NASA/TM—2010-216907

Effects of Gas Turbine Component Performance on Engine and Rotary Wing Vehicle Size and Performance

Christopher A. Snyder
Glenn Research Center, Cleveland, Ohio

Douglas R. Thurman
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

November 2010

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NASA Aeronautics and Space Database and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or cosponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include creating custom thesauri, building customized databases, organizing and publishing research results.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question via the Internet to *help@sti.nasa.gov*

- Fax your question to the NASA STI Help Desk at 443–757–5803

- Telephone the NASA STI Help Desk at 443–757–5802

- Write to:
  NASA Center for AeroSpace Information (CASI)
  7115 Standard Drive
  Hanover, MD 21076–1320

NASA/TM—2010-216907

Effects of Gas Turbine Component Performance on Engine and Rotary Wing Vehicle Size and Performance

Christopher A. Snyder
Glenn Research Center, Cleveland, Ohio

Douglas R. Thurman
U.S. Army Research Laboratory, Glenn Research Center, Cleveland, Ohio

Prepared for the
66th Annual Forum and Technology Display (AHS Forum 66)
sponsored by the American Helicopter Society
Phoenix, Arizona, May 11–13, 2010

National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

November 2010

Acknowledgments

We would like to thank the management of the Subsonic Rotary Wing vehicle project within the NASA Fundamental Aeronautics Program for supporting this research, and Mr. Michael Tong for his assistance using the Weight Analysis of Turbine Engines (WATE) code for engine weight analyses.

Available from

NASA Center for Aerospace Information
7115 Standard Drive
Hanover, MD 21076–1320

National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312

Available electronically at http://gltrs.grc.nasa.gov

Effects of Gas Turbine Component Performance on Engine and Rotary Wing Vehicle Size and Performance

Christopher A. Snyder
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Douglas R. Thurman
U.S. Army Research Laboratory
Glenn Research Center
Cleveland, Ohio

Abstract

In support of the Fundamental Aeronautics Program, Subsonic Rotary Wing Project, further gas turbine engine studies have been performed to quantify the effects of advanced gas turbine technologies on engine weight and fuel efficiency and the subsequent effects on a civilian rotary wing vehicle size and mission fuel. The Large Civil Tiltrotor (LCTR) vehicle and mission and a previous gas turbine engine study will be discussed as a starting point for this effort. Methodology used to assess effects of different compressor and turbine component performance on engine size, weight and fuel efficiency will be presented. A process to relate engine performance to overall LCTR vehicle size and fuel use will also be given. Technology assumptions and levels of performance used in this analysis for the compressor and turbine components performances will be discussed. Optimum cycles (in terms of power specific fuel consumption) will be determined with subsequent engine weight analysis. The combination of engine weight and specific fuel consumption will be used to estimate their effect on the overall LCTR vehicle size and mission fuel usage. All results will be summarized to help suggest which component performance areas have the most effect on the overall mission.

Nomenclature

ft	feet
GW	gross weight
HP	horsepower
HPC	high-pressure compressor
HPT	high-pressure turbine
lb_m	pounds mass
LCTR	Large Civil Tiltrotor
LCTR2	Large Civil Tiltrotor—iteration 2
LPC	low-pressure compressor
LPT	low-pressure turbine
MRP	maximum rated power
NPSS	Numerical Propulsion System Simulation
OPR	overall pressure ratio
PR	pressure ratio
PSFC	power specific fuel consumption, lb_m/hour/HP
sec	second
SOA	State Of the Art
T3	compression system exit temperature, °F
T4	combustor exit temperature, °F
°F	degrees Fahrenheit

Figure 1.—Conceptual view of LCTR2.

Introduction

The NASA Heavy Lift Rotorcraft System Investigation (Ref. 1) identified a large tiltrotor as the best concept to meet the various airspace and other requirements for the future, short-haul regional market. This evolved into a conceptual vehicle designated as LCTR2 (Large Civil Tiltrotor—iteration 2) (Ref. 2) as seen in Figure 1.

This vehicle iteration was designed to carry 90 passengers, at minimum cruising speed of 300 knots, 1,000 nautical mile range. It is powered by four turboshaft engines designed for 7,500 HP each (MRP, sea level static conditions, standard day). Other design features included a rotor tip speed of 650 ft/sec in hover and 350 ft/sec during cruise, enabled by a two-speed gearbox. This range of rotor tip speeds was needed to achieve the high level of performance and efficiency at two very different flight conditions.

Another contributor to efficient LCTR2 vehicle operations was an efficient and high power-to-weight gas turbine power plant. The previous study (Ref. 3) identified notional gas turbine characteristics and an engine layout that could meet fuel and weight requirements, while also identifying potential levels of component performance to meet overall vehicle objectives. However the inclusion of advanced technologies and better understanding component performance and designs for this particular engine size class might suggest different configurations that could better meet or exceed overall vehicle and mission requirements. This effort will therefore review the previous notional engine design, its component performance assumptions and revised baseline values for this effort. Then the analysis tools and methodology will be discussed, including some discussion on updated component performance assumptions and the inclusion of advanced compressor and turbine technologies. This will result in new engine configurations in terms of their specific size, weight and fuel consumption, which will then be used to estimate their effect on the overall vehicle for the baseline mission.

Gas Turbine Engine Study, Previous and Updated Assumptions

Previous engine efforts included several assumptions that helped define an optimum cycle (from a thermodynamic and power specific fuel consumption perspective). An example block representation of the turboshaft engine model is shown in Figure 2. Table 1 includes the sets of assumptions used in the previous parametric analyses and the updated baseline values. The previous assumptions came from a variety of sources (preliminary estimates from component technical experts and previous engine studies—although not necessarily from the same engine class). Each particular component performance assumption will be discussed further in the next section. The engine as defined met all performance requirements, although several areas needing refinement were also noted. Overall parameters from the previous optimum engine and an operational engine (Rolls Royce AE1107, the modern turboshaft engine powering the Bell Boeing V-22 rotorcraft) are listed in Table 2 and which suggest conditions (higher temperatures and pressures, reduced corrected flow rates and total engine weight) that will require significantly improved performance and possibly advanced technologies (aerodynamic and material/structural performance). Since this was a preliminary study, engine parameters were approximate values, to help define initial requirements for temperatures, pressures and applicable technologies at the relevant flow size. These would then be used to refine assumptions for the various component performances and the conceptual design (which was beyond the scope of the original work). Also during the previous effort, as the engine concept evolved from a single to two-spool gas generator core, the split of compression work performed by each spool of the compression system was assumed to be equal. The equal work split assumption will be revisited as part of this effort.

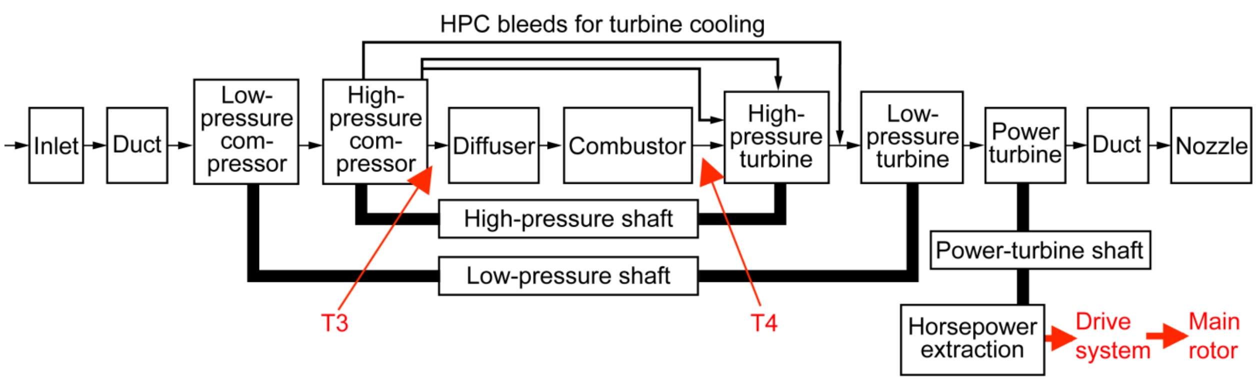

Figure 2.—Block representation of a two-spool core turboshaft gas turbine model (from Ref. 3).

TABLE 1.—GAS TURBINE ENGINE STUDY ASSUMPTIONS

Engine parameter	Prior-study assumptions (Ref. 3)	Updated baseline (For this study)
Compressor efficiency	85% polytropic efficiency	87% polytropic efficiency
Compression work split (Horsepower-HPC/Horsepower-LPC)	1.0 (equal splits)	0.67 (optimized splits)
Overall pressure ratio	10 to 60	10 to 60
Combustor temperature (design/maximum), °F	2000 to 3200	2400 to 3200
Turbine efficiency	85% adiabatic efficiency	87% adiabatic efficiency
Turbine cooling: metal temperature, °F	+200 from internal, advanced, ultra high bypass engine	Equal to internal, SOA high bypass engine
Turbine cooling: Relative cooling flow factor (as defined in Ref. 9)	Maintained from internal SOA turboshaft engine	Maintained from internal SOA turboshaft engine

TABLE 2.—GAS TURBINE ENGINE PARAMETERS

Parameter	AE1107 (Used in original LCTR study)	Notional engine (Concluded from LCTR2 study)
Horsepower	6,000	7,500[a]
Weight, lb_m	971	1,000[a]
Airflow, lb_m/sec	35.3	30
Power specific fuel consumption, lb_m/hour/HP	0.426	0.37[a]
Overall pressure ratio (OPR)	16.7	30
Compressor exit temperature, T3, °F	810	1099
Combustor exit temperature, T4, °F	2200	3000
Corrected flow: lb_m/sec		
Compressor entrance	35.5	30
Compressor exit	3.2	1.4

[a]Parameters are from Reference 3.

Analysis Methodology

The initial process was to develop improved performance estimates for the major engine components. These included compression efficiency, turbine efficiency and turbine cooling assumptions, which will be discussed later. With that information, a parametric assessment was performed varying engine overall pressure ratio (OPR) from 10 to 60, and combustor exit temperatures (T4) from 2400 to 3200 °F, to determine the optimum combination as defined as minimizing power specific fuel consumption (PSFC – lb_m/hour/HP). Each engine was sized (determination of airflow) to produce 7,500 HP (the engine size from the LCTR2 study). The object-oriented analysis framework, the Numerical Propulsion System Simulation (Ref. 4) (NPSS), was used to perform the gas turbine analyses. NPSS contains standard 0/1-D elements for the gas turbine components. These are configured into a representative steady-state, thermodynamic model. An example block diagram representative of a two-spool core (three-spool overall), turboshaft engine used within this effort is shown in Figure 3. As can be seen, compression is not only split between 2 spools (shafts), but the high pressure compressor (HPC) also is assumed to be an axial-centrifugal design. How the mix of compression between the axial and centrifugal components was determined will be discussed in the next section. Finally, utilizing the extensibility of NPSS, further elements were defined to drive specific parameters to desired values and insure continuity of mass, momentum and energy.

The gas turbine flow path layouts and weights were generated using the Weight Analysis of Turbine Engines (Ref. 5) (WATE) program. Using the output from NPSS (mass flows, temperatures, pressures, velocities, etc.) and further user input, WATE sizes the various mechanical and flow components for the gas turbine engine, determining materials, dimensions and weights for the different components represented according to conceptual level design rules and stress analyses. As part of the process, WATE also produces a graphical representation that can be used to check for reasonable component dimensions and ensure that there are no discontinuities or sharp turns in the gas flow path. The results of these analyses can form the basis for more detailed follow-on studies (which was done as reported in Refs. 6 and 7).

The previous NASA Heavy Lift Rotorcraft Systems Investigation (Ref. 1) also performed sensitivity studies which included estimates for the effect of changing engine weight and PSFC on the LCTR configuration gross weight and mission fuel. Those technology sensitivity results were used to provide a first-order estimate for the effects of different engine component technologies on vehicle and fuel weights and will be discussed later.

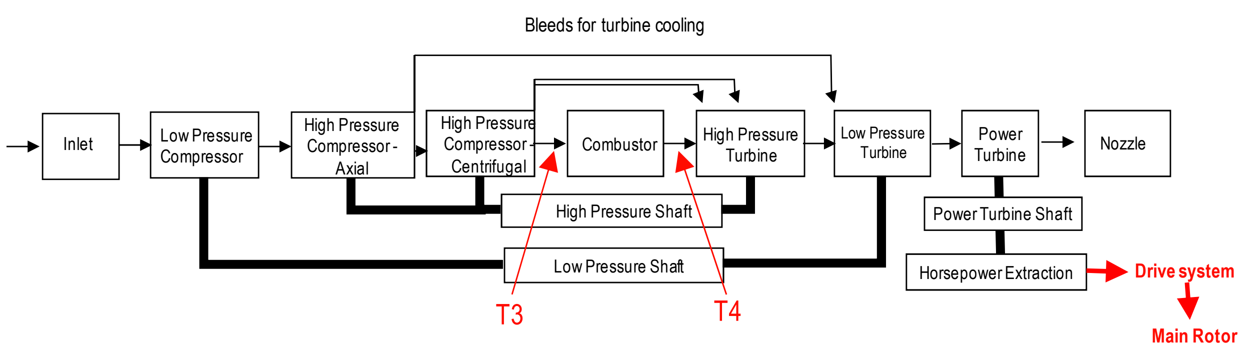

Figure 3.—Block representation of NPSS turboshaft gas turbine model.

Results and Discussion

In this section, assumptions for determining the baseline engine configuration while varying the compression system work split and centrifugal stage pressure ratio will be discussed, as will be the assumed baseline and advanced technology levels for the compression efficiency, turbine efficiency and turbine cooling. Then engine optimization results for each advanced technology applied separately and with all three technologies combined will be discussed. To conclude this section, the engine weights and PSFC results will be used to estimate effects on overall vehicle and mission sizing.

Compression System Work Split

In a single-spool engine, all compression is done with a single compressor that could consist of all axial stages or a mix of axial and a centrifugal stage. For such a device, the best mix of stage types comes from engine requirements (as determined by vehicle sizing and mission analysis) and compressor design effort (as is discussed in Ref. 6). For a two-spool gas generator core, the compression work is split between the high and low pressure spools; the choice of work split has some effect on the design and performance for the compression system and the overall engine. In the previous engine study, an equal work split was chosen between the two spools, assuming that the two stage turbine from the single-spool design would become one turbine stage for each spool. This assumption produced a viable, conceptual-level solution. In this study, the work split was varied for the initial baseline engine to values of Horsepower-HPC spool/Horsepower-LPC spool of 1.5, 1.0, and 0.667. With the assumed HPC configuration of an a priori unknown number of axial stages and a final centrifugal stage, a further possible variable is the pressure ratio of the centrifugal stage. For an aft-centrifugal stage, entrance conditions are already very high in pressure and temperature, limiting the pressure ratio and efficiency potentially obtainable. Pressure ratios of 2.0 and 2.6 were chosen for this initial configuration analysis. An optimum cycle was determined for each assumed horsepower split; and its size and weight were estimated. An example result of the effect of T4 and OPR on PSFC is shown in Figure 4, assuming a compression work split of 0.667 and a centrifugal stage pressure ratio of 2.6. For that combination of compression work split and centrifugal pressure ratio, to obtain a valid HPC axial stage pressure ratio (PR > 1), engine OPR had to be greater than 25. After reviewing the optimum PSFC results, if the minimum appears to have occurred between 2 values of OPR used, the case was rerun at an OPR halfway and optimum OPR was chosen from among those 3 OPR values. For example, it often appeared that the optimum occurred between an OPR of 40 and 45. The case was rerun with an OPR of 42.5, and the optimum was chosen from the cases with an OPR of 40, 42.5, and 45 which resulted in the minimum PSFC value.

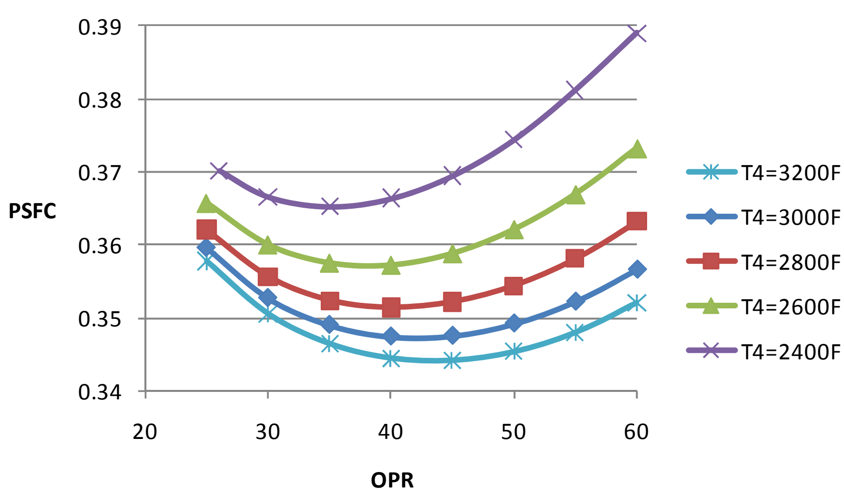

Figure 4.—PSFC versus OPR and T4 at HPC centrifugal PR = 2.6, compression work split of 0.667.

The results for this analysis are shown in Table 3, with minimum values for PSFC and engine weight noted. Optimum cycles all converged to the maximum allowable T4 resulting in the same OPR, due to thermal efficiency benefits for the reference component efficiencies and cooling technology. To achieve the given horsepower of 7,500, engine airflow varied less than 4 percent (maximum to minimum), engine weight varied by just over 7 percent, and PSFC varied only by about 1 percent. For a given compression work split, minimum weight was always realized at a compression work split of 0.667. A centrifugal pressure ratio of 2.6 achieved minimum PSFC. Since the LCTR2 has a cruise-dominated mission, PSFC was considered to be the more critical figure of merit. This resulted in the chosen compression work split of 0.667 and a centrifugal pressure ratio of 2.6 for the rest of this study. This configuration had the best PSFC and the second best engine weight. Fixing these parameters also reduced the number of engines analyzed to a manageable effort. The WATE representation for this baseline cycle is shown in Figure 5. As engine parameters changed, flow path geometries did slightly change (as well as the number of axial stages in the HPC), but this figure is representative of the various engines with differing technology assumptions. The WATE program determined 7 axial stages for the LPC, with the HPC consisting of 1 axial and 1 centrifugal stage. The number of axial stages was determined by maintaining an axial stage work factor that was consistent with the assumed level of efficiency for that component. The HPT and LPT each resulted in 1 stage, according to assumed study design rules, with a power turbine of 4 stages.

TABLE 3.—ENGINE RESULTS FROM COMPRESSION WORK SPLIT AND CENTRIFUGAL PR

Work split	Centrifugal pressure ratio	Airflow, lb_m/sec	OPR	T4, °F	PSFC, lb_m/hr/HP	Engine weight, lb_m
1.0	2.0	28.6	42.5	3200	0.3470	971
1.5	2.0	28.3	42.5	3200	0.3480	978
0.667	2.0	29.0	42.5	3200	0.3465	**913**
1.0	2.6	28.4	42.5	3200	0.3449	971
1.5	2.6	28.1	42.5	3200	0.3464	943
0.667	2.6	28.7	42.5	3200	**0.3442**	930

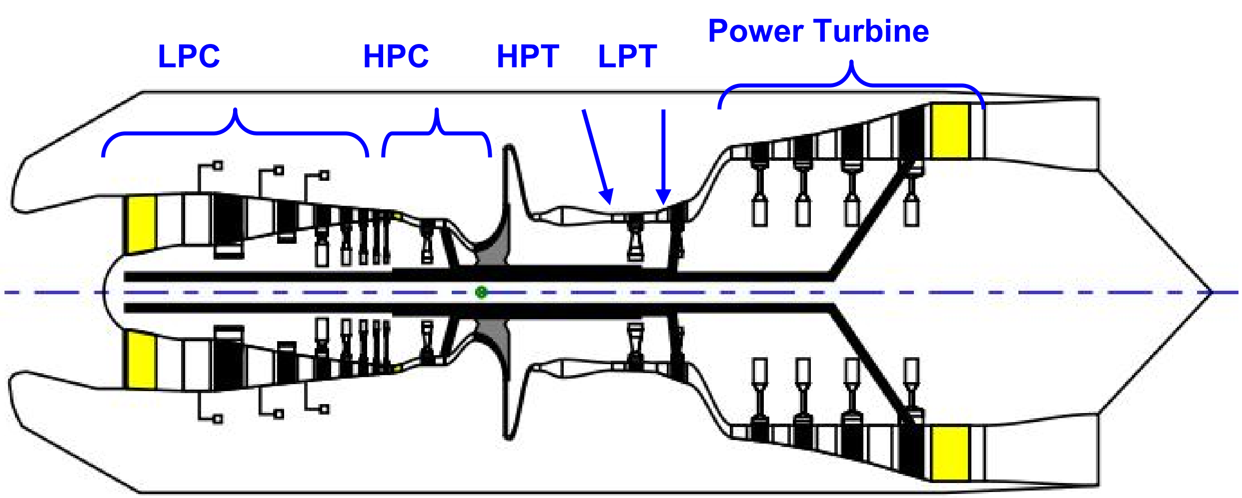

Figure 5.—WATE flow path representation for the baseline engine.

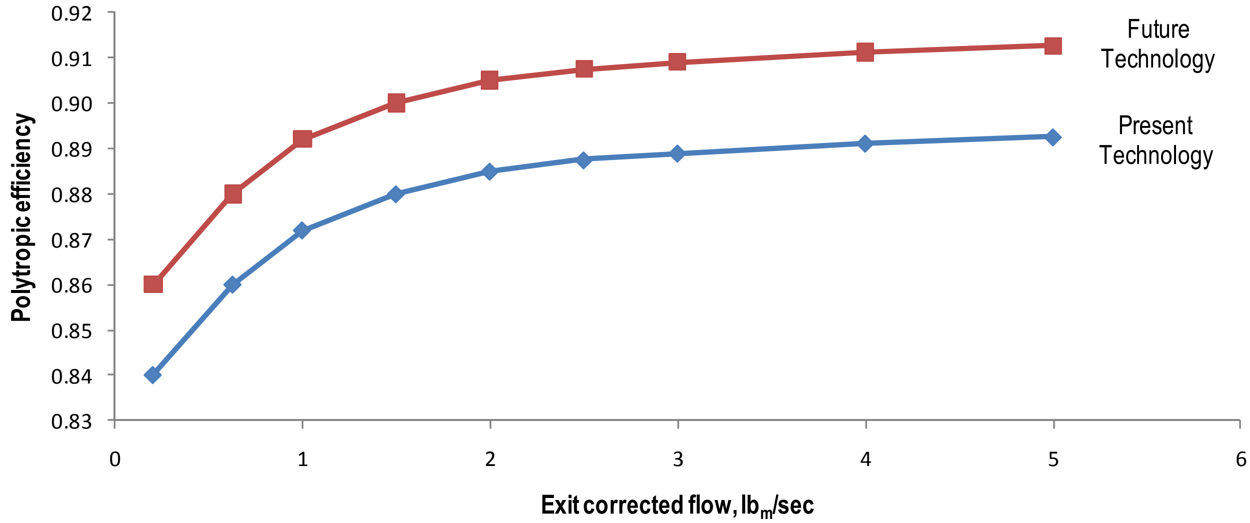

Figure 6.—Compressor polytropic efficiency versus flow and technology level.

Compression System Efficiency

Compression system efficiency is an important parameter for any gas turbine cycle. Improved compressor efficiency has a two-fold effect on overall engine efficiency. First, it directly affects the amount of work that must be produced from the turbine sharing the same shaft; an improvement in compression efficiency reduces turbine work and pressure ratio requirements. This can improve the gas generator exhaust pressure that subsequently produces the work output from the engine. Second, an improvement in compressor efficiency also results in cooler compressor bleed flows that are used for turbine cooling, also reducing that parasitic loss to the engine and can result in an improvement in engine performance. These topics and other aspects about compressors with respect to the Rotary-Wing Project are discussed in Reference 8. In the previous effort, compressor polytropic efficiency was assumed to be a constant, regardless of flow size. Reference 8 looked at this in greater detail and resulted in notional compressor polytropic efficiency curves that were used for this study and are shown in Figure 6 (at exit corrected flows greater than 5 lb_m/sec, the value for efficiency was maintained at that value). Thus the value for polytropic efficiency for the LPC, HPC axial stages and centrifugal stage were each set based on their respective exit corrected flows and assumed technology level. The effect of compression system efficiency on the optimum cycle parameters and overall engine PSFC and weight will be summarized and discussed at the end of this section.

Turbine Efficiency

Turbine efficiency is also an important parameter for any gas turbine cycle. Improved turbine efficiency enables further work potential for all components downstream in the gas turbine. Because turbines are downstream of the combustor, they are subjected to some of the highest temperatures found in the engine, while being required to maintain good performance and adequate life between maintenance periods. Since the previous engine study effort, there have been limited efforts to update turbine assumptions. Therefore, the levels of turbine efficiency were maintained from the earlier study with an assumption of 2 percent improvement (see Table 1), similar to the improvement in compression efficiency for future technology, to demonstrate the potential for improvement in engine performance and configuration with similar improvements in turbine performance.

Turbine Cooling

Turbine cooling flows are a parasitic loss to the cycle and represent flow that is not within the main engine flow stream at all times, resulting in the loss of potential work from this flow. However, the use of turbine cooling flows enables higher combustion (and downstream) operating temperatures, resulting in increased engine efficiency and work output, while maintaining turbine life. The method of Gauntner (Ref. 9) is used to estimate the amount of cooling flow required, based on the main gas temperature and mass flow entering each turbine stage, the turbine cooling flow gas temperature, allowable turbine metal temperature and relative cooling flow factor (1.0 is the base, lower numbers indicate less cooling flow is required). The previous study assumed that allowable turbine metal temperatures for this engine class would achieve values 200 °F greater than those assumed for large engines, while maintaining cooling flow effectiveness. It has been suggested that this is too aggressive to develop within the assumed time period and the more difficult environment in this, smaller, engine class. A smaller engine effectively has a higher surface area for cooling per turbine main flow than larger engines; thus for a given technology level, smaller engines will have a higher, relative cooling flow factor (require more cooling flow as a fraction of the main flow). For this study, maximum turbine metal temperature was assumed to be 1900 °F for rotors, 2000 °F for stators (same temperature levels assumed for present, large engines in NASA studies), while employing relative cooling flow factors previously used for small turboshaft engine internal studies (2.5 for rotors, 2.0 for stators). An additional, ultimate case was performed in which the cycle was reoptimized assuming no turbine cooling flow required. This could be illustrative of advanced materials and gives a potential of the performance benefit available if no turbine cooling were required.

Optimum Engines Results From Inclusion of Various Advanced Technologies

The results for the optimum engine are presented in Table 4. Significant improvements in PSFC and engine weight are possible employing the baseline assumptions on a new engine, with additional benefits realizable with advanced technologies. For each advanced technology assumption, optimum PSFC was realized at the highest T4 and some increase in engine OPR; the combination may be difficult to achieve for this engine size class. The conditions where each case optimized, combined with the small benefits from improved turbine cooling, suggest turbine cooling assumptions are probably too aggressive, and drive the cycle optimum to higher T4 and OPR than is truly potentially realizable. Thus, results from this effort highlight the need for more detailed turbine technology investigations before additional engine studies are warranted.

TABLE 4.—OPTIMUM ENGINE SIZING RESULTS FROM INCLUSION OF VARIOUS ADVANCED TECHNOLOGIES

Engine	Airflow, lb_m/sec	OPR	T4, °F	PSFC	Weight	Delta PSFC, percent	Delta weight, percent
LCTR2 (Ref. 2)	-----	-----	-----	0.3700	1000.0	Base	Base
Baseline (updated assumptions)	28.7	42.5	3200	0.3442	948.5	–7.0	–5.1
Baseline + Compressor efficiency	28.0	47.5	3200	0.3321	928.7	–10.2	–7.1
Baseline + Turbine efficiency	28.7	45.0	3200	0.3364	942.9	–9.1	–5.7
Baseline + Turbine cooling	27.1	45.0	3200	0.3407	933.9	–7.9	–6.5
Baseline + Advanced turbine materials (“no turbine cooling”)	19.5	60.0	3200	0.3144	902.1	–15.0	–9.8
Baseline + All technologies (except “no turbine cooling”)	26.4	52.5	3200	0.3223	918.7	–12.9	–8.1

Assuming material technologies that removed the requirement for turbine cooling altogether (no turbine cooling) realized the largest improvements in PSFC and engine weight. The significant reduction in gas generator airflow (–32 percent from the baseline) did reduce the gas generator size and weight, but the power turbine still had to derive a given amount of power from a significantly smaller and hotter gas flow. This resulted in the need for an additional power turbine stage for this engine configuration, versus the other technologies analyzed, which reduced the amount of weight benefit that was achieved. It should also be noted that for this configuration, at the high OPR, compressor exit conditions also impose stringent design constraints with exit conditions of 0.62 lb_m/sec corrected flow and almost 1400 °F. The combination of all technology advancements realized almost the same benefits as the no turbine cooling case, showing that some improvements across several areas can realize significant gains.

Effect of Engine Component Technology on Vehicle Gross and Mission Fuel Weights

As part of the heavy lift rotorcraft investigation reported in Reference 1, LCTR vehicle sensitivities to different technology assumptions were generated and reported. Although the LCTR vehicle reported in Reference 1 is similar to the present vehicle iteration, there have been some changes in the design requirements and technology assumptions that resulted in the LCTR2 baseline design, which should also affect the magnitude of the LCTR2 sensitivities to changes in engine performance and weight. They were used here as an initial estimate, to help indicate potential areas for further analysis and refinement, as well as suggest areas to maximize technology investment. The effects of drive system weight and the combination of engine PSFC and power to weight assumptions on the LCTR vehicle are listed in Table 5. Between these two sets of sensitivities, one can estimate the effects of engine weight and PSFC separately, which are shown in Table 6 and discussed here. Since engine weights are only about 1/3 as heavy as the total drive system, changes in engine weights should only have 1/3 of the effect on the LCTR vehicle as changes in drive system weights. This effect can then be removed from the engine technology effects for changing both the engine power to weight ratio and PSFC and will result in a separate factor for only the change in PSFC. These new sensitivities were then used to estimate the change in gross weight and mission fuel for the inclusion of advanced engine technologies studied as part of this effort and are exhibited in Table 7. Improvements in PSFC enabled substantial reductions for fuel consumption and overall vehicle gross weight. Engine weights are already pretty low and a much smaller fraction of the total vehicle, so gains there were smaller, but there is still some effect on gross weight and fuel. Since the "no turbine cooling" approach enabled the largest reduction in PSFC and engine weight, it also leads in the reduction of vehicle gross weight and mission fuel.

TABLE 5.—EFFECT OF ADVANCED ENGINE TECHNOLOGY ON LCTR (FROM REF. 1)

Attribute	Advanced technology (Baseline for LCTR)	Current technology	Percent change	Overall effect of current technology on LCTR vehicle (Base is advanced technology)
Drive system weight				
Weight technology factor	0.67	1.00	+50% drive system weight (drive is 13% of gross weight)	+23% Gross weight +21% Mission fuel
Engine technology				
PSFC, lb_m/hour/HP	0.3243	0.426	+31% fuel usage	+23% Gross weight +70% Mission fuel
Power/Weight (HP/lb_m)	7.48	6.49	+15% engine weight	

TABLE 6.—ESTIMATED EFFECTS OF ENGINE WEIGHT AND PSFC ON LCTR VEHICLE (BASED ON RESULTS FROM REF. 1)

Attribute	Change	Overall effect on LCTR vehicle	Rationale
Engine weight (only), from drive system weight	+50% lb_m/HP	+8% GW +7% Mission fuel	Engine weight is approximately 1/3 of drive system weight, ratio effect on LCTR from Table 5
Combined engine weight and PSFC	+31% PSFC +15% lb_m/HP	+23% GW +70% Mission fuel	Same cumulative effect as Table 5
Engine weight (only)	+15% lb_m/HP	+2.4% GW +2.1% Mission fuel	Effect of engine weight (only) using (15%/50%) lb_m/HP ratio
Engine PSFC (only)	+31% PSFC	+21% GW +68% Mission fuel	Remove effect of engine weight from cumulative effect of both engine weight and PSFC

TABLE 7.—ESTIMATED EFFECTS OF ADVANCED TECHNOLOGIES ON VEHICLE GROSS WEIGHT AND MISSION FUEL

	Effect of PSFC improvements			Effect of engine weight improvements			Combined effect	
Engine	Delta PSFC, percent	Delta GW, percent	Delta fuel, percent	Delta eng.Wt, percent	Delta GW, percent	Delta fuel, percent	Delta GW, percent	Delta fuel, percent
LCTR2 (Ref. 2)—base	----	----	----	----	----	-----	-----	-----
Baseline (updated assumptions)	–7.0	–4.7	–15	–5.1	–0.8	–0.7	–5.5	–16
Baseline + Compressor efficiency	–10.2	–6.9	–22	–7.1	–1.1	–1.0	–8.0	–23
Baseline + Turbine efficiency	–9.1	–6.2	–20	–5.7	–0.9	–0.8	–7.1	–21
Baseline + Turbine cooling	–7.9	–5.4	–17	–6.5	–1.0	–0.9	–6.4	–18
Baseline + Advanced turbine materials (“no turbine cooling”)	–15.0	–10.2	–38	–9.8	–1.6	–1.4	–11.8	–39

Conclusions

Engine component performance estimates for a LCTR2-sized turboshaft engine were updated and new, optimum engine thermodynamic, flow path and weight analyses have been performed to help estimate the effects of engine component performance on engine size, performance and subsequently, vehicle size and mission performance. The inclusion of state of the art values from commercial turbofan engines and advanced small-engine technologies suggested that there are still significant specific fuel consumption gains to be realized. The “no turbine cooling” approach gave the largest benefit, but the combination of all technologies (compressor and turbine efficiency, and turbine cooling flow reductions) realized similar improvements and might be the more balanced and obtainable technology path. Engine weights are already a fairly small fraction of the vehicle gross weight, so gains there were small, but notable. Overall, this and the previous study (Ref. 3) consistently identify the optimum engine cycle as a two-spool gas generator core, operating below 30 lb_m/sec mass flow, with elevated T4 (3000 to 3200 °F or more), and increased OPR, greater than 30 or even 40, for the LCTR2 engine class. While more detailed examination of the efficiencies and material capabilities is warranted, in concert with a full vehicle sizing analysis, these results describe alternative technology paths that can help refine future engine requirements for a LCTR.

References

1. Johnson, W., Yamauchi, G.K., and Watts, M.E., "NASA Heavy Lift Rotorcraft Systems Investigation," NASA/TP—2005-213467, September 2005.
2. Acree, C.W., Hyeonsoo, Y., and Sinsay, J.D., "Performance Optimization of the NASA Large Civil Tiltrotor," International Powered Lift Conference, London, UK, July 22–24, 2008.
3. Snyder, C.A., and Thurman, D.R., "Gas turbine characteristics for a Large Civil Tilt-Rotor (LCTR)," AHS International, 65th Annual Forum & Technology Display, Grapevine, Texas, May 27–29, 2009, NASA/TM—2010-216089.
4. Jones, Scott M., "An Introduction to Thermodynamic Performance Analysis of Aircraft Gas Turbine Engine Cycles Using the Numerical Propulsion System Simulation Code," NASA/TM—2007-214690.
5. Tong, M.T., and Naylor, B.A., "An Object-Oriented Computer Code for Aircraft Engine Weight Estimation," GT2008–50062, ASME Turbo-Expo 2008, June 9–13, 2008, NASA/TM—2009-215656.
6. Veres, Joseph P., "Compressor Study to Meet Large Civil Tilt Rotor Engine Requirements," AHS International, 65th Annual Forum & Technology Display, Grapevine, Texas, May 27–29, 2009, NASA/TM—2009-215641.
7. Veres, Joseph P., and Thurman, Douglas R., "Conceptual Design of a Two Spool Compressor for the NASA Large Civil Tilt Rotor Engine," AHS International, 66th Annual Forum & Technology Display, Phoenix, Arizona, May 11–13, 2010.
8. Welch, G.E., Hathaway, M.D., Skoch, G.J., and Snyder, C.A., "Rotary-Wing Relevant Compressor Aero Research and Technology Development Activities at Glenn Research Center," AHS International, 65th Annual Forum & Technology Display, Grapevine, Texas, May 27–29, 2009.
9. Gauntner, J.W., "Algorithm for Calculating Turbine Cooling Flow and the Resulting Decrease in Turbine Efficiency," NASA TM 81453, 1980.

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*
01-11-2010

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Effects of Gas Turbine Component Performance on Engine and Rotary Wing Vehicle Size and Performance

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Snyder, Christopher, A.; Thurman, Douglas, R.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
WBS 877868.02.07.03.07.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio 44135-3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E-17485

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001
and
U.S. Army Research Laboratory
Adelphi, Maryland 20783-1145

10. SPONSORING/MONITOR'S ACRONYM(S)
NASA, ARL

11. SPONSORING/MONITORING REPORT NUMBER
NASA/TM-2010-216907

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject Category: 07
Available electronically at http://gltrs.grc.nasa.gov
This publication is available from the NASA Center for AeroSpace Information, 443-757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
In support of the Fundamental Aeronautics Program, Subsonic Rotary Wing Project, further gas turbine engine studies have been performed to quantify the effects of advanced gas turbine technologies on engine weight and fuel efficiency and the subsequent effects on a civilian rotary wing vehicle size and mission fuel. The Large Civil Tiltrotor (LCTR) vehicle and mission and a previous gas turbine engine study will be discussed as a starting point for this effort. Methodology used to assess effects of different compressor and turbine component performance on engine size, weight and fuel efficiency will be presented. A process to relate engine performance to overall LCTR vehicle size and fuel use will also be given. Technology assumptions and levels of performance used in this analysis for the compressor and turbine components performances will be discussed. Optimum cycles (in terms of power specific fuel consumption) will be determined with subsequent engine weight analysis. The combination of engine weight and specific fuel consumption will be used to estimate their effect on the overall LCTR vehicle size and mission fuel usage. All results will be summarized to help suggest which component performance areas have the most effect on the overall mission.

15. SUBJECT TERMS
Turboshaft; Gas turbine engine; Performance prediction; Weight

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					STI Help Desk (email:help@sti.nasa.gov)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
U	U	U	UU	17	443-757-5802