 LP Turbine         0,9068  0,8914  0,603    3,878       WCHR/W25 =      0,02500
----------------------------------------------------     WCLN/W25 =      0,01667
HP Spool mech Eff 0,9900   Speed      18613 rpm          WCLR/W25 =      0,00333
LP Spool mech Eff 0,9900   Speed       5353 rpm          WBLD/W25 =      0,00000
----------------------------------------------------     WLkBy/W25=      0,00000
P22/P21=0,9882 P25/P24=0,9793 P45/P44=0,9774             WlkLP/W25=      0,00000
----------------------------------------------------
hum [%]      war0       FHV      Fuel
  0,0     0,00000    18413,0     Generic
```

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	434,405	25,9517	27,6593	28,1801	27,6165	25,7272	28,2634	28,7331	28,827	28,827	28,827	408,454	408,454	408,454
Total Temperature	R	444,378	480,044	604,401	604,401	1562,01	3070,12	2121,19	2107,12	1571,32	1571,32	1571,32	478,302	478,302	478,302
Static Temperature	R	370,172	450,935	584,966	580,91	1546,08	3065,68	2063,07	2070,52	1563,59	1548,27	1343,18	435,973	443,948	399,77
Total Pressure	psia	5,27271	6,53344	12,4791	12,2206	256,837	247,06	46,9294	45,8667	11,8288	11,8288	11,8288	6,64498	6,47106	6,47106
Static Pressure	psia	2,78418	5,25032	11,1259	10,6324	246,848	245,454	41,7327	42,5957	11,5976	11,15	6,35714	4,80659	4,98697	3,45722
Velocity	ft/s	943,589	590,994	484,161	532,3	459,932	262,175	917,981	728,303	325,836	562,456	1761,14	712,667	642,028	970,711
Area	in²	3187,95	201,215	160,249	154,317	20,0645	65,3892	81,203	102,312	636,353	379,692	184,512	2773,47	3021,58	2595,89
Mach Number		1	0,5676	0,408536	0,450705	0,243162	0,100719	0,425928	0,337312	0,17227	0,298747	1	0,696073	0,621435	0,990009
Density	lb/ft³	0,0203	0,031426	0,051335	0,049401	0,430934	0,216104	0,054599	0,055527	0,02002	0,019438	0,012775	0,029757	0,030319	0,023342
Spec Heat @ T	BTU/(lb*R)	0,239848	0,239962	0,240897	0,240897	0,266192	0,30836	0,290912	0,290396	0,275574	0,275574	0,275574	0,239956	0,239956	0,239956
Spec Heat @ Ts	BTU/(lb*R)	0,239612	0,239869	0,240672	0,240626	0,265722	0,308306	0,289536	0,289531	0,275321	0,27482	0,267903	0,239821	0,239847	0,239706
Enthalpy @ T	BTU/lb	-22,1298	-13,5776	16,3215	16,3215	257,702	710,727	423,784	419,491	267,612	267,612	267,612	-13,9953	-13,9953	-13,9953
Enthalpy @ Ts	BTU/lb	-39,9226	-20,5575	11,637	10,6592	253,474	709,354	406,944	408,891	265,491	261,29	205,63	-24,145	-22,2327	-32,8257
Entropy Function @ T		-0,659571	-0,38973	0,417289	0,417289	3,87641	6,88168	5,24696	5,21632	4,00564	4,00564	4,00564	-0,402436	-0,402436	-0,402436
Entropy Function @ Ts		-1,29816	-0,608374	0,302511	0,278071	3,83675	6,87516	5,1296	5,14234	3,9859	3,94654	3,38468	-0,72631	-0,662949	-1,02931
Exergy	BTU/lb	12,1144	19,1682	44,7466	44,181	274,38	645,171	357,517	353,432	197,648	197,648	197,648	19,5512	18,8346	18,8346
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,025792	0,023424	0,023032	0,022955	0,022955	0,022955	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0

Engine 2 Cruise Cycle Results.

Front LP Shaft Cone Length	in	7,73063
Middle LP Shaft Length	in	37,1597
Middle LP Shaft Radius	in	1,99519
Rear LP Shaft Cone Length	in	3,26085
HP Shaft Cone Length	in	4,82022
HP Shaft Length	in	3,68099
HP Shaft Radius	in	2,64163
Engine Length	in	114,132
Max Engine Diameter	in	78,6542
Nacelle Length (Bypass only)	in	75,4826
LP Shaft Mass	lbm	48,1634
HP Shaft Mass	lbm	12,7086
Gear Box Mass	lbm	0
Net Mass	lbm	2713,15
Total Mass	lbm	3527,1
LP Spool Inertia	lb*in²	93964
HP Spool Inertia	lb*in²	10196



Engine 2 Geometry

```
              W            T           P          WRstd
Station    lb/s            R        psia           lb/s      FN          =  31491,35 lb
 amb                  518,67      14,696                     TSFC        =    0,2339 lb/(lb*h)
  2    1484,999       518,67      14,549       1500,000      WF          =   2,04591 lb/s
 13    1392,187       563,48      18,913       1127,505      s NOX       =    1,6536
 21      92,812       601,31      23,278         63,089
 22      92,812       601,31      23,046         63,727      Core Eff =       0,4983
 24      92,812       928,60      92,182         19,798      Prop Eff =       0,0000
 25      92,812       928,60      90,339         20,202      BPR         =   15,0000
  3      90,956      1587,15     551,066          4,243      P2/P1       =    0,9900
 31      82,603      1587,15     551,066                     P3/P2       =     37,88
  4      84,649      3050,00     529,024          5,702      P5/P2       =    1,2992
405      88,362      2993,33     529,024                     NGV Out. 2 Stage HPT
 41      90,682      2960,16     529,024          6,018      P16/P13     =    0,9800
 43      90,682      2378,57     184,422                     P16/P6      =   1,02144
 44      93,002      2360,19     184,422                     P16/P2      =   1,27398
 45      94,549      2344,69     180,734         16,346      P6/P5       =   0,96000
 49      94,549      1435,97      18,902                     A8          =    489,70 in²
  5      94,858      1435,85      18,902        122,707      A18         =   4286,62 in²
  8      94,858      1435,85      18,146        127,819      XM8         =   0,56781
 18    1392,187       563,48      18,535       1150,516      XM18        =   0,58557
Bleed     0,000      1587,15     551,065                     WBld/W2     =   0,00000
-----------------------------------------------------        CD8         =   0,95072
Efficiency         isentr  polytr     RNI      P/P           CD18        =   0,94325
 Outer LPC         0,9000  0,9037   0,990    1,300           PWX         =     200,0 hp
 Inner LPC         0,9000  0,9064   0,990    1,600           V18/V8,id=      0,65517
 IP Compressor     0,8800  0,9005   1,315    4,000           WBLD/W22 =      0,00000
 HP Compressor     0,8800  0,9044   3,071    6,100           Wreci/W25=      0,00000
 Burner            0,9995                    0,960           Loading     =    100,00 %
 HP Turbine        0,9200  0,9105   4,710    2,869           WCHN/W25 =      0,06500
 LP Turbine        0,9200  0,8961   2,103    9,562           WCHR/W25 =      0,02500
-----------------------------------------------------        WCLN/W25 =      0,01667
HP Spool mech Eff 0,9900  Nom Spd   22238 rpm                WCLR/W25 =      0,00333
LP Spool mech Eff 0,9900  Nom Spd    3362 rpm                WBLD/W25 =      0,00000
IPC & LPT                 Nom Spd   11766 rpm                Gear Rat =      3,50000
-----------------------------------------------------        WLkBy/W25=      0,00000
P22/P21=0,9900 P25/P24=0,9800 P45/P44=0,9800                 WlkLP/W25=      0,00000
-----------------------------------------------------
hum [%]      war0        FHV      Fuel
   0,0    0,00000    18552,4      Generic
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	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	1485	92,8125	92,8125	92,8125	90,9562	84,649	93,0021	94,549	94,8584	94,8584	94,8584	1392,19	1392,19	1392,19
Total Temperature	R	518,67	601,314	928,596	928,596	1587,15	3050	2360,19	2344,69	1435,85	1435,85	1435,85	563,477	563,477	563,477
Static Temperature	R	472,304	572,802	901,008	893,837	1570,06	3045,61	2273,62	2301,68	1376,62	1387,52	1360,31	531,405	536,727	527,382
Total Pressure	psia	14,549	23,0456	92,1824	90,3387	551,066	529,024	184,422	180,734	18,9022	18,1461	18,1461	18,9134	18,5351	18,5351
Static Pressure	psia	10,4878	19,4312	82,6459	78,7181	528,464	525,628	157,133	166,976	16,0369	15,8765	14,6959	15,3995	15,6264	14,696
Velocity	ft/s	745,876	586,43	585,758	656,431	476,3	259,548	1128,78	794,837	890,987	804,86	1006,18	621,531	567,842	659,221
Area	in²	4783,51	248,911	92,1606	85,6546	30,2693	100,819	63,6034	87,481	487,577	549,521	465,57	4123,85	4492,76	4043,37
Mach Number		0,7	0,5	0,4	0,449998	0,25	0,1	0,5	0,35	0,5	0,45	0,567812	0,55	0,5	0,585568
Density	lb/ft³	0,059934	0,091561	0,247574	0,2377	0,908473	0,465825	0,186538	0,195807	0,031443	0,030884	0,029159	0,078216	0,078581	0,075212
Spec Heat @ T	BTU/(lb*R)	0,240085	0,240861	0,246873	0,246873	0,266933	0,30753	0,29551	0,295039	0,270793	0,270793	0,270793	0,240424	0,240424	0,240424
Spec Heat @ Ts	BTU/(lb*R)	0,239937	0,240532	0,246085	0,245925	0,266429	0,307471	0,293756	0,294156	0,268734	0,269112	0,268167	0,240126	0,240143	0,240113
Enthalpy @ T	BTU/lb	-4,31603	15,5774	95,2155	95,2155	264,371	703,458	493,276	488,425	230,234	230,234	230,234	6,45738	6,45738	6,45738
Enthalpy @ Ts	BTU/lb	-15,4337	8,7049	88,3588	86,6044	259,837	702,112	467,814	475,799	214,37	217,289	210,003	-1,26243	0,013668	-2,22709
Entropy Function @ T		-0,11924	0,399306	1,93874	1,93874	3,93818	6,84269	5,69656	5,66534	3,64159	3,64159	3,64159	0,171075	0,171075	0,171075
Entropy Function @ Ts		-0,446549	0,228713	1,82954	1,80105	3,8963	6,83625	5,53642	5,58616	3,47721	3,50797	3,43071	-0,034459	3,7123E-4	-0,06102
Exergy	BTU/lb	-0,357633	17,4508	91,6395	90,9206	253,274	587,557	380,66	376,2	109,684	108,231	108,231	9,42061	8,70171	8,70171
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,024768	0,022493	0,022117	0,022044	0,022044	0,022044	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0
Inner Radius	in	12,2715	18,3721	0	4,97766	4,96042	7,48966	7,48966	7,48966	7,86414	7,86414	3,55268	19,6299	15,2694	15,4645
Outer Radius	in	40,9051	20,4148	0	7,214	5,86037	9,39078	8,73731	9,16194	14,7325	15,3871	12,9807	41,2067	40,7829	40,0453
Axial Position	in	28,7563	28,7563	57,6669	130,458	89,7222	95,9477	102,486	103,22	116,22	130,216	143,485	60,6993	112,559	116,165

Engine 4 Take Off Cycle Results

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                 W           T           P         WRstd
Station  lb/s           R        psia       lb/s          FN          =   5711,10 lb
 amb                 393,85      3,458                    TSFC        =    0,6029 lb/(lb*h)
  2    649,779      444,38      5,220   1693,267          WF          =   0,95640 lb/s
 13    611,812      478,87      6,494   1330,263          s NOX       =    1,1930
 21     37,967      508,82      7,769     71,133          P5/P2       =    2,6613 EPR
 22     37,967      508,82      7,670     72,049          Core Eff    =    0,5777
 24     40,321      929,77     41,061     19,321          Prop Eff    =    0,8495
 25     41,323      929,77     40,279     20,186          BPR         =   16,1142
  3     40,496     1586,71    244,412      4,259          P2/P1       =    0,9900
 31     36,777     1586,71    244,412                     P3/P2       =     46,82
  4     37,734     3112,39    234,563      5,791          P5/P2       =    2,6613
405     39,387     3053,77    234,563                     NGV Out. 2 Stage HPT
 41     40,420     3019,23    234,563      6,110          P16/P13     =    0,9722
 43     40,420     2436,00     82,624                     P16/P6      =   0,46210
 44     41,453     2416,31     82,624                     P16/P2      =   1,20952
 45     42,142     2399,97     80,950     16,457          P6/P5       =   0,98352
 49     42,142     1609,51     13,892                     A8          =    489,70 in²
  5     42,279     1608,84     13,892     78,772          A18         =   4286,62 in²
  8     42,279     1608,84     13,663     80,092          XM8         =   1,00000
 18    611,812      478,87      6,314   1368,358          XM18        =   0,96842
Bleed    0,000     1586,71    244,412                     WBld/W2     =   0,00000
------------------------------------------------          CD8         =   0,95744
Efficiency        isentr  polytr    RNI     P/P           CD18        =   0,97206
 Outer LPC        0,8309  0,8361  0,426   1,244           PWX         =     200,0 hp
 Inner LPC        0,8309  0,8401  0,426   1,488           V18/V8,id=      0,37658
 IP Compressor    0,7349  0,7878  0,534   5,353           WBLD/W22 =      0,00000
 HP Compressor    0,8800  0,9043  1,367   6,068           Wreci/W25=      0,00000
 Burner           0,9986                  0,960           Loading     =    192,52 %
 HP Turbine       0,9165  0,9067  2,041   2,839           WCHN/W25 =      0,06500
 LP Turbine       0,9581  0,9483  0,917   5,827           WCHR/W25 =      0,02500
------------------------------------------------          WCLN/W25 =      0,01667
HP Spool mech Eff 0,9900   Speed     22238 rpm            WCLR/W25 =      0,00333
LP Spool mech Eff 0,9900   Speed      4397 rpm            WBLD/W25 =      0,00000
IPC & LPT                  Speed     15390 rpm
------------------------------------------------          WLkBy/W25=      0,00000
P22/P21=0,9873 P25/P24=0,9810 P45/P44=0,9797              WlkLP/W25=      0,00000
------------------------------------------------
hum [%]      war0        FHV     Fuel
   0,0   0,00000    18552,4    Generic
```
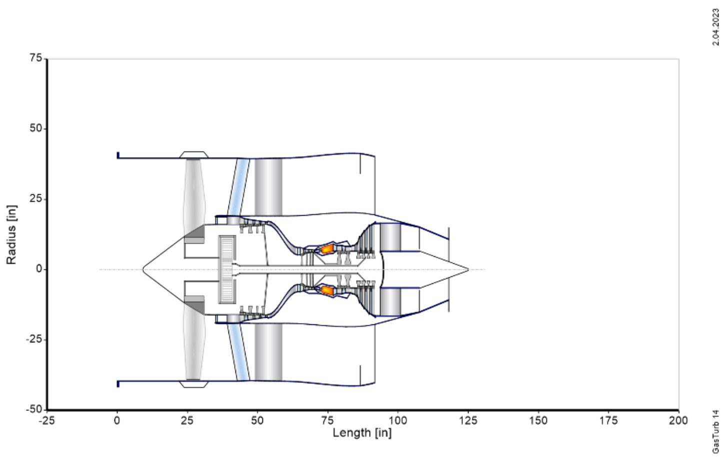

	Units	St 2	St 22	St 24	St 25	St 3	St 4	St 44	St 45	St 5	St 6	St 8	St 13	St 16	St 18
Mass Flow	lb/s	649,779	37,9672	40,3208	41,3228	40,4964	37,7337	41,4528	42,1415	42,2792	42,2792	42,2792	611,812	611,812	611,812
Total Temperature	R	444,378	508,822	929,765	929,765	1586,71	3112,39	2416,31	2399,97	1608,84	1608,84	1608,84	478,871	478,871	478,871
Static Temperature	R	370,172	474,353	903,693	895,053	1569,49	3107,81	2326,82	2355,78	1586,06	1590,61	1376,28	430,665	440,459	403,104
Total Pressure	psia	5,21998	7,67033	41,0613	40,2791	244,412	234,563	82,6243	80,9499	13,8918	13,6628	13,6628	6,49445	6,31365	6,31365
Static Pressure	psia	2,75633	6,00254	37,043	35,1076	234,309	233,011	70,1785	74,6882	13,1217	13,0543	7,34727	4,48215	4,71365	3,45807
Velocity	ft/s	943,589	643,103	569,442	656,201	478,116	266,325	1152,85	810,63	559,189	500,151	1781,31	760,533	678,893	953,469
Area	in²	4783,51	248,911	92,1606	85,6546	30,2693	100,819	63,6034	87,481	487,577	549,521	237,199	4123,85	4492,76	3990,65
Mach Number		1	0,602247	0,388303	0,449544	0,250997	0,101647	0,505223	0,353125	0,293685	0,262325	1	0,747378	0,659709	0,968404
Density	lb/ft³	0,020097	0,034154	0,110636	0,105868	0,402943	0,202368	0,081407	0,085573	0,02233	0,022152	0,014409	0,028091	0,028885	0,023154
Spec Heat @ T	BTU/(lb*R)	0,239848	0,240054	0,246906	0,246906	0,26692	0,308987	0,297106	0,296606	0,276876	0,276876	0,276876	0,239958	0,239958	0,239958
Spec Heat @ Ts	BTU/(lb*R)	0,239612	0,239944	0,246162	0,245951	0,266413	0,308932	0,295419	0,295791	0,276131	0,27628	0,269128	0,239805	0,239836	0,239717
Enthalpy @ T	BTU/lb	-22,1298	-6,67727	95,5061	95,5061	264,255	724,034	510,721	505,59	277,965	277,965	277,965	-13,8589	-13,8589	-13,8589
Enthalpy @ Ts	BTU/lb	-39,9226	-14,9423	89,026	86,901	259,686	722,616	484,161	492,458	271,716	272,966	214,554	-25,4178	-23,0694	-32,0263
Entropy Function @ T		-0,659571	-0,186239	1,9433	1,9433	3,93711	6,9453	5,80657	5,77425	4,10089	4,10089	4,10089	-0,398281	-0,398281	-0,398281
Entropy Function @ Ts		-1,29816	-0,431415	1,84031	1,80588	3,8949	6,93866	5,64331	5,69375	4,04385	4,05532	3,48054	-0,769126	-0,690531	-1,00028
Exergy	BTU/lb	11,8428	24,9048	114,879	114,36	277,953	655,356	444,617	439,805	209,771	209,322	209,322	18,9562	18,1933	18,1933
Gas Constant	BTU/(lb*R)	0,068607	0,068607	0,068607	0,068607	0,068607	0,068606	0,068606	0,068606	0,068606	0,068606	0,068606	0,068607	0,068607	0,068607
Fuel-Air-Ratio		0	0	0	0	0	0,026005	0,023617	0,023222	0,023145	0,023145	0,023145	0	0	0
Water-Air-Ratio		0	0	0	0	0	0	0	0	0	0	0	0	0	0

Engine 4 Cruise Cycle Results

Front LP Shaft Cone Length	in	0,939005
Middle LP Shaft Length	in	43,4589
Middle LP Shaft Radius	in	1,41809
Rear LP Shaft Cone Length	in	2,62535
HP Shaft Cone Length	in	4,16575
HP Shaft Length	in	4,4219
HP Shaft Radius	in	2,03461
Engine Length	in	124,872
Max Engine Diameter	in	87,6706
Nacelle Length (Bypass only)	in	91,6964
LP Shaft Mass	lbm	47,4415
HP Shaft Mass	lbm	9,71954
Gear Box Mass	lbm	0
Net Mass	lbm	2431,47
Total Mass	lbm	2431,47
LP Spool Inertia	lb*in²	73717,3
HP Spool Inertia	lb*in²	3068,12



Engine 4 Geometry