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An N+3 Technology Level Reference Propulsion System

Scott M. Jones, William J. Haller, and Michael T. Tong
Glenn Research Center, Cleveland, Ohio

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An N+3 Technology Level Reference Propulsion System

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National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Abstract

An N+3 technology level engine, suitable as a propulsion system for an advanced single-aisle transport, was developed as a reference cycle for use in technology assessment and decision-making efforts. This reference engine serves three main purposes: it provides thermodynamic quantities at each major engine station, it provides overall propulsion system performance data for vehicle designers to use in their analyses, and it can be used for comparison against other proposed N+3 technology-level propulsion systems on an equal basis. This reference cycle is meant to represent the expected capability of gas turbine engines in the N+3 timeframe given reasonable extrapolations of technology improvements and the ability to take full advantage of those improvements.

Nomenclature

AATT	Advanced Air Transport Technology Project
BPR	Bypass ratio
ERA	Environmentally Responsible Aviation Project
FPR	Fan pressure ratio
HPC	High pressure compressor
HPT	High pressure turbine
LPC	Low pressure compressor
LPT	Low pressure turbine
MCL	Maximum climb (flight Mach number 0.80, altitude 35000 ft) condition
NASA	National Aeronautics and Space Administration
OPR	Overall or operating pressure ratio
RTO	Rolling takeoff (flight Mach number 0.25, altitude 0 ft) condition
SFC	Engine thrust specific fuel consumption
SLS	Sea level static (flight Mach number 0.00, altitude 0 ft) condition
T_3	High pressure compressor exit temperature
T_4	Burner exit temperature, high pressure turbine entrance temperature
VAFN	Variable area fan nozzle

Introduction

The Advanced Air Transport Technology (AATT) Project has an overarching goal to investigate and develop technologies and concepts with the potential to revolutionize the energy efficiency and environmental compatibility of fixed wing transport aircraft. The primary focus of the AATT project is the N+3, or far term, timeframe. Figure 1 shows the potential benefits for a set of NASA-generated environmental metrics that serve as goals to guide technology development. N+3 represents an entry-into-service aircraft in the 2030 to 2040 timeframe. Because of constrained budgets, it is imperative that projects prioritize investment decisions in an attempt to maximize value for their limited technology v2013.1

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_2e per MJ for fuel and/or energy source used

Figure 1.—NASA's Subsonic Transport System Level Metrics.

development resources. To support this objective, the systems analysis team within the AATT project was tasked with performing an assessment to quantify the potential fuel burn reduction for an advanced, N+3 propulsion system applicable to a single-aisle commercial aircraft (e.g., CFM56-7 thrust class system suitable for a Boeing 737-800 aircraft). The results provided AATT project management with an initial estimate of how much progress the advanced propulsion system technologies make toward meeting the aggressive, long-term fuel burn reduction targets. In addition, the assumptions utilized in the study provide discipline experts with improvement targets to assist in the formulation of technology development plans.

The approach for the conceptual design activity began with the formulation of an N+3 technology level propulsion system. To ensure consistency, a review of the propulsion technology levels used in previous NASA system assessments was conducted. The Environmentally Responsible Aviation (ERA) effort was a NASA project that focused on development of technologies for advanced, commercial transports in the N+2 timeframe (Ref. 1). The N+3 technology assumptions leverage this previous work, in addition to NASA-sponsored small core engine research conducted under multiple NASA Research Announcements. Consequently, an N+3 technology level engine suitable as a propulsion system for an advanced single-aisle transport was developed as the reference cycle for use in this assessment. This reference engine serves three main purposes:

- Provides thermodynamic quantities at each major engine station, allowing component researchers to have relevant information about the engine environment necessary for their design
- Provides overall propulsion system performance data for vehicle designers to use in their analyses
- Can be compared to other proposed N+3 technology level propulsion systems on an equal basis

This reference cycle is meant to represent the expected capability of gas turbine engines in the N+3 timeframe given reasonable extrapolations of technology improvements and the ability to take full advantage of those improvements. It is not meant to represent an actual engine product for which cost, among other practical trade-offs, will impact the final propulsion system design.

Assumptions

The N+3 reference propulsion system is an advanced engine sized to meet the thrust required for a 737-800 class transport. Since the study's goal was to quantify the potential fuel burn reduction from advanced propulsion, a current technology in-house representation of the 737-800 airframe was used. The engine architecture was assumed to be a two-spool, separate flow gas turbine engine, but with features that make it an evolution of currently-fielded aircraft propulsion systems. Engines in the single-aisle thrust class, such as the CFM56-7B, have bypass ratios (BPR) on the order of 5; but advancements in turbomachinery and materials technology have enabled higher bypass ratios. In a move to improve propulsive efficiency, fan pressure ratio was decreased to the point that a geared system was required to match optimal speeds for the fan and low pressure turbine (LPT). Therefore, the N+3 system employs a gear box and a variable area fan nozzle (VAFN). The VAFN was required to maintain reasonable fan performance over the entire flight envelope. Other technology areas in the engine are also assumed to have been enhanced over N+2 levels. These technologies include improved turbomachinery aerodynamics, advanced turbine cooling techniques, and ceramic matrix composite (CMC) materials. Other engine technologies envisioned for future generations of propulsion systems, such as cooled cooling air, alternative fuels, or intercooled/regenerative cycles that use heat exchangers, were not considered.

The specific technology improvements for the reference engine were based primarily on research and studies from the ERA Project. The ERA assessments characterized the expected technology performance levels for a wide array of propulsion systems spanning the envisioned breadth of vehicle size classes in the N+2 timeframe. The N+3 reference engine system assumed performance levels at least as good as the ERA N+2 single-aisle system. Based on those efforts, the following component-specific performance was used:

- Fan—the N+3 fan technology is similar to the N+2 level, but the fan pressure ratio (FPR) has been reduced to 1.3 to improve specific fuel consumption. The fan polytropic efficiency is 97 percent, about the same as the N+2 level. This value may seem aggressive, but not overly so due to the low pressure ratio and the gearing, allowing the fan to spin at a much lower speed than the low pressure compressor (LPC) and low pressure turbine (LPT) to which it is mechanically coupled. Gear loss is 1 percent. Fan diameter is about 100 in.
- LPC—the gear system allows the LPC to rotate at a much higher speed and, therefore, an increase in the pressure ratio to around three was assumed for this component. The peak LPC polytropic efficiency is about 93 percent, roughly 1 percent higher than the N+2 level.
- High Pressure Compressor (HPC)—the HPC pressure ratio is approximately 14 to yield the target Overall Pressure Ratio (OPR) of 55. The HPC polytropic efficiency was a function of the core size parameter, which is a corrected mass flow surrogate for the blade height of the last stage of the HPC. The nominal efficiency of 91 percent is for a core size of 6.0 lbm/sec; the N+3 HPC has a core size of approximately 3.0 lbm/sec and an assumed polytropic efficiency roughly 2 percent below the nominal value was employed.
- High Pressure Turbine (HPT)—the HPT is a two-stage turbine with a polytropic efficiency of 91 percent, 1 percent higher than the N+2 level. The HPT is assumed to have 3160 °R (2700 °F) CMCs for its vanes and advanced thermal barrier coatings and improved cooling features for the rotors. The maximum turbine inlet temperature (T_4) is about 3360 °R and required HPT cooling is about 15 percent, with 13 percent of that for the four HPT blade rows and 2 percent for the turbine disks and cavity cooling. In current engines, a small amount of HPT power is extracted along with a portion of high pressure bleed air for external, aircraft-related needs. However, for the N+3 timeframe it was assumed there would be no engine air extracted. Therefore, the amount of horsepower required to support external (customer) requirements was increased accordingly.

- LPT—the LPT has a polytropic efficiency of 92 percent which is the same as the N+2 level. The LPT is uncooled which is an advancement over the N+2 technology level. This would typically lead to higher aerodynamic efficiency; however, the N+3 LPT assumed a higher loading to eliminate the need for increased stage count. Since a loading increase will typically reduce efficiency, the benefit from reduced cooling and the penalty from higher loading were assumed to offset each other.
- Combustor—the burner has a 4 percent stagnation pressure drop. The advanced combustor is envisioned to be a lean-burn design. Based on NASA/industry testing, this technology appears to enable significant reductions in Landing-Takeoff NO_X (LTO NO_X) levels which will meet or exceed the N+3 goal values.
- Fan Nozzle—the fan nozzle has a variable exit area. The required area at top-of-climb is roughly 25 percent less than the maximum sea-level-static (SLS) value. Nozzle area is varied to maintain the fan operating line along the peak efficiency contour on the fan map. No limit was placed on the amount of fan nozzle area variation; at low thrust levels this resulted in extremely large nozzle areas.

Overall Cycle Design

The overall engine cycle design observed specific design rules and assumptions. From previous vehicle studies, it was determined that the in-house model of the 737-800 had a thrust target requirement of 22800 lbf at rolling takeoff conditions (RTO). A net thrust of approximately 6000 lbf was also required at maximum climb conditions (MCL). It was decided to set the fan pressure ratio equal to 1.3 at the MCL condition. This decision was based on making FPR as low as possible in order to achieve the minimum uninstalled SFC, but not so low as to create engine diameters in excess of 100 in. Installation effects would also drive the optimum fan pressure ratio away from lower values. Rather than vary the LPC/HPC pressure ratio split, the LPC pressure ratio was set equal to 3.0 at MCL, and the overall pressure ratio was allowed to vary from 30 to 80, effectively determining the MCL HPC pressure ratio. The cycle maximum turbine inlet temperature, T_4, was allowed to vary between 3000 to 3800 °R. This maximum temperature occurs at the RTO condition; the turbine inlet temperature at the MCL condition was set to match the thrust lapse requirement. Engine airflow (or fan diameter) was set to provide the required RTO net thrust. At the sea-level-static (SLS) condition, the turbine inlet temperature was set to provide a net thrust of 28620 lbf based on the Boeing Equivalent Thrust target (1.2553*RTO thrust (Ref. 2)). Engine bypass ratio was determined by a lower limit on the ratio of core nozzle jet velocity to the ideally expanded fan nozzle jet velocity; this ratio was not permitted below 1.4 at the notional cruise point (90 percent of the MCL thrust). Component polytropic efficiencies at the MCL point were set as indicated above, with the exception of HPC polytropic efficiency. Due to the large variation in HPC blade height with engine OPR, the HPC polytropic efficiency was varied as a function of the core size parameter as shown in Figure 2. This efficiency penalty is considered conservative given current research in the area of small core gas turbines. Turbine cooling flow percentages were also varied as functions of the cooling air temperature, T_3, and maximum gas path temperature, T_4.

The results from the OPR/T_4 design space study are shown in Figure 3. Under the assumptions made, it is clear that little improvement can be made in SFC once OPR reaches 55; also, the impact of core size and turbine cooling prevent taking advantage of very high cycle temperatures. However, it should be noted that slight reductions in the core size penalty can alter the shape of the SFC contours and permit slight improvements for higher T_4 and OPR cycles. Therefore, a maximum cycle T_4 of 3400 °R and an OPR of 55 were chosen for the reference N+3 cycle design, even though a slightly better optimum could be found closer to 3300 °R and 60 OPR. The design space and cycle analyses were done in the Numerical Propulsion System Simulation (NPSS) code (Ref. 3); results for the MCL, cruise, RTO, and SLS points are shown in Table 1(a) to (d). The N+3 reference engine thrust and SFC performance over a relevant range of flight Mach numbers, altitudes, and throttle settings is shown in the Appendix.

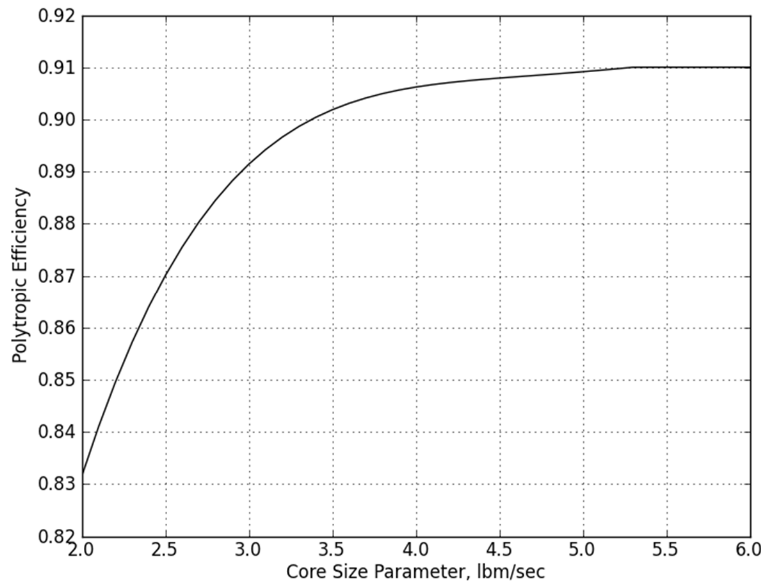

Figure 2.—Assumed High Pressure Compressor Efficiency Trend.

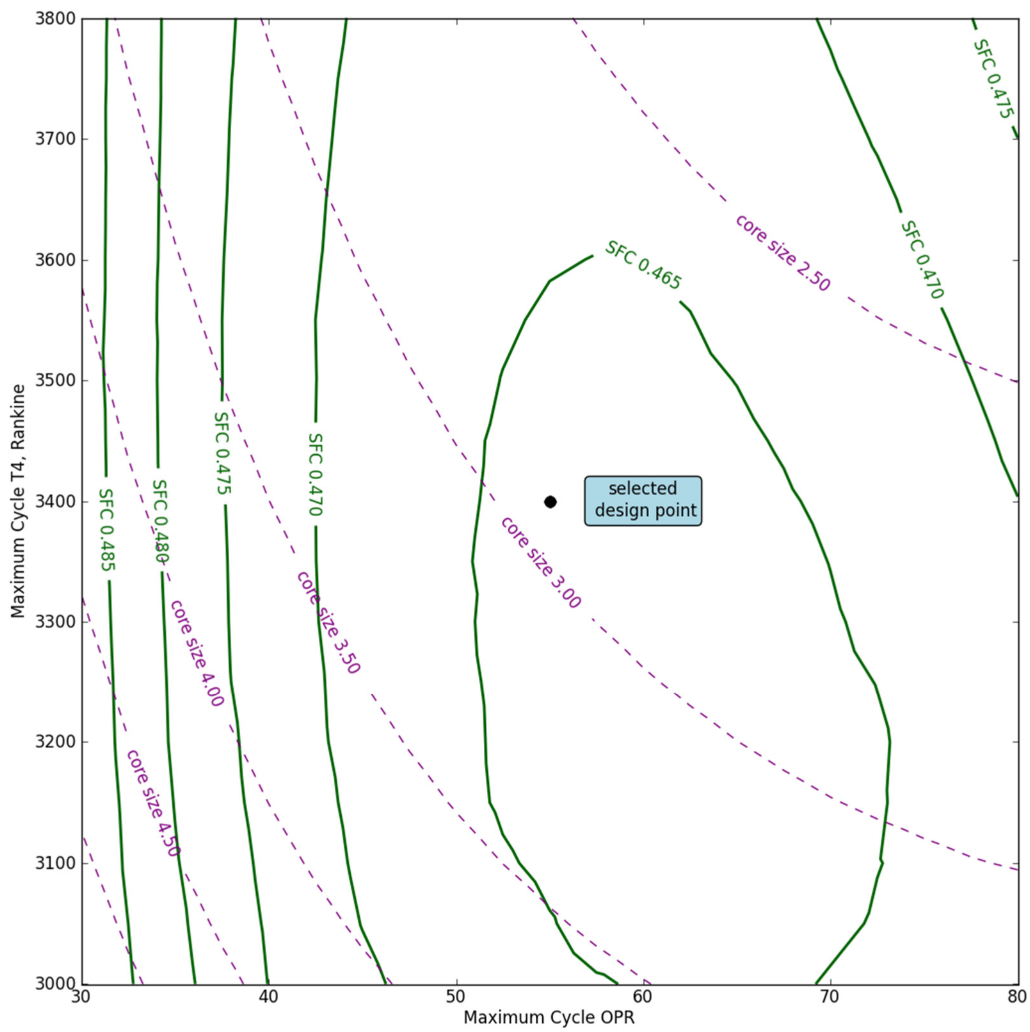

Figure 3.—N+3 Engine Cycle Design Space.

TABLE 1(a).—ENGINE PROPERTIES AT THE FLIGHT MN 0.80, 35000 ft ALTITUDE, STANDARD DAY CONDITION

Model: N+3 Gear Drive Reference Turbofan Engine, Top of Climb Conditions

MN	altitude	dTamb	Fnet	SFC	Wfuel	BPR	VTAS	OPR	T4	T41	core size	q
0.800	35000.0	0.00	6073.2	0.4636	2815.79	23.9878	461.27	55.000	3150.0	3052.6	2.91	223.26

FLOW STATION DATA

station	flow	Pt	Tt	FAR	Wc	Ps	Ts	density	area	MN	gamma
	lbm/s	psia	Rankine		lbm/s	psia	Rankine	lbm/ft^3	in^2		
inlet entrance	813.51	5.272	444.41	0.0000	2098.93	3.458	393.85	0.023697	6349.0	0.8000	1.40094
fan entrance	813.51	5.262	444.41	0.0000	2103.13	4.043	412.13	0.026479	7109.8	0.6250	1.40094
fan exit	813.51	6.840	480.17	0.0000	1681.62	5.953	461.44	0.034818	7098.0	0.4500	1.40067
fan bypass	780.95	6.840	480.17	0.0000	1614.32	5.953	461.44	0.034818	6813.9	0.4500	1.40067
fan core	32.56	6.840	480.17	0.0000	67.30	5.953	461.44	0.034818	284.1	0.4500	1.40067
LPC entrance	32.56	6.772	480.17	0.0000	67.98	5.893	461.44	0.034470	286.9	0.4500	1.40067
LPC exit	32.56	20.316	678.88	0.0000	26.94	17.684	652.63	0.073138	113.8	0.4500	1.39663
HPC entrance	32.56	20.011	678.88	0.0000	27.35	17.419	652.63	0.072041	115.6	0.4500	1.39663
HPC exit	31.91	282.210	1531.17	0.0000	2.85	265.701	1507.47	0.475735	17.2	0.3000	1.34875
burner entrance	27.61	282.210	1531.17	0.0000	2.47	265.701	1507.47	0.475735	14.9	0.3000	1.34875
burner exit	28.40	270.922	3150.00	0.0283	3.80	269.238	3145.71	0.231061	67.5	0.1000	1.27318
HPT exit	32.69	65.856	2235.57	0.0245	15.14	62.143	2205.53	0.076066	92.9	0.3000	1.30226
LPT entrance	32.69	65.527	2235.62	0.0245	15.22	57.558	2168.96	0.071642	66.3	0.4500	1.30226
LPT exit	33.34	5.911	1298.75	0.0240	131.15	5.448	1271.74	0.011565	691.6	0.3500	1.34570
core nozzle entrance	33.34	5.852	1298.82	0.0240	132.48	5.612	1284.92	0.011792	945.0	0.2500	1.34569
core nozzle exit	33.34	5.852	1298.88	0.0240	132.48	3.458	1132.91	0.008240	393.4	0.9120	1.34569
fan nozzle entrance	780.95	6.738	480.17	0.0000	1638.91	5.863	461.44	0.034296	6917.7	0.4500	1.40067
fan nozzle exit	780.95	6.738	480.17	0.0000	1638.91	3.558	399.97	0.024011	4775.2	1.0000	1.40067

TURBOMACHINERY PERFORMANCE DATA

	Wc	PR	eff	Ncorr	efPoly	power	% SM
fan	2103.13	1.300	0.9689	100.0	0.9700	-9862.1	14.99
LPC	67.98	3.000	0.8894	110.0	0.9050	-2200.2	42.50
HPC	27.35	14.103	0.8469	100.0	0.8900	-9805.2	18.00
HPT	3.80	4.114	0.9313	100.0	0.9100	10155.2	
LPT	15.22	11.085	0.9410	100.0	0.9200	12184.1	

ducts	dPt/Pt	MN
fan to LPC	0.0100	0.4500
LPC to HPC	0.0150	0.4500
HPT to LPT	0.0050	0.3000
LPT exit	0.0100	0.3500
fan bypass	0.0150	0.4500

shafts	RPM
HP shaft	20871.0
LP shaft	6772.0
fan shaft	2184.5

SECONDARY FLOWS	fraction	W	Tt	Pt
HPT chargeable	0.0693	2.2566	1531.17	282.210
HPT non-charge	0.0625	2.0354	1531.17	282.210
other	0.0200	0.6511	1115.65	58.423

burner	eff	dPt/Pt	Wfuel	FAR	EINOx
	0.9990	0.0400	0.78216	0.02833	13.113

inlet	recovery	ramDrag
	0.9980	19687.4

nozzles	PR	Cfg	Cv	Athroat	Vactual	Fg	Videal
fan nozzle	1.949	0.9975	0.9975	4775.22	978.4	24226.2	1000.5
core nozzle	1.692	0.9999	0.9999	393.42	1480.8	1534.4	1480.9

TABLE 1(b).—ENGINE PROPERTIES AT THE FLIGHT MN 0.80, 35000 ft ALTITUDE, STANDARD DAY CRUISE POWER CONDITION

Model: N+3 Gear Drive Reference Turbofan Engine, Cruise Conditions

MN	altitude	dTamb	Fnet	SFC	Wfuel	BPR	VTAS	OPR	T4	T41	core size	q
0.800	35000.0	0.00	5465.8	0.4644	2538.37	24.5519	461.27	51.462	3035.1	2941.4	2.93	223.26

FLOW STATION DATA

station	flow lbm/s	Pt psia	Tt Rankine	FAR	Wc lbm/s	Ps psia	Ts Rankine	density lbm/ft^3	area in^2	MN	gamma
inlet entrance	795.64	5.272	444.41	0.0000	2052.82	3.458	393.85	0.023697	6209.5	0.8000	1.40094
fan entrance	795.64	5.262	444.41	0.0000	2056.93	4.120	414.34	0.026836	7109.8	0.6015	1.40094
fan exit	795.64	6.717	477.58	0.0000	1670.46	5.859	459.26	0.034431	7098.0	0.4461	1.40069
fan bypass	764.50	6.717	477.58	0.0000	1605.08	5.857	459.22	0.034423	6813.9	0.4466	1.40069
fan core	31.14	6.717	477.58	0.0000	65.38	5.903	460.25	0.034616	284.1	0.4335	1.40069
LPC entrance	31.14	6.654	477.58	0.0000	65.99	5.849	460.28	0.034300	286.9	0.4331	1.40069
LPC exit	31.14	19.860	669.30	0.0000	26.17	17.458	645.21	0.073031	113.8	0.4335	1.39694
HPC entrance	31.14	19.583	669.30	0.0000	26.54	17.221	645.27	0.072033	115.6	0.4329	1.39694
HPC exit	30.52	264.541	1489.43	0.0000	2.87	248.857	1465.94	0.458199	17.2	0.3019	1.35097
burner entrance	26.41	264.541	1489.43	0.0000	2.49	248.857	1465.94	0.458199	14.9	0.3019	1.35097
burner exit	27.12	253.960	3035.05	0.0267	3.80	252.377	3030.87	0.224798	67.5	0.0998	1.27725
HPT exit	31.22	61.567	2147.46	0.0231	15.16	58.083	2118.23	0.074026	92.9	0.3000	1.30617
LPT entrance	31.22	61.259	2147.51	0.0231	15.24	53.783	2082.64	0.069717	66.3	0.4500	1.30617
LPT exit	31.84	5.589	1246.60	0.0226	129.80	5.161	1221.07	0.011410	691.6	0.3453	1.34986
core nozzle entrance	31.84	5.535	1246.67	0.0226	131.08	5.313	1233.51	0.011628	945.0	0.2468	1.34985
core nozzle exit	31.84	5.535	1246.73	0.0226	131.09	3.458	1102.30	0.008469	393.4	0.8584	1.34985
fan nozzle entrance	764.50	6.617	477.58	0.0000	1629.16	5.771	459.23	0.033916	6917.7	0.4465	1.40069
fan nozzle exit	764.50	6.617	477.58	0.0000	1629.16	3.495	397.81	0.023710	4746.8	1.0000	1.40069

TURBOMACHINERY PERFORMANCE DATA

	Wc	PR	eff	Ncorr	efPoly	power	% SM
fan	2056.93	1.276	0.9692	97.0	0.9702	-8947.9	15.79
LPC	65.99	2.984	0.9121	107.0	0.9244	-2029.8	39.72
HPC	26.54	13.508	0.8510	99.0	0.8925	-8997.4	19.55
HPT	3.80	4.125	0.9314	100.1	0.9114	9347.4	
LPT	15.24	10.960	0.9390	99.0	0.9175	11088.6	

ducts	dPt/Pt	MN
fan to LPC	0.0093	0.4335
LPC to HPC	0.0139	0.4335
HPT to LPT	0.0050	0.3000
LPT exit	0.0097	0.3453
fan bypass	0.0148	0.4466

shafts	RPM
HP shaft	20511.8
LP shaft	6569.2
fan shaft	2119.1

SECONDARY FLOWS	fraction	W	Tt	Pt
HPT chargeable	0.0693	2.1583	1489.43	264.541
HPT non-charge	0.0625	1.9467	1489.43	264.541
other	0.0200	0.6228	1089.13	55.470

burner	eff	dPt/Pt	Wfuel	FAR	EINOx
	0.9990	0.0400	0.70510	0.02670	8.536

inlet	recovery	ramDrag
	0.9980	19254.9

nozzles	PR	Cfg	Cv	Athroat	Vactual	Fg	Videal
fan nozzle	1.914	0.9975	0.9975	4746.80	975.7	23358.6	985.5
core nozzle	1.601	0.9999	0.9999	393.42	1376.2	1362.1	1376.3

TABLE 1(c).—ENGINE PROPERTIES AT THE FLIGHT MN 0.25, 0 ft ALTITUDE, HOT DAY CONDITION

Model: N+3 Gear Drive Reference Turbofan Engine, Rolling Takeoff Conditions

MN	altitude	dTamb	Fnet	SFC	Wfuel	BPR	VTAS	OPR	T4	T41	core size	q
0.250	0.0	27.00	22800.0	0.2891	6590.89	25.7674	169.59	42.892	3400.0	3299.5	2.96	92.57

FLOW STATION DATA

station	flow	Pt	Tt	FAR	Wc	Ps	Ts	density	area	MN	gamma
	lbm/s	psia	Rankine		lbm/s	psia	Rankine	lbm/ft^3	in^2		
inlet entrance	1903.72	15.349	552.49	0.0000	1881.21	14.696	545.67	0.072692	13173.8	0.2500	1.39973
fan entrance	1903.72	15.303	552.49	0.0000	1886.87	12.673	523.51	0.065338	7109.8	0.5261	1.39973
fan exit	1903.72	18.633	585.49	0.0000	1595.26	16.496	565.49	0.078738	7098.0	0.4208	1.39912
fan bypass	1832.60	18.633	585.49	0.0000	1535.67	16.483	565.36	0.078690	6813.9	0.4223	1.39912
fan core	71.12	18.633	585.49	0.0000	59.60	16.808	568.53	0.079799	284.1	0.3866	1.39912
LPC entrance	71.12	18.495	585.49	0.0000	60.04	16.695	568.63	0.079246	286.9	0.3854	1.39912
LPC exit	71.12	49.276	789.40	0.0000	26.17	43.317	761.21	0.153594	113.8	0.4340	1.39228
HPC entrance	71.12	48.588	789.40	0.0000	26.54	42.727	761.29	0.151488	115.6	0.4335	1.39228
HPC exit	69.70	642.433	1721.97	0.0000	2.91	603.389	1694.79	0.960952	17.2	0.3070	1.33952
burner entrance	60.32	642.433	1721.97	0.0000	2.51	603.389	1694.79	0.960952	14.9	0.3070	1.33952
burner exit	62.15	616.736	3400.00	0.0304	3.79	612.934	3395.48	0.487315	67.5	0.1002	1.26566
HPT exit	71.53	149.113	2430.94	0.0263	15.26	140.578	2398.29	0.158246	92.9	0.3035	1.29490
LPT entrance	71.53	148.350	2430.96	0.0263	15.34	129.992	2358.32	0.148810	66.3	0.4559	1.29490
LPT exit	72.95	17.817	1517.63	0.0257	102.93	16.988	1499.69	0.030582	691.6	0.2682	1.33189
core nozzle entrance	72.95	17.713	1517.69	0.0257	103.54	17.277	1508.31	0.030925	945.0	0.1936	1.33188
core nozzle exit	72.95	17.713	1517.75	0.0257	103.54	14.696	1448.46	0.027391	393.4	0.5350	1.33188
fan nozzle entrance	1832.60	18.387	585.49	0.0000	1556.23	16.274	565.45	0.077681	6917.7	0.4214	1.39912
fan nozzle exit	1832.60	18.387	585.49	0.0000	1556.23	14.696	549.22	0.072222	5531.9	0.5750	1.39912

TURBOMACHINERY PERFORMANCE DATA

	Wc	PR	eff	Ncorr	efPoly	power	% SM
fan	1886.87	1.218	0.9676	87.9	0.9685	-21354.3	17.09
LPC	60.04	2.664	0.9207	97.6	0.9307	-4958.0	38.48
HPC	26.54	13.222	0.8497	98.9	0.8906	-23843.4	22.19
HPT	3.79	4.136	0.9320	102.7	0.9071	24193.5	
LPT	15.34	8.326	0.9439	93.9	0.9264	26578.0	

ducts	dPt/Pt	MN
fan to LPC	0.0074	0.3866
LPC to HPC	0.0140	0.4340
HPT to LPT	0.0051	0.3035
LPT exit	0.0059	0.2682
fan bypass	0.0132	0.4223

shafts	RPM
HP shaft	22269.3
LP shaft	6634.3
fan shaft	2140.1

SECONDARY FLOWS	fraction	W	Tt	Pt
HPT chargeable	0.0693	4.9296	1721.97	642.433
HPT non-charge	0.0625	4.4464	1721.97	642.433
other	0.0200	1.4224	1268.62	135.587

burner	eff	dPt/Pt	Wfuel	FAR	EINOx
	0.9990	0.0400	1.83080	0.03035	44.812

inlet	recovery	ramDrag
	0.9970	16938.1

nozzles	PR	Cfg	Cv	Athroat	Vactual	Fg	Videal
fan nozzle	1.251	0.9975	0.9975	5531.92	658.9	37528.0	660.5
core nozzle	1.205	0.9999	0.9999	393.42	974.7	2210.1	974.8

TABLE 1(d).—ENGINE PROPERTIES AT THE FLIGHT MN 0.0, 0 ft ALTITUDE, HOT DAY CONDITION

Model: N+3 Gear Drive Reference Turbofan Engine, Sea Level Static Conditions

MN	altitude	dTamb	Fnet	SFC	Wfuel	BPR	VTAS	OPR	T4	T41	core size	q
0.000	0.0	27.00	28620.8	0.1751	5011.34	27.5091	0.00	36.634	3169.7	3076.3	2.99	0.00

FLOW STATION DATA

station	flow	Pt	Tt	FAR	Wc	Ps	Ts	density	area	MN	gamma
	lbm/s	psia	Rankine		lbm/s	psia	Rankine	lbm/ft^3	in^2		
inlet entrance	1723.77	14.696	545.67	0.0000	1768.07	14.696	545.67	0.072692		0.0000	1.39984
fan entrance	1723.77	14.622	545.67	0.0000	1776.96	12.462	521.30	0.064523	7109.8	0.4834	1.39984
fan exit	1723.77	17.173	572.32	0.0000	1549.54	15.332	554.09	0.074685	7098.0	0.4058	1.39938
fan bypass	1663.31	17.173	572.32	0.0000	1495.19	15.310	553.86	0.074609	6813.9	0.4084	1.39938
fan core	60.46	17.173	572.32	0.0000	54.35	15.804	558.91	0.076322	284.1	0.3466	1.39938
LPC entrance	60.46	17.071	572.32	0.0000	54.68	15.723	559.04	0.075912	286.9	0.3449	1.39938
LPC exit	60.46	42.667	756.67	0.0000	25.15	37.962	732.07	0.139962	113.8	0.4128	1.39372
HPC entrance	60.46	42.129	756.67	0.0000	25.48	37.508	732.22	0.138264	115.6	0.4115	1.39372
HPC exit	59.25	525.781	1628.69	0.0000	2.93	493.120	1602.14	0.830753	17.2	0.3101	1.34385
burner entrance	51.28	525.781	1628.69	0.0000	2.54	493.120	1602.14	0.830753	14.9	0.3101	1.34385
burner exit	52.68	504.749	3169.71	0.0271	3.79	501.621	3165.40	0.427813	67.5	0.0999	1.27349
HPT exit	60.65	120.997	2250.88	0.0235	15.34	113.979	2219.73	0.138623	92.9	0.3044	1.30240
LPT entrance	60.65	120.374	2250.93	0.0235	15.42	105.263	2181.48	0.130268	66.3	0.4578	1.30240
LPT exit	61.86	16.815	1442.79	0.0230	90.17	16.223	1429.76	0.030631	691.6	0.2320	1.33777
core nozzle entrance	61.86	16.741	1442.85	0.0230	90.57	16.428	1435.99	0.030885	945.0	0.1680	1.33777
core nozzle exit	61.86	16.741	1442.91	0.0230	90.57	14.696	1396.07	0.028418	393.4	0.4446	1.33776
fan nozzle entrance	1663.31	16.961	572.32	0.0000	1513.90	15.132	553.98	0.073727	6917.7	0.4071	1.39938
fan nozzle exit	1663.31	16.961	572.32	0.0000	1513.90	14.696	549.37	0.072202	6315.0	0.4572	1.39938

TURBOMACHINERY PERFORMANCE DATA

	Wc	PR	eff	Ncorr	efPoly	power	% SM
fan	1776.96	1.174	0.9617	81.0	0.9626	-15609.1	20.70
LPC	54.68	2.499	0.9232	90.4	0.9324	-3805.3	34.67
HPC	25.48	12.480	0.8519	98.0	0.8918	-18817.4	24.21
HPT	3.79	4.172	0.9321	103.1	0.9105	19167.5	
LPT	15.42	7.159	0.9432	89.5	0.9266	19610.6	

ducts	dPt/Pt	MN
fan to LPC	0.0059	0.3466
LPC to HPC	0.0126	0.4128
HPT to LPT	0.0051	0.3044
LPT exit	0.0044	0.2320
fan bypass	0.0124	0.4084

shafts	RPM
HP shaft	21583.1
LP shaft	6078.9
fan shaft	1960.9

SECONDARY FLOWS	fraction	W	Tt	Pt
HPT chargeable	0.0693	4.1909	1628.69	525.781
HPT non-charge	0.0625	3.7801	1628.69	525.781
other	0.0200	1.2093	1204.03	112.984

burner	eff	dPt/Pt	Wfuel	FAR	EINOx
	0.9990	0.0400	1.39204	0.02714	18.490

inlet	recovery	ramDrag
	0.9950	0.0

nozzles	PR	Cfg	Cv	Athroat	Vactual	Fg	Videal
fan nozzle	1.154	0.9975	0.9975	6314.95	524.0	27089.3	525.3
core nozzle	1.139	0.9999	0.9999	393.42	796.6	1531.6	796.7

Engine Flowpath and Weight Estimation

Following the cycle design, estimates of the engine weight and flowpath dimensions were developed for the N+3 reference engine. The NASA software tool WATE++ (Weight Analysis of Turbine Engines (Ref. 4)), was used to create an engine diagram and weight associated with the thermodynamic cycle detailed in the previous section. The cycle data required for WATE++ execution, such as air mass flow, temperatures, pressures, pressure ratios, etc., were obtained from the NPSS cycle output. Data from both the aerodynamic design point (top-of-climb) and a set of off-design cases was used to encompass the maximum thermodynamic conditions experienced (i.e., temperature and pressure) in order to size each engine component. The cycle data was combined with material properties and component design rules to determine an acceptable engine flowpath; the component design rules considered geometric, stress, and turbomachinery stage-loading limits. Notable component technology improvements are discussed below.

The fan diameter of the reference engine is about 100 in., significantly larger than previous engines in this thrust class. Without improvements in inlet and nacelle design and technology, much of the propulsive efficiency benefits derived from reducing the FPR will be eroded by increased nacelle drag. The N+3 engine design targeted similar levels of nacelle drag despite the increased diameter; the N+3 engine's inlet length-to-diameter ratio was about 0.4, the minimum required to avoid flow separation for this geometry (Ref. 5). Advanced, short inlets face operability challenges such as maintaining good performance in crosswinds and distorted flow: it was assumed that the N+3 inlet could be designed to maintain high performance despite these challenges.

The N+3 reference engine HPT and LPT stator vane material was assumed to be high temperature (i.e., 3rd generation) CMCs. Nickel-based alloys were used for the turbine rotor blades, with the exception of the last stage LPT which used titanium aluminide. No cooling air was required for the LPT.

An empirical correlation was used to calculate the gearbox and lubrication system weight required as part of the LP shaft. The correlation is a function of maximum delivered output power and gear ratio; it was developed based on data from over fifty rotorcraft, tilt rotor, and turboprop aircraft. This correlation is shown in Figure 4 where hp is the power delivered to the fan in horsepower and RPM is the fan speed in revolutions per minute. The N+3 reference engine gear ratio is equal to 3.1.

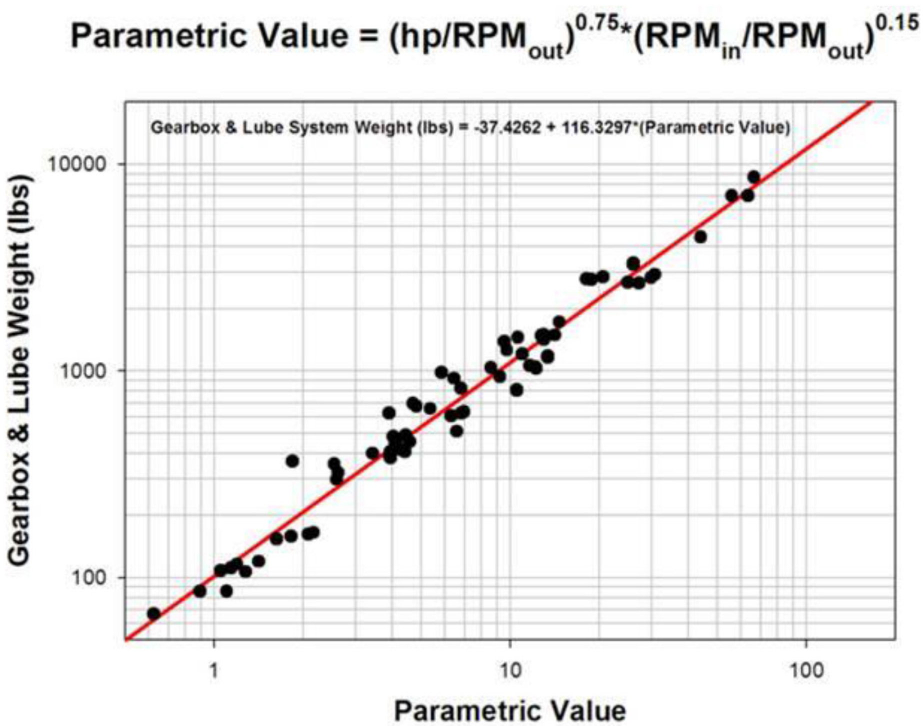

Figure 4.—Transmission and Lubrication System Correlation.

For the N+3 turbomachinery design, stage counts from the N+2 engine were maintained despite an increase in OPR. This required an increase of 10 to 25 percent in loading for the N+3 compressors and turbines. This decision was deliberate; these loading increases provided turbomachinery discipline experts with aggressive goals in formulation of their technology development plans. Should the targets be deemed too infeasible as technology matures, the engine flowpath can be modified accordingly.

In summary, a conceptual-level systems analysis study was conducted to quantify the potential fuel burn reduction of propulsion system technologies envisioned in the N+3 timeframe. An engine cycle analysis identified an "optimal" engine design that took advantage of an array of aerodynamic, materials, structures and cooling improvements. Upon completion of the cycle analysis, an engine flowpath was created and an overall propulsion system weight was produced. Table 2 lists some of the aeromechanical design features of the N+3 reference engine; a cross section of the engine from the performance and weight estimation is shown in Figure 5. Table 3 shows a comparison between the N+3 reference engine and an in-house model of a current technology system similar to the CFM56-7B turbofan. It is readily obvious that the improvement in fuel efficiency of the advanced engine comes at a significant cost in propulsion system size and weight. Although it was not done for this study, maximizing the fuel burn benefit to the aircraft therefore requires balancing the trade between engine efficiency and engine size.

TABLE 2.—PRINCIPAL MECHANICAL DESIGN PARAMETERS

Mechanical design parameter	Value
Total engine pod weight (lbm)	9350
Fan diameter (in.)	100
Nacelle maximum diameter (in.)	121
Engine length, fan face to nozzle (in.)	135
Fan/LPC/HPC/HPT/LPT stages	1-3-8-2-3
LP RPM, gear ratio	6800, 3.1
HP RPM	21000
LPC 1st stage loading, $\Delta h/U_t^2$	0.30
HPC 1st stage loading, $\Delta h/U_t^2$	0.26
HPT 1st stage loading, $\Delta h/U_t^2$	1.20
LPT 1st stage loading, $\Delta h/U_t^2$	3.05
HPC last stage blade height (in.)	0.42

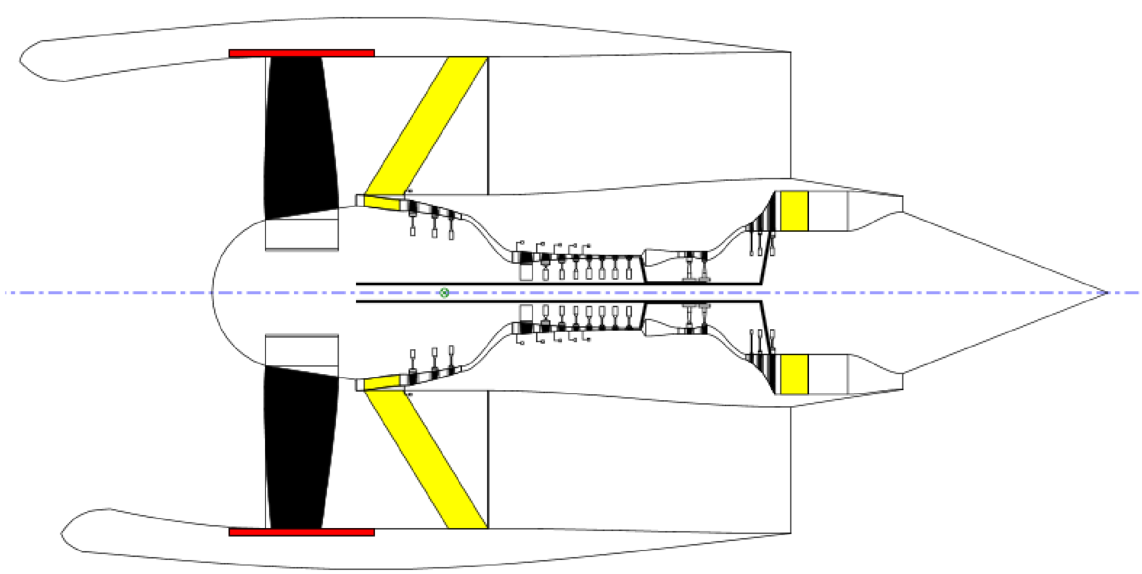

Figure 5.—Cross-Section of the Engine.

TABLE 3.—SUMMARY OF NASA MODEL OF CURRENT TECHNOLOGY ENGINE AND N+3 ENGINE

	CFM56	N+3
FPR	1.7	1.3
OPR	32	55
BPR	5.3	24
T4max, Rankine	3160	3400
Secondary flows, %	19%	15%
Fan diameter, inches	63	100
MCL net thrust, lbf	5780	6070
MCL SFC, lbm/hr/lbf	0.650	0.464
RTO net thrust, lbf	22800	22800
RTO SFC, lbm/hr/lbf	0.474	0.289
System weight, lbm	7700	9300

Fuel Burn Improvement

Because the study objective was to isolate the fuel burn benefit of the advanced propulsion system from that of an advanced vehicle, a current technology baseline airframe was employed. NASA Langley's Systems Analysis Branch has made a rigorous in-house representation of the 737-800 aircraft (Ref. 6). The results of the cycle analysis work indicated the N+3 engine has a 28 percent improvement in SFC. The weight analysis predicted the N+3 engine would show a weight increase of about 21 percent over the baseline CFM56-7B engine. Figure 6 shows the sensitivity of the in-house 737-800 aircraft fuel burn to changes in engine SFC and weight. The aforementioned N+3 characteristics combine to produce about a 30 percent reduction in fuel burn on this size vehicle, about half of the N+3 overall goal. It must be noted that penalties for increased nacelle drag and landing gear length/weight are not captured in this assessment. Although the impact was beyond the scope of this effort, previous work (Ref. 7) provides some insight into the potential magnitude of these effects. As seen in Figure 7, nacelle drag has a penalty on the order of twice that of the engine weight at the 1.3 FPR of the N+3 engine. Conversely, the required weight increase coming from extending the landing gear length has minimal effect.

The conceptual design study indicated a potential for fuel burn improvement of 25 to 30 percent utilizing N+3 propulsion system technologies on a single-aisle aircraft. Achieving these ambitious gains will require overcoming a multitude of technology development challenges, such as:

- Maintaining high efficiency and tight tolerances in axial turbomachinery with extremely small blade passage heights
- Development of robust materials with high temperature and increased loading capability
- Advances in subsonic inlet design to maintain short length while maintaining operability

The N+3 engine cycle described here should be viewed as an initial foray into the potential system performance that could be available in the future should near-term technology advancements occur as predicted. These results should be viewed as a reference system, or "stake-in-the-ground", allowing AATT projects and the disciplines it supports to best direct their efforts. It is expected that this reference propulsion system will be updated as technology matures, more information becomes available, and further investigations are conducted.

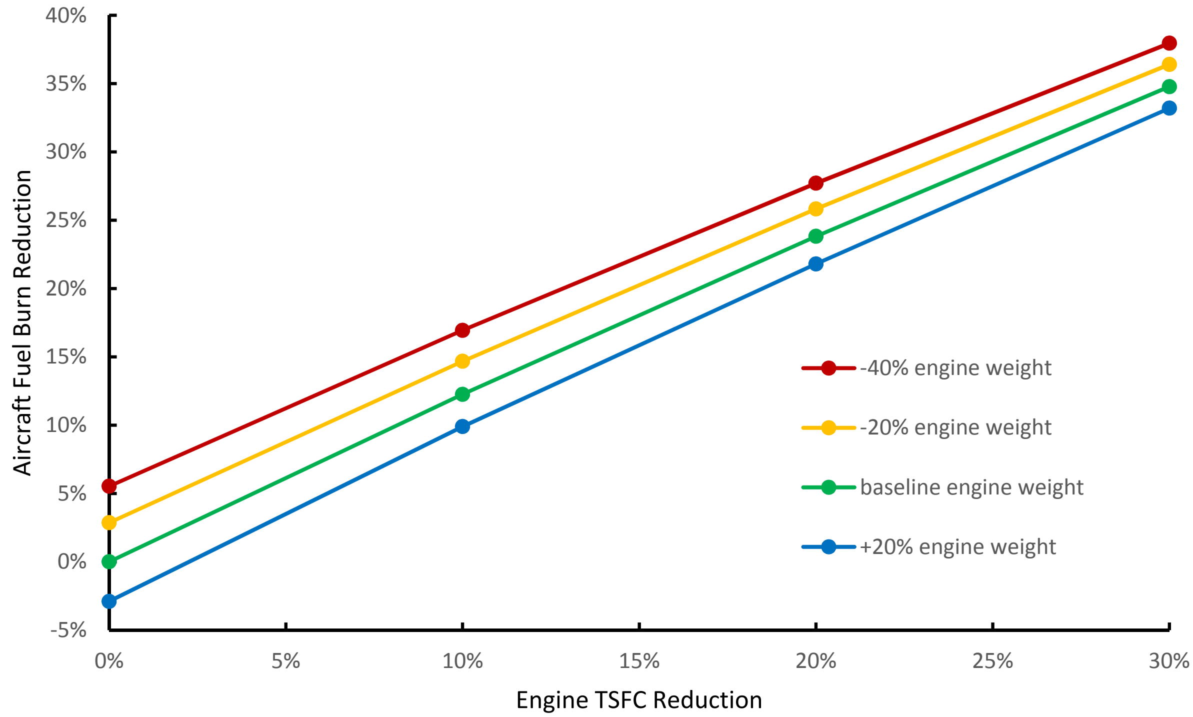

Figure 6.—Fuel Burn Sensitivities for NASA's 737-800 Airplane.

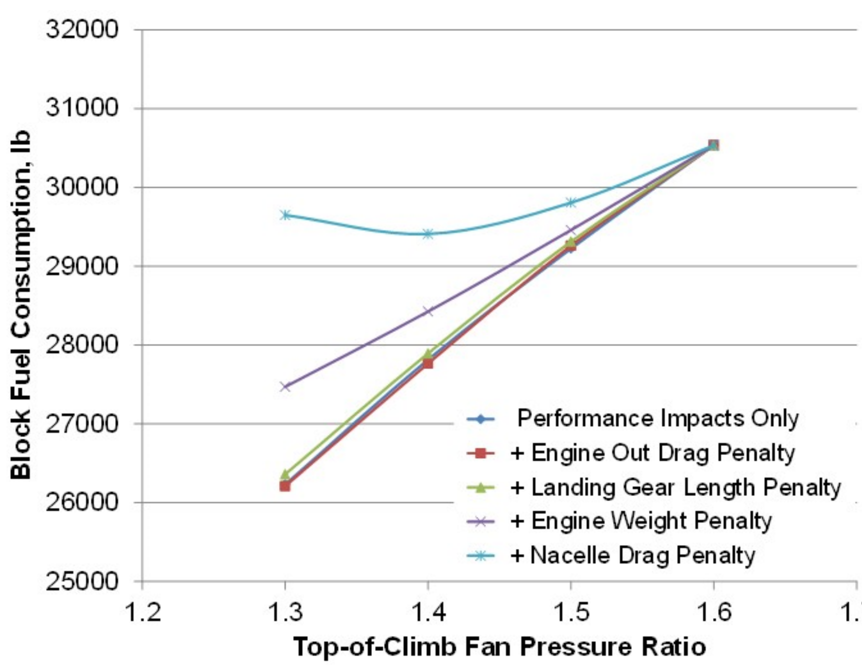

Figure 7.—Penalty Sensitivities for Representative Single-Aisle Aircraft.

Appendix—N+3 Engine Performance

Mach	altitude ft	dTamb degF	%Thrust	Net Thrust lbf	Fuel Flow lbm/hr	TSFC lbm/(hr-lbf)
0.00	0.0	27.0	100.	28620.6	5011.2	0.1751
0.00	0.0	27.0	90.	25758.5	4424.2	0.1718
0.00	0.0	27.0	80.	22896.8	3850.9	0.1682
0.00	0.0	27.0	70.	20034.3	3296.0	0.1645
0.00	0.0	27.0	60.	17172.3	2786.1	0.1622
0.00	0.0	27.0	50.	14310.3	2289.4	0.1600
0.00	0.0	27.0	40.	11448.2	1840.8	0.1608
0.00	0.0	27.0	30.	8586.2	1414.6	0.1648
0.00	0.0	27.0	20.	5724.1	1015.1	0.1773
0.10	0.0	27.0	100.	25604.0	5588.2	0.2183
0.10	0.0	27.0	90.	23043.6	4956.2	0.2151
0.10	0.0	27.0	80.	20483.2	4384.9	0.2141
0.10	0.0	27.0	70.	17922.7	3818.3	0.2130
0.10	0.0	27.0	60.	15362.3	3266.7	0.2126
0.10	0.0	27.0	50.	12801.9	2748.7	0.2147
0.10	0.0	27.0	40.	10241.5	2238.8	0.2186
0.10	0.0	27.0	30.	7681.2	1768.1	0.2302
0.10	0.0	27.0	20.	5120.8	1311.5	0.2561
0.20	0.0	27.0	100.	23549.4	6233.7	0.2647
0.20	0.0	27.0	90.	21194.5	5564.5	0.2625
0.20	0.0	27.0	80.	18840.3	4933.3	0.2619
0.20	0.0	27.0	70.	16484.6	4348.9	0.2638
0.20	0.0	27.0	60.	14129.7	3762.5	0.2663
0.20	0.0	27.0	50.	11774.6	3190.9	0.2710
0.20	0.0	27.0	40.	9419.8	2636.7	0.2799
0.20	0.0	27.0	30.	7064.8	2090.3	0.2959
0.20	0.0	27.0	20.	4709.9	1567.1	0.3327
0.25	0.0	27.0	100.	22799.7	6590.8	0.2891
0.25	0.0	27.0	90.	20519.6	5903.6	0.2877
0.25	0.0	27.0	80.	18239.8	5240.5	0.2873
0.25	0.0	27.0	70.	15959.8	4630.1	0.2901
0.25	0.0	27.0	60.	13679.9	4025.3	0.2943
0.25	0.0	27.0	50.	11399.9	3424.1	0.3004
0.25	0.0	27.0	40.	9119.9	2843.0	0.3117
0.25	0.0	27.0	30.	6839.9	2261.9	0.3307
0.25	0.0	27.0	20.	4559.9	1698.5	0.3725
0.30	0.0	27.0	100.	21211.2	6648.2	0.3134
0.30	0.0	27.0	90.	19090.1	5976.7	0.3131
0.30	0.0	27.0	80.	16969.0	5325.7	0.3138
0.30	0.0	27.0	70.	14847.8	4722.0	0.3180
0.30	0.0	27.0	60.	12726.7	4123.7	0.3240
0.30	0.0	27.0	50.	10605.5	3524.4	0.3323
0.30	0.0	27.0	40.	8484.5	2940.0	0.3465
0.30	0.0	27.0	30.	6363.4	2352.6	0.3697
0.30	0.0	27.0	20.	4242.2	1774.8	0.4184
0.00	5000.0	27.0	100.	25683.8	4514.7	0.1758
0.00	5000.0	27.0	90.	23115.5	3948.7	0.1708
0.00	5000.0	27.0	80.	20546.9	3445.9	0.1677

0.00	5000.0	27.0	70.	17978.7	2945.9	0.1639
0.00	5000.0	27.0	60.	15410.2	2482.1	0.1611
0.00	5000.0	27.0	50.	12841.9	2038.3	0.1587
0.00	5000.0	27.0	40.	10273.5	1632.0	0.1589
0.00	5000.0	27.0	30.	7705.1	1254.2	0.1628
0.00	5000.0	27.0	20.	5136.8	897.9	0.1748
0.20	5000.0	27.0	100.	21372.0	5594.5	0.2618
0.20	5000.0	27.0	90.	19234.8	4989.2	0.2594
0.20	5000.0	27.0	80.	17097.6	4401.5	0.2574
0.20	5000.0	27.0	70.	14960.2	3862.3	0.2582
0.20	5000.0	27.0	60.	12823.3	3341.3	0.2606
0.20	5000.0	27.0	50.	10685.9	2823.9	0.2643
0.20	5000.0	27.0	40.	8548.8	2330.6	0.2726
0.20	5000.0	27.0	30.	6411.5	1841.8	0.2873
0.20	5000.0	27.0	20.	4274.4	1375.8	0.3219
0.30	5000.0	27.0	100.	19329.3	5959.7	0.3083
0.30	5000.0	27.0	90.	17396.2	5348.5	0.3075
0.30	5000.0	27.0	80.	15463.5	4754.3	0.3075
0.30	5000.0	27.0	70.	13530.5	4186.1	0.3094
0.30	5000.0	27.0	60.	11597.6	3654.0	0.3151
0.30	5000.0	27.0	50.	9664.7	3119.5	0.3228
0.30	5000.0	27.0	40.	7731.7	2593.6	0.3355
0.30	5000.0	27.0	30.	5798.8	2071.1	0.3572
0.30	5000.0	27.0	20.	3865.8	1556.9	0.4027
0.25	10000.0	27.0	100.	18480.5	5218.0	0.2824
0.30	10000.0	27.0	100.	17333.4	5276.0	0.3044
0.40	10000.0	27.0	100.	15536.2	5423.3	0.3491
0.50	10000.0	27.0	100.	14109.7	5597.1	0.3967
0.30	15000.0	0.0	100.	17165.2	5082.7	0.2961
0.40	15000.0	0.0	100.	15588.3	5240.2	0.3362
0.50	15000.0	0.0	100.	14366.7	5435.5	0.3783
0.60	15000.0	0.0	100.	13481.5	5676.4	0.4210
0.50	20000.0	0.0	100.	12179.0	4521.5	0.3713
0.60	20000.0	0.0	100.	11785.9	4871.6	0.4133
0.70	20000.0	0.0	100.	11394.2	5182.6	0.4549
0.60	25000.0	0.0	100.	9510.8	3844.4	0.4042
0.70	25000.0	0.0	100.	9436.7	4200.3	0.4451
0.75	25000.0	0.0	100.	9487.5	4415.6	0.4654
0.80	25000.0	0.0	100.	9598.1	4659.8	0.4855
0.70	30000.0	0.0	100.	7545.6	3283.3	0.4351
0.70	30000.0	0.0	90.	6791.1	2952.7	0.4348
0.70	30000.0	0.0	80.	6036.5	2639.1	0.4372
0.70	30000.0	0.0	70.	5282.0	2337.2	0.4425
0.70	30000.0	0.0	60.	4527.6	2051.2	0.4531
0.70	30000.0	0.0	50.	3772.8	1765.1	0.4678
0.70	30000.0	0.0	40.	3018.2	1487.1	0.4927
0.70	30000.0	0.0	30.	2263.7	1207.5	0.5334
0.70	30000.0	0.0	20.	1509.2	929.0	0.6155
0.70	30000.0	0.0	5.	377.3	459.7	1.2184

0.80	30000.0	0.0	100.	7672.9	3639.5	0.4743
0.80	30000.0	0.0	90.	6905.6	3275.4	0.4743
0.80	30000.0	0.0	80.	6138.3	2930.7	0.4774
0.80	30000.0	0.0	70.	5371.0	2596.7	0.4835
0.80	30000.0	0.0	60.	4603.8	2281.5	0.4956
0.80	30000.0	0.0	50.	3836.5	1965.0	0.5122
0.80	30000.0	0.0	40.	3069.0	1655.3	0.5394
0.80	30000.0	0.0	30.	2301.9	1344.1	0.5839
0.80	30000.0	0.0	20.	1534.6	1033.4	0.6734
0.80	30000.0	0.0	5.	383.6	506.6	1.3205
0.85	30000.0	0.0	100.	7807.1	3855.0	0.4938
0.85	30000.0	0.0	90.	7026.3	3468.1	0.4936
0.85	30000.0	0.0	80.	6245.6	3103.3	0.4969
0.85	30000.0	0.0	70.	5464.9	2750.8	0.5033
0.85	30000.0	0.0	60.	4684.2	2416.6	0.5159
0.85	30000.0	0.0	50.	3903.5	2082.3	0.5335
0.85	30000.0	0.0	40.	3122.8	1753.7	0.5616
0.85	30000.0	0.0	30.	2342.1	1424.0	0.6080
0.85	30000.0	0.0	20.	1561.4	1093.7	0.7004
0.85	30000.0	0.0	5.	390.4	534.7	1.3697
0.70	35000.0	0.0	100.	5974.0	2543.0	0.4257
0.70	35000.0	0.0	90.	5376.5	2290.6	0.4260
0.70	35000.0	0.0	80.	4779.2	2051.4	0.4292
0.70	35000.0	0.0	70.	4181.9	1819.6	0.4351
0.70	35000.0	0.0	60.	3584.7	1600.1	0.4464
0.70	35000.0	0.0	50.	2987.0	1380.8	0.4623
0.70	35000.0	0.0	40.	2389.5	1167.0	0.4884
0.70	35000.0	0.0	30.	1792.2	953.2	0.5319
0.70	35000.0	0.0	20.	1194.8	741.1	0.6203
0.70	35000.0	0.0	5.	298.7	382.3	1.2799
0.80	35000.0	0.0	100.	6073.2	2815.8	0.4636
0.80	35000.0	0.0	90.	5465.9	2538.4	0.4644
0.80	35000.0	0.0	80.	4858.7	2275.2	0.4683
0.80	35000.0	0.0	70.	4251.3	2019.3	0.4750
0.80	35000.0	0.0	60.	3644.0	1776.6	0.4876
0.80	35000.0	0.0	50.	3036.6	1533.6	0.5051
0.80	35000.0	0.0	40.	2429.2	1296.3	0.5336
0.80	35000.0	0.0	30.	1822.0	1058.1	0.5807
0.80	35000.0	0.0	20.	1214.7	820.5	0.6755
0.80	35000.0	0.0	5.	303.7	417.0	1.3731
0.85	35000.0	0.0	100.	6178.8	2981.2	0.4825
0.85	35000.0	0.0	90.	5561.2	2686.5	0.4831
0.85	35000.0	0.0	80.	4943.0	2408.0	0.4872
0.85	35000.0	0.0	70.	4325.2	2137.2	0.4941
0.85	35000.0	0.0	60.	3707.4	1880.8	0.5073
0.85	35000.0	0.0	50.	3089.4	1624.1	0.5257
0.85	35000.0	0.0	40.	2471.4	1371.8	0.5551
0.85	35000.0	0.0	30.	1853.6	1119.1	0.6037
0.85	35000.0	0.0	20.	1235.8	866.6	0.7012
0.85	35000.0	0.0	5.	308.9	437.5	1.4162

0.70	40000.0	0.0	100.	4700.2	2002.4	0.4260
0.70	40000.0	0.0	90.	4230.2	1807.1	0.4272
0.70	40000.0	0.0	80.	3760.1	1621.8	0.4313
0.70	40000.0	0.0	70.	3290.1	1441.7	0.4382
0.70	40000.0	0.0	60.	2820.1	1270.1	0.4504
0.70	40000.0	0.0	50.	2350.1	1099.9	0.4680
0.70	40000.0	0.0	40.	1880.1	933.5	0.4965
0.70	40000.0	0.0	30.	1410.1	769.2	0.5455
0.70	40000.0	0.0	20.	940.1	605.5	0.6442
0.70	40000.0	0.0	5.	235.0	328.0	1.3955
0.80	40000.0	0.0	100.	4777.7	2215.6	0.4637
0.80	40000.0	0.0	90.	4299.9	2000.5	0.4652
0.80	40000.0	0.0	80.	3822.1	1796.1	0.4699
0.80	40000.0	0.0	70.	3344.3	1597.1	0.4775
0.80	40000.0	0.0	60.	2866.7	1407.8	0.4911
0.80	40000.0	0.0	50.	2388.8	1218.7	0.5102
0.80	40000.0	0.0	40.	1911.1	1034.1	0.5411
0.80	40000.0	0.0	30.	1433.3	849.7	0.5928
0.80	40000.0	0.0	20.	955.5	666.5	0.6975
0.80	40000.0	0.0	5.	238.9	352.9	1.4772
0.85	40000.0	0.0	100.	4860.8	2344.4	0.4823
0.85	40000.0	0.0	90.	4374.8	2116.1	0.4837
0.85	40000.0	0.0	80.	3888.6	1899.8	0.4886
0.85	40000.0	0.0	70.	3402.6	1689.4	0.4965
0.85	40000.0	0.0	60.	2916.5	1489.1	0.5106
0.85	40000.0	0.0	50.	2430.4	1288.9	0.5303
0.85	40000.0	0.0	40.	1944.4	1093.1	0.5622
0.85	40000.0	0.0	30.	1458.2	897.4	0.6154
0.85	40000.0	0.0	20.	972.2	701.9	0.7220
0.85	40000.0	0.0	5.	243.0	368.1	1.5146
0.70	45000.0	0.0	100.	3698.1	1589.9	0.4299
0.70	45000.0	0.0	90.	3328.2	1438.5	0.4322
0.70	45000.0	0.0	80.	2958.5	1293.9	0.4374
0.70	45000.0	0.0	70.	2588.6	1153.7	0.4457
0.70	45000.0	0.0	60.	2218.9	1018.7	0.4591
0.70	45000.0	0.0	50.	1849.0	886.1	0.4792
0.70	45000.0	0.0	40.	1479.3	757.0	0.5117
0.70	45000.0	0.0	30.	1109.4	631.1	0.5688
0.70	45000.0	0.0	20.	739.6	502.6	0.6796
0.70	45000.0	0.0	5.	184.9	293.8	1.5890
0.80	45000.0	0.0	100.	3759.4	1757.5	0.4675
0.80	45000.0	0.0	90.	3383.5	1590.6	0.4701
0.80	45000.0	0.0	80.	3007.5	1431.0	0.4758
0.80	45000.0	0.0	70.	2631.6	1275.6	0.4847
0.80	45000.0	0.0	60.	2255.7	1126.6	0.4995
0.80	45000.0	0.0	50.	1879.7	978.9	0.5208
0.80	45000.0	0.0	40.	1503.8	835.2	0.5554
0.80	45000.0	0.0	30.	1127.8	692.7	0.6142
0.80	45000.0	0.0	20.	751.9	550.0	0.7315
0.80	45000.0	0.0	5.	188.0	308.6	1.6415

0.85	45000.0	0.0	100.	3824.4	1858.6	0.4860
0.85	45000.0	0.0	90.	3441.9	1681.2	0.4884
0.85	45000.0	0.0	80.	3059.5	1512.0	0.4942
0.85	45000.0	0.0	70.	2677.1	1347.8	0.5035
0.85	45000.0	0.0	60.	2294.6	1190.0	0.5186
0.85	45000.0	0.0	50.	1912.2	1033.3	0.5404
0.85	45000.0	0.0	40.	1529.8	880.9	0.5759
0.85	45000.0	0.0	30.	1147.3	729.3	0.6357
0.85	45000.0	0.0	20.	764.9	577.5	0.7550
0.85	45000.0	0.0	5.	191.2	318.3	1.6644

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