NASA NNA06BC41C Task Order 10 and
NASA NNA09DA56C Task Order 2, 4 and 5

The Effect of Rotor Cruise Tip Speed, Engine Technology and Engine/Drive System RPM on the NASA Large Civil Tiltrotor (LCTR2) Size and Performance

Mark Robuck
The Boeing Company, Philadelphia, PA

Joseph Wilkerson
The Boeing Company, Philadelphia, PA

Robert Maciolek
The Boeing Company, Philadelphia, PA

Dan Vonderwell
Rolls-Royce Corporation, Indianapolis, IN

March 2012

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National Aeronautics and Space Administration

Ames Research Center
Moffett Field, California 94035

Prepared for Glenn Research Center
under Contract NAS1- NNA06BC41C

March 2012

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Prepared for Glenn Research Center

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March 2012

ABSTRACT

A multi-year study was conducted under NASA NNA06BC41C Task Order 10 and NASA NNA09DA56C task orders 2, 4, and 5 to identify the most promising propulsion system concepts that enable rotor cruise tip speeds down to 54% of the hover tip speed for a civil tiltrotor aircraft. Combinations of engine RPM reduction and 2-speed drive systems were evaluated. Three levels of engine and the drive system advanced technology were assessed; 2015, 2025 and 2035. Propulsion and drive system configurations that resulted in minimum vehicle gross weight were identified.

Design variables included engine speed reduction, drive system speed reduction, technology, and rotor cruise propulsion efficiency. The NASA Large Civil Tiltrotor, LCTR, aircraft served as the base vehicle concept for this study and was resized for over thirty combinations of operating cruise RPM and technology level, quantifying LCTR2 Gross Weight, size, and mission fuel. Additional studies show design sensitivity to other mission ranges and design airspeeds, with corresponding relative estimated operational cost.

The lightest vehicle gross weight solution consistently came from rotor cruise tip speeds between 422 fps and 500 fps. Nearly equivalent results were achieved with operating at reduced engine RPM with a single-speed drive system or with a two-speed drive system and 100% engine RPM. Projected performance for a 2025 engine technology provided improved fuel flow over a wide range of operating speeds relative to the 2015 technology, but increased engine weight nullified the improved fuel flow resulting in increased aircraft gross weights. The 2035 engine technology provided further fuel flow reduction and 25% lower engine weight, and the 2035 drive system technology provided a 12% reduction in drive system weight. In combination, the 2035 technologies reduced aircraft takeoff gross weight by 14% relative to the 2015 technologies.

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LIST OF SYMBOLS AND ACRONYMS

A	Total Rotor Disk Area
AEO	All Engines Operating
APU	Auxiliary Propulsion Unit
ASM	Available Seat Mile
b	Wing Span
CD	Drag Coefficient
CG	Center of Gravity
CL	Lift Coefficient
COTS	Commercial Off The Shelf
CT	Rotor Thrust Coefficient
DL	Disk Loading (GW/A)
DOC	Direct Operating Cost
EIS	Entry In Service date
EW	Aircraft Empty Weight
FAA	Federal Aviation Administration
Fe	Equivalent Flat Plate Area (drag)
FEM	Finite Element Model
FH	Flight Hour
FM	Hover Figure of Merit
FMEA	Failure Modes and Effects Analysis
FPS	Feet per second
GW	Aircraft Gross Weight
HOGE	Hover Out-of-Ground Effect
HP	Horsepower
HPT	High Pressure Turbine
HUMS	Health and Usage Monitoring System
IP	Intermediate Pressure
ISA	International Standard Atmosphere
KTAS	Knots True Airspeed
LCTR	Large Civil Tilt Rotor
L/D	Lift to Drag Ratio
LH	Left Hand
LPT	Low Pressure Turbine
MCP	Maximum Continuous Power
MRP	Maximum Rated Power
MWGB	Mid-Wing Gearbox
n	number of blades
nmi	nautical miles
OWE	Operating Weight Empty
PRGB	PropRotor Gearbox
PT	Power Turbine
OEI	One Engine Inoperative
RH	Right Hand
RPM	Revolutions per Minute
S	Wing reference area
SDGW	Structural Design Gross Weight
SFC	Specific Fuel Consumption (lb fuel/hr/SHP)
SHP	Shaft Horsepower
SLS	Sea Level Static atmospheric condition
SRW	Subsonic Rotary Wing
t/c	Thickness to chord ratio
TAGB	Tilt Axis Gearbox
TRL	Technology Readiness Level
VAATE	Versatile Affordable Advanced Turbine Engines
VB	Visual Basic programming language
V/STOL	Vertical and Short Take-off and Landing
WBS	Work Breakdown Structure
W/S	Wing loading (GW/S)
X	non dimensional blade section radial location r/R
σ	rotor solidity (blade area / disk area)
μ	advance ratio, flight speed / rotor tip speed
Ω	angular velocity

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1.0 BACKGROUND

This report summarizes efforts and accomplishments for a study project conducted under the following NASA contracts:

- NASA NNA06BC41C Task Order 10 entitled, "Engine/Gearbox Assessment for 50% Variable Rotor Tip Speed".
- NASA NNA09DA56C Task Order 2 entitled, "Option 1 & 3 Dual Speed Gearbox Evaluation for 50% Variable Rotor Speed".
- NASA NNA09DA56C Task Order 4 entitled, "Engine/Gearbox Assessment for 50% Variable Rotor Speed – Extended Tasks".
- NASA NNA09DA56C Task Order 5 entitled, "50% Engine-gearbox Design Study".

The purpose of these study contracts is to identify and evaluate propulsion system concepts to achieve approximately 50% rotor tip speed variation for a large tiltrotor air vehicle and to investigate the most advantageous speed variation strategies and technologies for the integrated engine and drive system. The evaluation is performed for the subject air vehicle, the NASA Large Civil Tiltrotor (LCTR2) with a simplified vehicle sizing tool. Propulsion and drive system configurations that resulted in minimum vehicle gross weight and fuel burn were investigated. This is accomplished by considering propulsion system configurations, speed reduction through drive system or engine technologies, and also the effects of engine and drive system technologies available at year 2015, 2025 and 2035. Design variables included engine speed reduction fraction, drive system speed reduction fraction, technology factors, efficiencies, configuration variables (fuel quantity, vehicle size), etc. A limited number of configurations were examined within the project scope. Operational characteristics including range, speed, and mission specifics were constrained initially, but studied in a sensitivity assessment in later tasks. The LCTR2 mission profile was specified as 1000 nautical miles (nmi) cruise at 310 ktas airspeed and 25,000 ft altitude, which ultimately was determined to be a favorable design space for this concept vehicle.

The sizing studies were initially conducted for three tip speeds evaluated (350 fps, 500 fps, 650 fps). Additional analysis was performed to investigate the optimum for this study (minimum weight and fuel burn) and focused on the 310 ktas airspeed at 422 fps tip speed (65% rotor speed) with the engine operating at 100% speed and a two-speed drive system used to produce the lower rotor speed. Higher air speeds of 350 ktas and 375 ktas were also examined, but proved to be less favorable in both sizing and operating cost. Results of the sizing studies are presented in this report as well as engine and drive system configuration data, study methodology, an assessment of technology effects, barriers, and recommendations for further work.

2.0 INTRODUCTION

Rotorcraft propulsion systems have predominantly been designed to operate within a narrow range of rotor tip speeds; however the operational demands for a tiltrotor aircraft are best satisfied with a multi-speed capability. A case in point is the V-22 propulsion system which operates at a higher (103.8%) speed for hover operations and at a lower (84%) speed for airplane mode cruise conditions.

Great interest has been generated from NASA studies of slowed rotor operation and vehicle system studies described in report NASA TP-2005-213467 [1] which defined the advantages of the Large Civil Tiltrotor (LCTR) for the air transportation system. More recently the LCTR concept was optimized and described in a NASA report[2]. This effort produced the LCTR2 concept that was sized to carry 90 passengers and baggage (19,800 pounds) for 1,200 nautical miles. The NASA defined vehicle takeoff gross weight is approximately 107,700 pounds. The baseline LCTR2 air vehicle has two 65 foot rotors near the wing tips, with four-7,500 HP turboshaft engines (two engines within the tilting nacelle at each rotor) with an estimated total cruise power requirement of 11,900 HP. Rotor tip speed was selected as 650 fps during takeoff / hover and climb, and 350 fps for the cruise condition; this feature of the LCTR vehicle defined the 54% variable rotor tip speed which provides operational benefits in reduced noise and improved efficiency. Previous high level vehicle studies have been performed and no consensus has been formed about the preferred propulsion system configuration to achieve the variable rotor speeds. This study considers operation at full speed, and partial speed operation at 77%, 65% and 54% rotor tip speed for climb and cruise segment of a mission profile. Although the nominal mission includes takeoff and hover requirements, the climb and cruise segments dominate fuel usage. The cruise condition is 310 ktas, 25,000 ft altitude and additional sensitivity studies were conducted at 350 ktas and 375 ktas.

The primary goal of this study is to identify the engine and drive system concepts, technology barriers and needs to achieve a 54% rotor cruise tip speed variation with a fixed rotor diameter, vehicle, and mission. Secondary goals were added as the project evolved to find optimum conditions in terms of vehicle size, fuel burn, operating costs and sensitivities for additional ranges and airspeeds.

2.1 Tasks

This report summarizes efforts and accomplishments by Boeing and Rolls-Royce engineers for the following NASA Task Orders. More detailed Statements of Work are in Appendix A.

- NASA NNA06BC41C Task Order 10 entitled, “Engine/Gearbox Assessment for 50% Variable Rotor Tip Speed”. The purpose of the study contract is to identify and evaluate propulsion system concepts to achieve approximately 50% rotor tip speed variation for a large tiltrotor air vehicle and to investigate the most advantageous speed variation strategies and technologies for the integrated engine and drive system. The evaluation is

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[1] Johnson, Wayne, Yamauchi, Gloria K, and Watts, Michael E., “NASA Heavy Lift Rotorcraft Systems Investigation”, NASA TP-2005-213467, 2005.

[2], Acree, C.W., Jr., Yeo, Hyeonsoo, and Sinsay, Jeffrey D., “Performance Optimization of the NASA Large Civil Tiltrotor”, 2008 International Powered Lift Conference, London, UK, July 22-24, 2008

performed for the subject air vehicle, the NASA Large Civil Tiltrotor (LCTR2) with a simplified vehicle sizing tool. Providing 50% variable rotor tip speed capability with either (or both) the drive or engine system will require advancement in the state of art for propulsion technology and therefore an evaluation of technology readiness is also performed.

- NASA NNA09DA56C Task Order 2 entitled, "Option 1 & 3 Dual Speed Gearbox Evaluation for 50% Variable Rotor Speed". The major goal of this task order contract is to explore design options and constraints for speed changing mechanisms identified in the previous Task Order 10 Project. This task develops the design details and characteristics of the speed changing gearbox module as well as analytical model creation for dynamic speed changing events using commercial software tools.
- NASA NNA09DA56C Task Order 4 entitled, "Engine/Gearbox Assessment for 50% Variable Rotor Speed – Extended Tasks". During the course of the Task Order 10 contract study, an optimum rotor cruise tip speed could not be determined from the 650 fps, 500fps and 350 fps design cases. Focusing on the 2035 entry-in-service (EIS) technology level, a wider range of operating conditions is evaluated, including an additional intermediate rotor cruise tip speed, and sensitivity to cruise airspeed and mission range. A fourth engine configuration is defined to complement the efforts that have already been performed. A new engine performance deck is generated and applied to the all rotor cruise tip speeds.
- NASA NNA09DA56C Task Order 5 entitled, "50% Engine-gearbox Design Study". The intent of this task is to maintain the same vehicle and focus on EIS 2035 technology levels for the drive system (engine and gearbox / transmission), including a wider range of operating conditions' (greater range of rotor cruise tips speeds, airspeeds, and mission ranges,) and additional engine performance data to refine and complement the efforts that have already been performed. Operating and Support (O&S) costs are estimated for some of the vehicle results as well.

In general terms, these studies attempt to identify the engine and drive system concepts, technology barriers and needs that enable the LCTR2 concept, and enhance its commercial viability by the following means.

- Validate performance benefits of the NASA LCTR2 concept that applies reduced rotor tip speed in cruise.
- Identify the best combinations of engine and drive system RPM, and rotor cruise tip speed by comparative quantitative analysis of mission performance.
- Explore sensitivity to mission range and cruise airspeed, and provide estimates of operating cost to quantify the benefits of alternative designs.

The initial scope and strategy in this study was to evaluate rotor performance and subsequent LCTR2 weight, size and performance for three rotor cruise tip speeds (650 fps, 500 fps, 350 fps), driven by combinations of engine RPM or drive system RPM reductions, for three technology levels. Engine and drive system technology included commercial off the shelf (COTS) and technology expected for EIS 2025 and EIS 2035. NASA's LCTR2 mission profile, operational range, and cruise airspeed were applied throughout this study. The approach was to resize the LCTR2 by applying different rotor designs (cruise tip speeds), engine and drive system weight, and performance at different technology levels to quantify the relative benefits and identify the most promising solutions, as measured by gross weight, installed SHP, mission fuel, or operating costs. Rotor speed variability from 100% to 54% was achieved with two methods investigated in this study – changing gear ratios in the output/transmission drive train and/or highly variable output speed gas turbine engines.

As the project evolved during the multi-year effort, a fourth engine design was added. The new 2035 engine with a fixed-geometry, variable-speed power turbine (FG-VSPT) was lighter than the previous 2035 engine, which had a variable-geometry variable-speed power turbine, referred to as (VG-VSPT). The LCTR2 was sized for several combinations of engine RPM and drive system RPM, for each rotor cruise tip speed design.

The final portion of the study is focused on sensitivity of the LCTR2 concept to the design cruise airspeed and range, where initial evaluations focused on the NASA LCTR2 1000 nmi cruise range at 310 ktas airspeed. A cost analysis was also conducted as an integral part of this phase, addressing operational cost.

The study project was executed with Boeing engineers responsible for overall vehicle sizing, drive system conceptual design and integration tasks, with assistance from Rolls-Royce teammates for propulsion related tasks. Rolls-Royce evaluated the impact of variable engine output speed on performance and identified cycle compromises and design features which would mitigate these impacts. The combination of engine speed reduction, drive system speed reduction, technology factors, and rotor hover and cruise efficiency drive the aircraft Gross Weight, Empty Weight, and Fuel.

Results of these sizing studies are presented in this report as well as engine and drive system configuration data, study methodology, an assessment of technology effects, barriers, and recommendations for further work. Climb and cruise segments drive the fuel consumption, which has a major effect on aircraft size for the LCTR2 long-range rotorcraft. The primary performance parameters are airframe drag, engine power-to-weight and SFC, and prop-rotor cruise efficiency.

2.2 NASA LCTR2 Configuration

The LCTR2 design, size and performance, was generated by cruising at 25,000 ft altitude and 310 ktas airspeed. The Boeing study task was not to change or optimize the overall LCTR2 concept or operational conditions, so Boeing performance evaluations and aircraft re-sizing retained the same cruise altitude and airspeed to allow direct comparison to the NASA design.

Many design requirements are imposed on commercial aircraft designs, primarily for safety. Only the critical ones that directly impact aircraft size and performance are usually addressed in a conceptual design study, such as this. NASA had selected a four-abreast seating arrangement that determined the basic fuselage width and length for 90 seats, while accounting for cockpit, entry doors, lavatories, galley, baggage area, and flight attendant seats. Boeing retained the LCTR2 general arrangement, shown in Figure 1. Specifics of the basic LCTR2 design

Figure 1. Large Civil Tilt-Rotor 2

(NASA Ames Research Center)

are available in Appendix B.

2.3 NASA LCTR2 Design Conditions

The NASA mission profile for their LCTR2 study program transports 90 passengers and baggage, weighing 19,800 lb, over a 1000 nmi mission range, accounting for fuel in a taxi segment, an alternate destination and reserve fuel. Installed shaft horsepower (SHP) was required to satisfy a hover-out-of-ground-effect (HOGE) takeoff at 5,000 ft altitude and ambient temperature of ISA+20°C with full passenger and fuel loads. Figure 2 displays the mission profile.

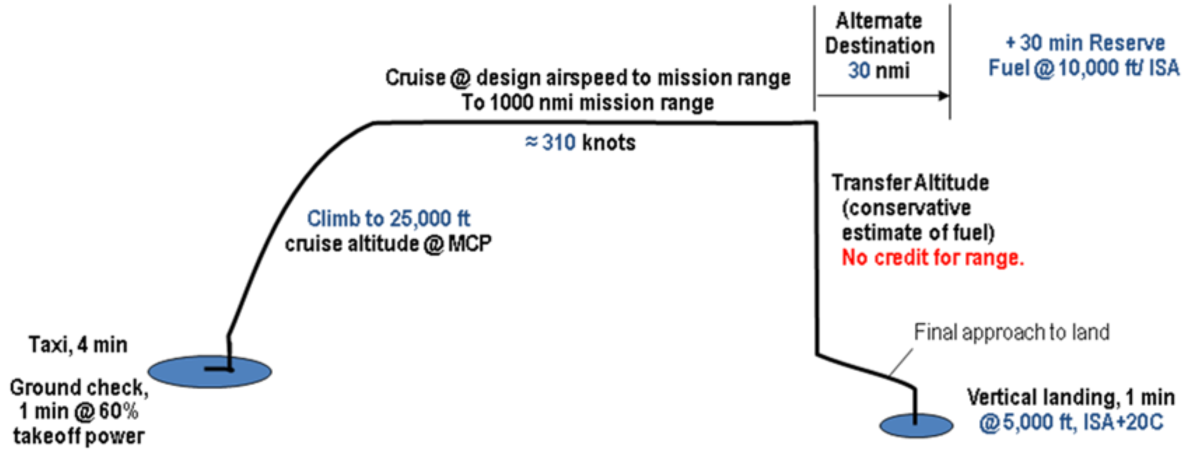


Figure 2. NASA Mission Profile for LCTR2 Study

A major performance factor is the ability to recover from a one-engine-inoperative (OEI) condition during a vertical takeoff and safely return to the take-off pad or continue the takeoff to a (sustainable) flight safety speed. To satisfy that requirement NASA selected a 4-engine arrangement with an assumed built-in 20% contingency (emergency) power capability, where contingency power is, by definition, beyond the engines’ rated takeoff power. That guaranteed an OEI safety margin if the engines were sized to the initial takeoff condition, or larger, and Boeing accepted that solution to the OEI requirement. This study was not tasked to address how the engines provide a 20% contingency power.

Tiltrotor aircraft designs must have satisfactory maneuver capability at all airspeeds, just as fixed wing aircraft. NASA had conducted an in-depth analysis of that requirement, resulting in increased rotor solidity for the LCTR2 to satisfy a banked maneuver at low airspeed (about 80 ktas) while the tiltrotor is still in the conversion corridor. Boeing applied NASA’s rotor solidity.

The NASA LCTR2 characteristics include a takeoff gross weight of 107,700 pounds, with 65 foot rotors near the wing tips. The LCTR2 design rotor tip speed is a relatively low 650 fps during takeoff / hover to maintain high rotor efficiency and to manage noise levels during takeoff and hover. Rotor cruise tip speed is 350 fps, or 54% of the hover RPM.

3.0 TECHNICAL APPROACH

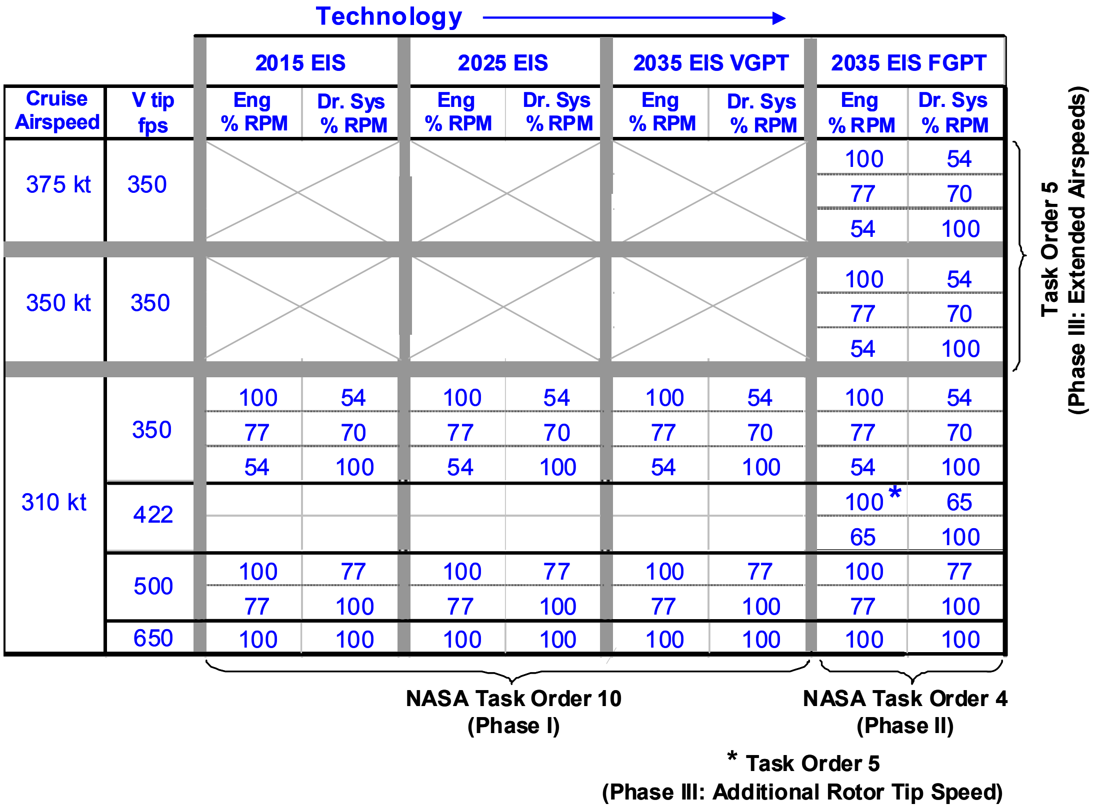
3.1 Study Design Matrix

LCTR2 overall vehicle size, geometry, performance, installed engine HP, and rotor efficiency were evaluated over a matrix of rotor cruise tip speeds, combinations of drive system and engine rpm, and technology level. Reduced rotor cruise tip speeds are achieved by either:

- Reduced engine RPM (such as the V-22) with rotor speed directly geared to the engine RPM via a fixed ratio drive system, or
- A 2-speed drive system that changes gear ratios in flight allowing the engine to operate at 100% RPM, or
- A combination of reduced engine RPM and an advanced 2-speed drive system.

Figure 3 shows the matrix of design combinations. Task Order 10 focused on the LCTR2 310 ktas cruise airspeed designs. Task Order 4 focused on the 2035 FG-VSPT engine with excursions to higher cruise airspeeds and with cost analysis. Four rotor performance maps were developed and applied at the 310 ktas cruise airspeed, with tip speeds of 650 fps, 500 fps, 422 fps, and 350 fps. There are 26 combinations for the 310 ktas airspeed designs.

Two additional rotor designs and performance maps were developed under Task Order 5 for higher cruise airspeeds of 350 ktas and 375 ktas, adding 2 additional rotor maps and 3 engine/ drive system combinations each for a total of 32 distinct designs.



Technology →

		2015 EIS		2025 EIS		2035 EIS VGPT		2035 EIS FGPT	
Cruise Airspeed	V tip fps	Eng % RPM	Dr. Sys % RPM	Eng % RPM	Dr. Sys % RPM	Eng % RPM	Dr. Sys % RPM	Eng % RPM	Dr. Sys % RPM
375 kt	350							100	54
								77	70
								54	100
350 kt	350							100	54
								77	70
								54	100
310 kt	350	100	54	100	54	100	54	100	54
		77	70	77	70	77	70	77	70
		54	100	54	100	54	100	54	100
	422							100 *	65
								65	100
	500	100	77	100	77	100	77	100	77
		77	100	77	100	77	100	77	100
	650	100	100	100	100	100	100	100	100

Task Order 5
(Phase III: Extended Airspeeds)

NASA Task Order 10
(Phase I)

NASA Task Order 4
(Phase II)

* Task Order 5
(Phase III: Additional Rotor Tip Speed)

Figure 3. Design Matrix of Engines, Technology and Cruise RPM Combinations

3.2 Analysis Methods and Tools

3.2.1 Methodology and Ground Rules for Aircraft Resizing

Boeing Rotorcraft generally uses the VASCOMP sizing program[3,4] to evaluate aircraft size and performance for tiltrotor type aircraft. However, the work to be performed in this study required evaluation at different combinations of engine RPM and drive system RPM, which are not independently modeled in VASCOMP. A spreadsheet approach provided flexibility, while emulating the general VASCOMP sizing process. Aircraft weight, engine performance, rotor performance, mission performance and overall vehicle sizing are provided by the sizing analysis. Drive system weight and losses are estimated and applied in the spreadsheet for single-speed and dual-speed designs, at each technology level. Data tables and curve fits are used to model the propulsion system and rotor performance.

Team-mate and subcontractor Rolls-Royce provided tabulated engine data for each of four different technology engines, at specified engine operating RPMs. Three original engine technologies at three operating RPMs gave nine combinations of engine data. A fourth engine technology was evaluated at four RPMs, bringing the total to thirteen sets of engine data. Each set of data covers power available, fuel flow and residual thrust over an operating range of Mach number and altitudes. Fuel flow is modeled at each specific engine output RPM, as a function of power demand, Mach number and altitude via tabulated data and curve fits of referred fuel flow versus referred power. Residual jet engine thrust from the Rolls-Royce data is accounted for in hover and cruise, as a function of altitude, Mach number, and engine SHP.

Boeing estimated the rotor cruise propulsive efficiency for each rotor design (cruise tip speed of 650 fps, 500 fps, 422 fps or 350 fps) as a function of advance ratio and thrust coefficient. These were modeled as tabulated data in the sizing program.

NASA provided values for the LCTR2 aircraft dimensions, empty weight (EW), mission fuel, and empty weight/gross weight ratios (EW/GW), rotor performance and mission performance. Table 1 lists the many NASA LCTR2 design features preserved in this study.

---

[3] Schoen, A. H., Rosenstein, H., Stanzione, K.A., Wisniewski, J.S., “User's Manual for VASCOMP II, The V/STOL Aircraft Sizing and Performance Computer Program” Prepared by the Boeing Vertol Company, D8-0375, 3rd revision, 1980.

[4] Wilkerson, Joseph, "VASCOMP III, The V/STOL Aircraft Sizing and Performance Computer Program, User's Manual", Boeing Rotorcraft, D210-13635-1, 2002.

Table 1. Ground Rules To Preserve NASA LCTR2 Attributes

Preserved Attribute	Consequence
NASA mission profile, fixed equipment weight, and 90 passengers.	Basis for sizing study
NASA design cruise airspeed and altitude (310 ktas, 25,000 ft)	Allowing direct comparison to NASA's LCTR2 performance evaluations.
LCTR2 limit load factor of 3.0	Structure weight scaled proportional to GW.
Wing loading, sweep and taper ratio.	Wing area varies with GW.
Wing span of wingtip extensions.	Same overall wing span for same rotor diameter.
Overall Wing span	Varies with GW to preserve LCTR2 1.5' clearance between inboard rotor tip and side of body.
Wing aspect ratio LCTR2 AR=11.44	AR is a fallout to preserve LCTR2 1.5' inboard rotor tip clearance. Higher AR gives slightly lower induced drag.
Used VASCOMP equation for Oswald induced drag factor.	Based on wing aspect ratio. Generally slightly lower efficiency than NASA.
Horizontal tail volume coefficient and tail moment arm.	Horizontal tail area depends on wing area and MAC.
Rotor hover Ct/σ, hover disc loading, and number of blades.	Rotor solidity is therefore preserved. Rotor diameter varies with GW.
NASA hover Download/Thrust	Justified by maintaining LCTR2 disc loading and wing loading
NASA fuel flow conservatism factor	5% fuel conservatism
Equivalent flat plate area (fe) was scaled from the NASA fe of 34.18 sq.ft.	Total fe changes with area of wing and tail surfaces.
Fuselage fe was retained	Kept NASA LCTR2 dimensions
Engine sized to greater of HOGE HP or HP for design airspeed at altitude.	All resized designs capable of HOGE and reaching the design cruise airspeed.
Transmission sized to greater of HOGE or cruise torque (cruise for low Vtip)	Transmission torque rating adjusted for low rotor cruise tip speeds, where applicable.
HP available for climb and cruise limited by transmission cruise rating.	Note: Climb was performed at rotor cruise RPM.
LCTR 4-engine arrangement was preserved, retaining one-engine-inoperative (OEI) performance.	OEI HOGE SHP is 90% of takeoff SHP, obtained with 4 engines and the NASA 20% contingency power, when engines are sized to HOGE at the design GW (or for cruise if greater).

The essence of the aircraft sizing model is further described below.

- Model the Rolls-Royce engine performance at each specific engine RPM, including power available, fuel consumption, and residual thrust.

- Scale the Rolls-Royce baseline engine to satisfy the greater of hover takeoff power or cruise power. Engine scaling, at a given technology level, assumes SFC is preserved for the same relative power, altitude and Mach number.
- Build up aircraft empty weight (EW) from the major aircraft components, using VASCOMP parametric weight relationships.
- Base aircraft drag primarily on the LCTR2 reference data. Wing profile drag is scaled with wing area and induced drag efficiency is based on wing aspect ratio.
- Model each rotor's cruise performance as a bi-variant table of advance ratio (μ) and thrust coefficient (CT). Model rotor hover Figure of Merit (FM) versus the hover CT at the LCTR2 hover tip speed of 650 fps.
- Evaluate mission performance with standard performance equations for hover, climb, and cruise, at specific airspeed and altitude. Engine performance and rotor performance are obtained from table lookup routines at the specific operating condition and gross weight.
- A VB iteration script executes the process sequentially to converge on a new size aircraft.

3.3 Drive Systems Configuration

NASA LCTR2 vehicle parameters and mission specifics are used to develop configuration data and concepts for the integrated engine and drive systems in this study. The LCTR configuration has evolved to a high wing, tilting nacelle aircraft, like the V-22 in many respects, except with four engines, 2 engines at each nacelle. The LCTR2 adopted the tilting nacelle architecture for perhaps the same reasons as the V-22:

- Smaller CG shift during transition to and from cruise mode
- Less complexity at nacelle transition joint with fewer spiral bevel gears in the drive system
- Smaller overall nacelle size with reduced frontal area

Disadvantages are also known and include:

- Hot exhaust temperatures near the tarmac
- Complexity of engine and transmission lubrication systems

There have been many studies[5,6] performed for other tiltrotor drive system arrangements including low wing/ fixed engine concepts which were also considered in earlier LCTR configurations. Since the LCTR2 configuration is similar to the V-22 configuration, which has undergone the scrutiny of development with many reviews and trade studies and is currently in production, it serves as the baseline architecture and point of reference for this project.

A simple block diagram of the notional baseline drive system for this study, shown in Figure 4, consists of 5 transmissions – a left-hand (LH) and right-hand (RH) PropRotor Gearbox (PRGB, borrowing V-22 nomenclature), LH and RH Tilt Axis Gearboxes (TAGB) and a Mid-Wing Gearbox (MWGB) for cabin accessory power. The PRGB transmissions are power-

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[5] Vittorio Caramaschi; "The Eurofar Vehicle Overview"; Agusta S.p.A; 47th Annual Forum Proceedings; May 6-9, 1991

[6] C. W. Acree, Jr. and Wayne Johnson, Ames Research Center; "Performance, Loads and Stability of Heavy Lift Tiltrotors", AHS Vertical Lift Aircraft Design Conference, San Francisco, California, January 18-20, 2006.

combining transmissions which collect power from the 2 engines (per nacelle) and deliver power to the rotor system. The PRGB transmissions are located near the rotor system to minimize the weight of the heavy rotor shaft. The TAGB transmissions are located on the nacelle tilting axis which is assumed to be aft of the wing spar similar to the V-22.

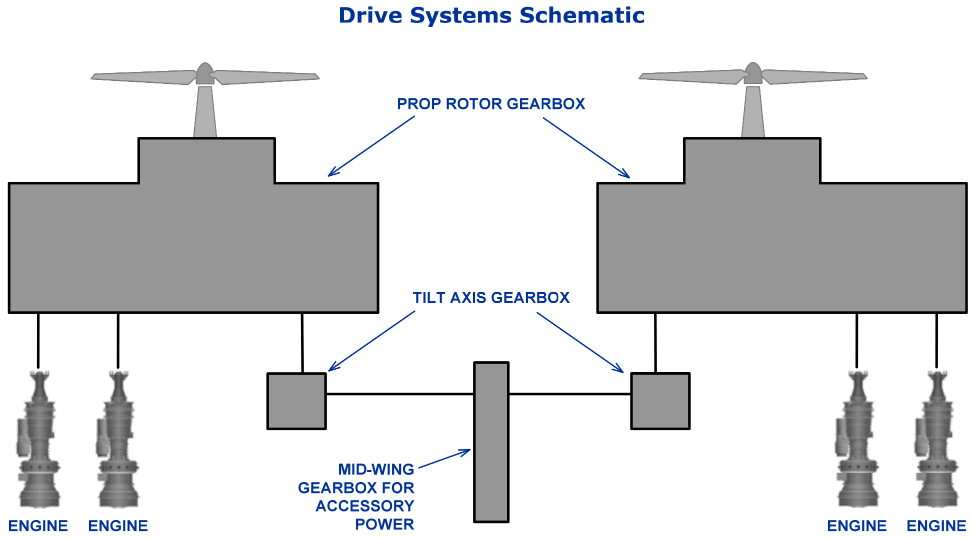

Figure 4. Drive System Block Diagram

Referring to the goals of this project and Figure 3, it is evident that a number of drive system variations must be considered in this study. To satisfy the rotor's reduced cruise tip speed, a variable or multi-speed configuration is needed, and for operation scenarios where all the rotor speed reduction is accomplished with engine speed variation, a single ratio transmission is required. In addition, this study considered variations in the basic arrangement and required reduction ratios to determine a preferred configuration.

Locations for discrete ratio, speed changing mechanisms (or continuously variable mechanisms) are carefully chosen to minimize weight, consistent with safety and reliability requirements, and design practices. Within this study, variable speed needs are met with 2 speed geared reduction modules. Variable speed devices were not seen as an advantage over 2 speed devices since the cruise condition uses a fixed ratio (low gear ratio) and this condition dominates the usage spectrum. Conventional wisdom suggests that the location of any shifting transmissions should be near the high speed portions of the drive system, to minimize weight, and this was verified through the weights analysis in this study. Location of the speed changing module (near the engines) is subject to gear and bearing speed limitations, since some planetary based shifting gearboxes operate with high planet speeds. A potential location for the speed changing device could be within the PRGB, at the power-combining bull gear output shaft where only 2 speed reduction transmissions would be required to service 4 engines and 2 rotors. This location would still operate at a moderately high rotational speed while allowing the fewest transmission modules. The disadvantages with this location include:

- Weight penalty for lower speed/ higher torque location
- Higher criticality for the speed changing module since a failure could take 2 engines off-line
- Speed changing events would involve 2 engines at the same time

Another option was selected for the location of the speed changing modules because of these perceived disadvantages. Speed changing modules are located at the input stage of the PRGB transmissions for all configurations in this study. This requires 4 individual speed changing modules, one at each engine input shaft. This configuration is potentially the lightest weight and most flexible configuration for speed changing events. There are additional benefits with this location in that the modules would be accessible and repairable since they can be configured as a 'line replaceable unit'. Further details on the drive system arrangements and variations are described in later sections of this report.

3.4 Engine Cycle Data Lineage

NASA, Boeing and Rolls-Royce/LibertyWorks defined the engine technology strategy for this study as a team. Four engines, representing 2015 (COTS), 2025, and 2035 technology levels, were used in two aircraft drive system versions: one with a rotor gearbox featuring a gear change mechanism and another without gear change capability. This produces variation in rotor speed from 100% to 54% speed. Scalable installation and performance data were provided by Rolls-Royce for three engines with technology consistent with the 2015, 2025, and 2035 time frames. Each configuration and performance model was assigned individual Preliminary Design (PD) model numbers:

- PD627 designates the 2015 engine
- PD646 designates the 2025 engine
- PD647 designates the 2035 engine with VG-VSPT.
- PD628 designates the 2035 engine with FG-VSPT

The COTS baseline PD627 engine is based on a conventional turbofan core modified to a turboshaft engine with a multistage axial (variable geometry) compressor, and power turbine. It is in the 7500-9500 hp class with a pressure ratio equivalent to current engines. The 2025 EIS engine (PD646) is an upgraded 2015 design, reflecting improvements in materials and cooling, and the incorporation of a wide speed-range capable power turbine design that includes variable-geometry. The aircraft's reduced speed performance will benefit from both an improvement in engine performance and from a power turbine that is specifically designed for variable rotor speed applications. Advanced concept architecture is used for the 2035 EIS candidate (PD647). As with the 2025 engine, the 2035 engine incorporates a variable-geometry, wide speed-range capable power turbine (VG-VSPT) design to optimize performance over the planned range of output speeds. Coupling reduced dry engine weight with high efficiency at low RPMs and turbine variability, the 2035 EIS engine represents the most advanced technology solution for the LCTR2.

Another 2035 technology engine was introduced later in the study, as the fourth engine concept. This PD628 engine concept applied many of the previous 2035 engine features, but with a fixed-geometry wide speed-range capable power turbine, labeled the 2035 FG-VSPT. It sacrifices some fuel flow and available SHP at off design conditions, but the fixed-geometry power turbine is 20% lighter than the previous VG-VSPT. This turned out to be the best match for the LCTR2.

3.4.1 Rolls-Royce Engine Models

Engine performance modeling is a significant part of this study to evaluate the overall impact of engine technology and engine operating RPM on the LCTR2 vehicle.

Rolls-Royce developed four engine models to evaluate the benefit of different levels of advanced engine technology on power available, engine fuel flow, and engine weight, at 100% engine RPM and for several reduced RPMs, supporting the Design Matrix of Figure 3.

Each engines' maximum rated power (MRP) at SLS was nominally 8100 SHP, per Boeing request. Rolls-Royce provided tabulated data for power (SHP) available, fuel flow and residual net jet thrust for each engine at the following conditions:

- NASA LCTR takeoff condition of 5,000' / ISA+20°C
- MRP, Intermediate Rated power, and Maximum Continuous power (MCP) across a range of airspeeds up to Mach=0.7, at every 5000 ft of altitude up to 35,000 ft.

The engine performance data is considered Rolls-Royce Proprietary and is not provided with this report. But graphs of shaft horsepower available and referred normalized fuel flow are included.

Fuel flow data collapsed well across all altitudes, for all engines, when expressed as referred fuel flow versus referred SHP, and was therefore easily modeled as functions of referred SHP and Mach number. Mission fuel was calculated from the Rolls-Royce engine fuel flow data at the power required for each flight segment during the mission analysis. Cruise fuel was at the LCTR2 cruise altitude and airspeed; 25,000 ft, 310 ktas for all configurations, unless indicated otherwise.

Residual net jet engine thrust was accounted for in all mission segments, using Rolls-Royce data as a function of altitude, Mach number, and engine SHP. Fuel flow and residual jet thrust were scaled by an engine scale factor defined in the sizing process.

3.4.2 Rolls-Royce 2025 EIS Engine Model

Takeoff power available from the Rolls-Royce 2025 engine (PD646-11751) is 8088 SHP MRP at SLS. The 2025 engine exhibits improved performance at 54% RPM, due to the variable-geometry PT design. That performance improvement comes at the expense of a 200 lb weight increase per engine (800 lb for the aircraft). The reference SHP for the 2025 engine is essentially the same as for the 2015 engine (8088 HP vs. 8100 HP).

The 2025 engine provides far more power than the 2015 engine when operating at 54% RPM. At the cruise condition (25,000 ft, Mach 0.5, 54% RPM) the 2025 engine has 23.6% more power available than the COTS engine, which is a great advantage when resizing the aircraft.

3.4.3 Rolls-Royce 2035 EIS Engine (VG-VSPT)

The Rolls-Royce 2035 EIS engine (PD647-11772) also delivers 8100 SHP MRP at SLS. Advanced Versatile Affordable Advanced Turbine Engines (VAATE) technology is applied to project future capability in this design and includes the variable-geometry, wide speed-range capable power turbine (VG-VSPT) with associated weight for controls.

3.4.4 Rolls-Royce 2035 EIS Engine (FG-VSPT)

This engine (PD628-25233) has VAATE advanced technology with high OPR and two-spool core, similar to the PD647-11772 above, but it has a fixed-geometry power turbine, designated as FG-VSPT. The fixed-geometry power turbine was designed & optimized for an extended RPM operability range, optimized at 90% speed operation with some consideration to part-speed performance down to the 54% RPM condition while maintaining respectable SHP capability.

The FG-VSPT is about 20% lighter than its VG-VSPT cousin, making it especially attractive to the four-engine LCTR2 aircraft.

3.5 Six Rotor Designs

NASA performed extensive studies[7,8] to refine the design of the LCTR2 rotor system in previous work, including aeroelastic, performance and dynamic analyses. This study applies the NASA rotor blade airfoils and planform taper ratio for the LCTR2 in an independent evaluation of rotor performance. Four cruise tip speeds are evaluated (650 fps, 500 fps, 422 fps, and 350 fps), with an applicable twist distribution for each tip speed to operate best at the LCTR2 nominal 310 ktas cruise airspeed. These four rotor designs were employed during the trade-off of reduced engine rpm versus variable speed drive system technology to achieve the objective rotor cruise tip speeds.

Boeing designed two additional rotors for higher cruise airspeeds; one for 350 ktas cruise and the other for 375 ktas cruise. Both rotor designs applied the 350 fps rotor tip speed, partially since existing engine data was available at that 54% RPM. The 375 ktas design required thinner airfoils across the blade radius to avoid adverse drag divergence, where the helical blade tip Mach number is 0.71 at 375 ktas, 25,000 ft.

Section 6 has definitions of the six rotor designs and predicted performance.

3.6 Vehicle Resizing Methodology

The LCTR2 was resized for each of the engine technologies, at each combination of engine rpm and drive system rpm shown in Figure 3. The method and assumptions were described in Section 3.2. Drive system weight and efficiency was adjusted for each distinct rpm reduction and for the technology level associated with the year of the engine technology. Engine weight depended on the year of engine technology as provided by Rolls-Royce. A minor adjustment was made to the wing weight as a function of the rotor helical tip Mach number, to approximately account for the beneficial effect of reduced blade Mach number on whirl flutter divergence at reduced rotor cruise tip speeds.

Maximum similarity was maintained with the NASA LCTR2 aircraft geometry, providing more focus on the rotor performance sensitivity to cruise tip speed and the effect of reduced engine rpm or drive system rpm on the overall aircraft performance. In general, rotor diameter and wing area were allowed to change with aircraft GW in response to changes in empty weight and mission fuel, maintaining the LCTR2 disc loading and wing loading. A more complete set of assumptions are listed in section 3.2.1 Table 1.

3.6.1 Mission Description and Analysis

In all cases, the LCTR2 was resized to the NASA mission profile shown in Figure 2, except for the excursions with mission range at the end of the study. No attempt was made to find a more optimum altitude.

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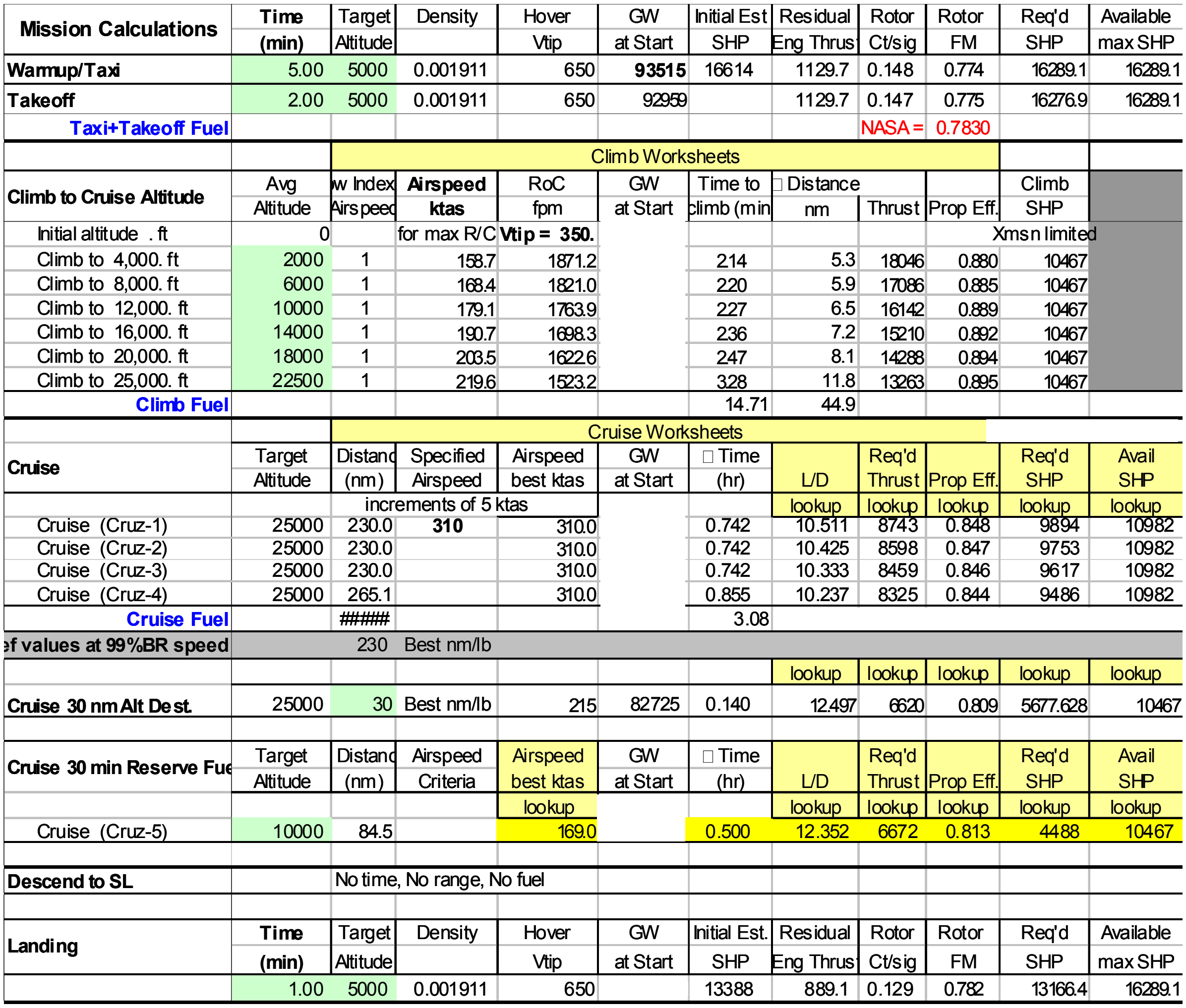
[7] Yeo, H., Sinsay, J.D., and Acree, C.W., "Blade Loading Criteria for Heavy Lift Tiltrotor Design," AHS Southwest Region Technical Specialists' Meeting, Dallas, TX, October 2008.

[8] Acree, C.W., Johnson, W., "Aeroelastic Stability of the LCTR2 Civil Tiltrotor," AHS Southwest Region Technical Specialists' Meeting, Dallas, TX, October 2008.

Mission fuel was calculated for each LCTR2 mission segment and summed up to total fuel required. The aircraft mission fuel was calculated at seven (7) climb altitudes, sequentially evaluated at the corresponding gross weight during climb, and at four (4) cruise segments. Fuel burn within each cruise segment was calculated by the Breguet range equation and GW was updated at the end of each segment. A 5% fuel flow conservatism was applied, consistent with the NASA design. A sample of the mission analysis worksheet is shown in Figure 5 (for the 310 ktas, 350 fps Vtip, and 100% engine RPM). Values in the yellow highlighted cells are calculated from other worksheets in the analysis, for the specific altitude and current GW. Values for SFC, Fuel Flow, and incremental segment fuel have been deleted to protect proprietary engine performance data.

Separate worksheets calculate LCTR2 performance versus airspeed for each segment of climb and cruise, providing that information back to the Analysis Worksheet. This study assumed rotor tip speed in climb was the same as cruise. In fact, the NASA analyses assumed that rotor tip speed in climb was higher than cruise to avoid torque limited power in climb. Residual jet engine is accounted for in all mission segments, Hover takeoff/landing, climb, and cruise. Residual jet thrust depends on the generated power (HP), but the required SHP depends on the amount of residual thrust from the engine, decreasing the propeller thrust required and thereby decreasing shaft power required. This was modeled by an initial estimate of HP for zero jet thrust. The residual jet thrust was based on that, and a new HP required was calculated taking advantage of the residual jet thrust.

At 310 ktas cruise, Figure 5 shows that SHP required is less than HP available, and it is within maximum rated transmission limits.



Mission Calculations	Time (min)	Target Altitude	Density	Hover Vtip	GW at Start	Initial Est SHP	Residual Eng Thrus	Rotor Ct/sig	Rotor FM	Req'd SHP	Available max SHP
Warmup/Taxi	5.00	5000	0.001911	650	**93515**	16614	1129.7	0.148	0.774	16289.1	16289.1
Takeoff	2.00	5000	0.001911	650	92959		1129.7	0.147	0.775	16276.9	16289.1
Taxi+Takeoff Fuel								NASA =	0.7830		
		Climb Worksheets									
Climb to Cruise Altitude	Avg Altitude	w Index Airspeed	**Airspeed ktas**	RoC fpm	GW at Start	Time to climb (min	□ Distance nm	Thrust	Prop Eff.	Climb SHP	
Initial altitude . ft	0		for max R/C	**Vtip = 350.**						Xmsn limited	
Climb to 4,000. ft	2000	1	158.7	1871.2		214	5.3	18046	0.880	10467	
Climb to 8,000. ft	6000	1	168.4	1821.0		220	5.9	17086	0.885	10467	
Climb to 12,000. ft	10000	1	179.1	1763.9		227	6.5	16142	0.889	10467	
Climb to 16,000. ft	14000	1	190.7	1698.3		236	7.2	15210	0.892	10467	
Climb to 20,000. ft	18000	1	203.5	1622.6		247	8.1	14288	0.894	10467	
Climb to 25,000. ft	22500	1	219.6	1523.2		328	11.8	13263	0.895	10467	
Climb Fuel						14.71	44.9				
		Cruise Worksheets									
Cruise	Target Altitude	Distanc (nm)	Specified Airspeed	Airspeed best ktas	GW at Start	□ Time (hr)	L/D	Req'd Thrust	Prop Eff.	Req'd SHP	Avail SHP
		increments of 5 ktas					lookup	lookup	lookup	lookup	lookup
Cruise (Cruz-1)	25000	230.0	**310**	310.0		0.742	10.511	8743	0.848	9894	10982
Cruise (Cruz-2)	25000	230.0		310.0		0.742	10.425	8598	0.847	9753	10982
Cruise (Cruz-3)	25000	230.0		310.0		0.742	10.333	8459	0.846	9617	10982
Cruise (Cruz-4)	25000	265.1		310.0		0.855	10.237	8325	0.844	9486	10982
Cruise Fuel		#####				3.08					
ef values at 99%BR speed		230	Best nm/lb								
							lookup	lookup	lookup	lookup	lookup
Cruise 30 nm Alt Dest.	25000	30	Best nm/lb	215	82725	0.140	12.497	6620	0.809	5677.628	10467
Cruise 30 min Reserve Fue	Target Altitude	Distanc (nm)	Airspeed Criteria	Airspeed best ktas	GW at Start	□ Time (hr)	L/D	Req'd Thrust	Prop Eff.	Req'd SHP	Avail SHP
				lookup			lookup	lookup	lookup	lookup	lookup
Cruise (Cruz-5)	10000	84.5		169.0		0.500	12.352	6672	0.813	4488	10467
Descend to SL		No time, No range, No fuel									
Landing	**Time (min)**	Target Altitude	Density	Hover Vtip	GW at Start	Initial Est. SHP	Residual Eng Thrus	Rotor Ct/sig	Rotor FM	Req'd SHP	Available max SHP
	1.00	5000	0.001911	650		13388	889.1	0.129	0.782	13166.4	16289.1

Figure 5. Sample Analysis Worksheet

3.6.2 Component Weight Estimation

The NASA LCTR2 weights for Fixed Useful Load, Fixed Equipment, and Payload were kept fixed throughout the study. Resizing the LCTR2 required estimating changes in component structural weights due to dimensional changes of the wing and rotor, and drive system and engine weights due to the installed power. Those effects on the aircraft empty weight, plus changes in mission fuel required, resulted in a new aircraft gross weight as the aircraft was resized.

3.6.2.1 Engine System Weights

One significant difference between Boeing weight and NASA LCTR2 weight is the size and weight of primary engines. NASA assumed notional off-the-shelf engines of 7500 SHP class for each of the 4 LCTR2 engines, giving 30,000 SHP available takeoff power. About 19,000 SHP was required for LCTR2 hover at the SDGW of 107,124 lb, or about 23,400 SHP to hover at the max GW of 123,192 lb. While the installed SHP significantly exceeded that required for hover, NASA may have selected that size to maintain high altitude cruise with one engine inoperative (OEI), a factor not considered in this study. An oversized engine generally results in additional engine weight and requires more fuel as the engines would be operating at part power in the cruise condition.

Boeing sized LCTR2 engines only to the power required for hover at the standard-design gross weight (SDGW), 5000 ft altitude / ISA+20°C takeoff condition, or to cruise power, which ever was greater. Very few cases in this study were sized by cruise.

Dry weight of the four NASA LCTR2 engines was about 3150 lb, or 9.5 SHP/lb. That power-to-weight ratio is much higher than Rolls-Royce estimated for the 2015 or 2025 engines, but is close to their estimated value for the advanced VAATE technology in the 2035 time frame. Table 2 and Figure 6 show the Rolls-Royce projected dry engine weight and power-to-weight ratio for the 2015, 2025 and 2035 engines used in this study. They had generally lower SHP/lb than the NASA estimate, except for the 2035 FG-VSPT Rolls-Royce engine, which was quite close to the NASA value.

Table 2. Engine Dry Weights (Reference, Unscaled Engine)

Engine	Reference SHP Per Engine (MRP/SLS)	Engine Dry Weight	Dry Engine SHP /lb
2015 PD 627 (COTS)	8100 HP	1356 lb	5.97
2025 PD646	8088 HP	1556 lb	5.20
2035 VG-VSPT PD647	8088 HP	1020 lb	7.93
2035 FG-VSPT PD628	8086 HP	807 lb	10.00
NASA LCTR2	7500 HP	787 lb	9.52

A standard aircraft weight breakdown includes an Engine Systems weight, accounting for the engine's exhaust system, starting system and controls; and an Engine Section weight, accounting for the structure required to mount the engine and react shaft torque output. These two components tend to be functions of the dry engine weight, thereby compounding the influence of dry engine weight on vehicle empty weight, shown in Figure 7. Every pound of dry engine weight introduces 2.25 lb to aircraft empty weight, and an added pound of empty weight increases vehicle GW by roughly 2 pounds when resized. So each extra pound of dry engine weight compounds to add about 4.5 pounds to vehicle GW.

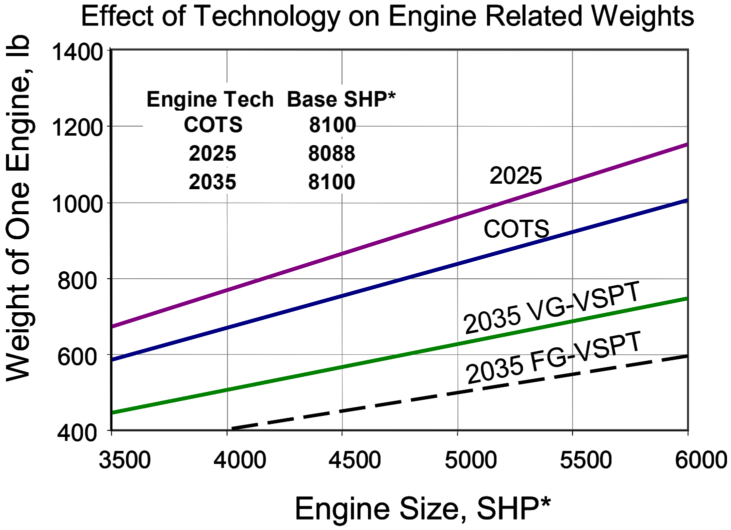


Figure 6. Effect of Technology on Dry Engine Weight Growth

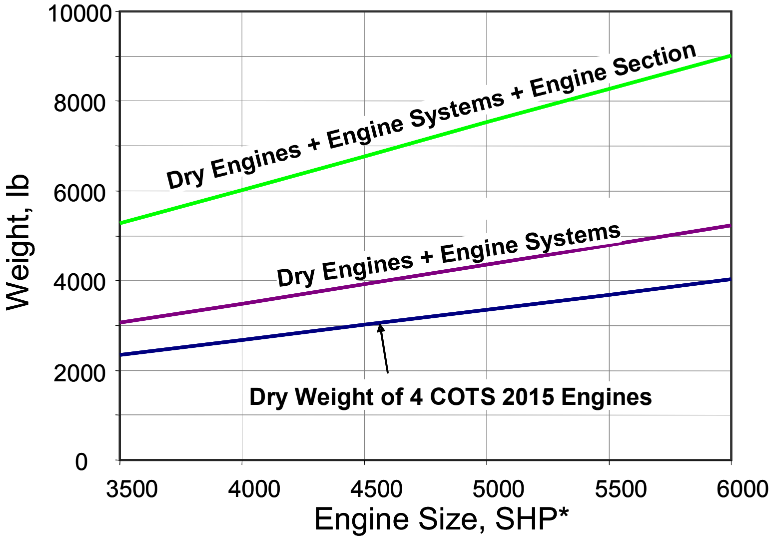


Figure 7. Weight Growth Impact of Installed SHP

3.6.2.2 System Level Weight Comparison

Boeing initially compared NASA LCTR2 component weights to Boeing in-house weight trends, for the structure, rotor, and drive system; using the NASA LCTR2 geometry and NASA weights for engines, engine systems, contingency weight, fixed useful load, fixed equipment and payload. Component weights were estimated without resizing the aircraft. Boeing's weight trends estimated the drive system to be 7% heavier than the NASA drive system weight. The rotor, wing, and landing gear weights were 4.7%, 15.4%, and 17.1% higher, respectively. However, these were compensated by a much lighter fuel system weight, resulting in only a 3.6% net increase in empty weight. These differences were chalked up to Boeing's parametric weight trends being based on different historical data from NASA's historical data, taking confidence in the relatively small difference in empty weight.

Basic drive system weight changed in accordance with both the RPM reduction and the year of technology to stay consistent with the engine technology. Drive system (efficiency) losses were estimated as a percent power loss for cruise operating conditions, which changed with both RPM reduction and technology level.

All structural weights were estimated at a 2025 technology level, to avoid any confusion about structural weight impact versus the primary objective of evaluating rotor cruise operating tip speed and the engine rpm versus drive system rpm reduction.

Supporting information can be found in Appendix D.

4.0 PROPULSION SYSTEM ASSESSMENT

4.1 Description of 2015 Technology Engine

A 2010 ‘design freeze' technology level was applied to the COTS (2015) engine, taking into account a product cycle that would result in a certified engine in the 2015 timeframe. The 2015 engine performance was provided in deck form, which allowed engine scaling for size and weight to arrive at an optimum engine size for a given mission and load. This engine was used to establish a baseline configuration. Figure 8 is representative of the 2015 COTS engine.

Figure 8. Representative Image of the EIS 2015 Engine

The engine configuration is axial core with a conventional compressor and cooled turbine, along with a free power turbine. The turbine in this turboshaft application is only driving a power output shaft and will therefore be referred to it as a power turbine, consistent with the helicopter world. The engine is flat rated to 109°F (42.8°C) at 7500 shp with the capability of increasing power by 20% during one engine inoperative (OEI) conditions.

The compressor has variable-geometry stators to allow satisfactory operation at off-design speeds. The power turbine matching was optimized to provide good efficiency between 80 and 100% speed. As such, the engine is well suited for a variable speed transmission/rotor system with operation down to a 77% shift point. When coupled with a fixed transmission gear ratio, there is an appreciable drop in performance at PT speeds below 77%, resulting in non-optimal performance at 54% PT speed due to the wide variation in power turbine inlet incidence angle, which occurs at significantly reduced power turbine speeds.

The Rolls-Royce PD627 2015 (COTS) baseline engine is a current technology turbofan engine core. The core consists of an advanced, highly loaded eight-stage axial compressor followed by an annular combustor and a high-work, single-stage high-pressure turbine. The power is directed to the front end through a shaft driven by a two-stage power turbine. The PD627 engine utilizes a fixed-geometry power turbine operated over the desired range of power turbine speeds, with 100% power turbine speed defined as 15,000 rpm. Delivered power is controlled by a dual full-authority digital engine control (FADEC) and torque sensing mechanism near the inlet. A substantiation of the 2015 engine component technologies is provided in Appendix C.

4.1.1 Analysis and Substantiation

Boeing conducted initial sizing with the Rolls-Royce PD627 2015 (COTS) engine at the LCTR2 rotor cruise tip speed of 350 fps, achieved by an advanced 2-speed drive system. Boeing extracted performance data from the Rolls-Royce supplied engine data and formatted it in tables and graphs. The COTS engine data accounted for inlet particle separator (IPS) and exhaust diffuser assumptions for hover operations. The same data format and analysis tools were used to model all three Rolls-Royce engines.

A comparison of power available from the NASA engine and the 2015 COTS engine is shown in Figure 9, where the COTS engine power has been adjusted to 7500 SHP takeoff power at SLS, the same as the NASA engine. The COTS engine shows a linear MRP lapse rate with altitude. The MRP lapse rate of the NASA engine was 77% of its SLS HP when operating at 5K'/ISA+20°C[9]. In contrast, the COTS engine develops 90.8% of its SLS HP when at 5K'/ISA+20°C. This is a significant difference given that the engine size was determined by that takeoff condition for most cases sized in this study.

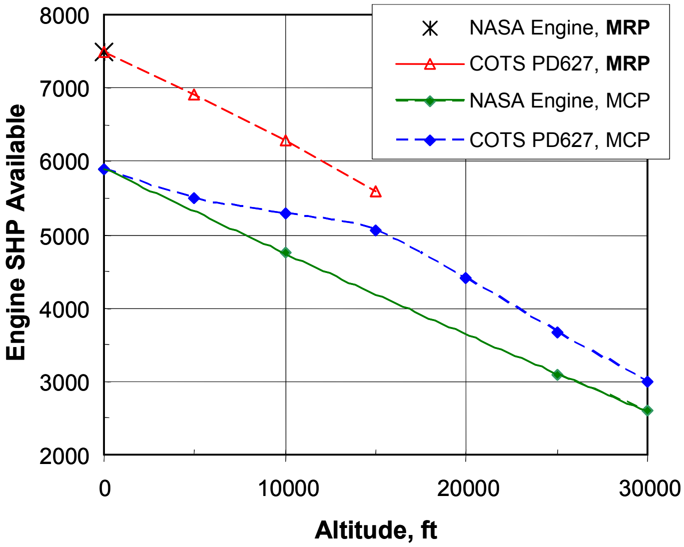


Figure 9. Compare NASA Engine SHP Available, Relative to PD627 (M=0)

The Rolls-Royce COTS engine also has roughly 20% more MCP cruise power available at cruise altitudes above 15,000 ft than the NASA engine, giving it a relative advantage for cruise sized cases. In fact, the increased cruise power available from the COTS engine is probably an underlying cause of the Boeing analysis sizing the engine for hover for most cases.

4.2 Evaluation of The 2025 Technology Engine

The 2025 engine, designated as PD646, utilizes the 2015 engine architecture with future technology insertion. The PD646 engine model consists of the baseline PD627 (2015) core, with turbine cooling and improved HP turbine materials to allow an increase in cycle temperatures, and a redesigned power turbine. The two-stage fixed-geometry power turbine in the PD627 engine has been replaced by a three-stage variable-geometry power turbine designed to provide better performance over the large range of power turbine speeds required for the LCTR2 mission trades. The power turbine design was influenced by the desire to maximize cruise performance at a reduced output shaft speed while minimizing any impact to the power available at takeoff and 100% shaft speed. The resulting design represents a compromise between these two requirements. The variable-geometry vanes will accommodate the wide variation in incidence associated with the change in rotor speed and improve SFC at the 54% low-speed, high power cruise condition.

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[9] Wayne Johnson, Gloria Yamauchi, Ames Research Center; Michael Watts, Langley Research Center; "NASA Heavy Lift Rotorcraft Systems Investigation", NASA/TP-2005-213467, December, 2005; Figure 8.

Maintaining a common core geometry makes it possible to directly compare the effects of technologies, such as variable turbine geometry, on overall aircraft performance, weight, and size. Turbine variability results in a slight decrease in turbine efficiency at takeoff. This affects engine power delivery for an OEI (hover) condition, and results in an increase in engine core size to recover power lost compared to the baseline 2015 engine, at a constant turbine inlet temperature. This would result in a significantly heavier engine, neutralizing any gains realized by the turbine variability. To account for this loss in power, a turbine temperature increase compatible with engine development over a 10-year period was introduced, so power output at the OEI ground hover condition was equal to the COTS engine, at the same physical core size. The 2025 engine variable turbine control system and mechanism does result in an increase in power plant system weight, which is accounted for in the aircraft studies.

The 2025 engine data were supplied to Boeing in tabular form, with scaling factors to allow performance, weight, and envelopes to be estimated across a broad power range. Three stage power turbine maps were developed, featuring variable-geometry stators on the second and third stage, for 100%, 77% and 54% rotor speed conditions. Base 100% (speed) turbine efficiency was calculated and compared to turbine efficiency at 54%, resulting in a 14.5% loss for a turbine with no variable geometry, and a 4 to 4-1/2% loss for a turbine with variable geometry, a significant improvement. The same turbine operating at 77% showed virtually no loss.

The turbine blades are designed to minimize the loss over a range of speeds but do not alter the incidence. As a result, the turbine design can be optimized at some point between 50 and 100% speed to allow for the best efficiency over the mission profile. These approaches have an adverse effect on efficiency at 100% speed but result in an appreciable overall improvement in efficiency over the bulk of the mission profile.

4.2.1 2025 Component Technologies

Rolls-Royce has previous design and development experience with variable turbine vanes systems. The variable vane arrangement envisioned for the PD646 power turbine is similar to the GMA800 variable HP vane stage that was tested by LibertyWorks on the XTE17/1 engine. The GMA800 provides a strong experience base that supports the design of the PD646 power turbine. Design elements demonstrated by this prior experience include:

- High temperature, low leakage seal systems
- High temperature vane support/bearing systems
- Actuation system materials and construction
- Actuator design and thermal management

4.3 Evaluation of EIS 2035 Technology Engines

The 2035 engine configuration is a significant departure from the two-shaft engine used in the baseline 2015 and derivative 2025 engines. A new, advanced core was assumed to be developed for the EIS 2035 engines. This advanced core compression would be accomplished in two spools, increasing maximum temperatures and pressures present in the cycle (versus the COTS and 2025 engines), but significantly improving engine efficiency and weight. The 2035 engine incorporates an advanced cycle featuring a higher overall pressure ratio (OPR) to deliver significant gains in efficiency with a reduced core size. The advantages associated with high OPR engine cycles are well understood, however, several challenges have limited the development of such engines. These challenges include: engine operability, component efficiencies sized for the resultant low exit flow rates, mechanical concerns at elevated compressor discharge temperatures, and increases in cooling flow also associated with high compressor exit temperatures. PD647 brings together a variety of Rolls-Royce and VAATE technologies to solve these issues. A summary of the advanced technology found in the PD647 design includes:

- Three-shaft (two spool) engine architecture
- Axial-centrifugal HP compressor with active clearance control
- Compact annular combustor
- Advanced HP turbine design featuring Lamilloy®[10] construction
- Counter-rotating vaneless IP turbine
- Cooled, cooling air technology
- Uncooled variable-geometry power turbine

Two versions of the advanced technology 2035 variable-speed power turbine (VSPT) engines models were constructed for this study, one with a variable-geometry turbine, referred to as VG-VSPT, the other with a fixed-geometry turbine, referred to as FG-VSPT.

4.3.1 Description of The 2035 Variable Geometry Engine (VG-VSPT)

The 2035 PD647 VG-VSPT engine shown in Figure 10 is an advanced cycle engine featuring a high overall pressure ratio (OPR) that delivers significant gains in efficiency and reduced core size. The aggressive OPR target of the 2035 engine resulted in a departure from the architecture employed in the 2015 and 2025 engines. To provide good operability and part power efficiency, the 2035 engine is a three-shaft design with Intermediate Pressure (IP) and High Pressure (HP) spools.

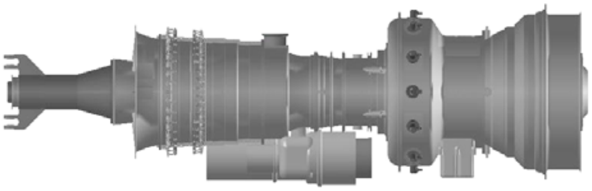

Figure 10. Representative Image of the EIS 2035 VG-VSPT Engine

The IP compressor is an all-axial configuration, while the HP compressor is an axial-centrifugal unit that has an appreciable efficiency benefit over an all-axial design given the low exit corrected flow rates produced by the high OPR cycle. Both the HP and IP turbines make full use of the advanced materials and cooling technologies based on projected technology maturation within this time period. The engine also embodies advanced controls and diagnostic technologies. As with the 2025 engine, power turbine (vane) variability was included to improve engine performance at the low speed (54%) cruise point. The 2035 engine data were also supplied in tabular form with scaling factors to provide engine data across the power spectrum.

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[10] Lamilloy is a registered trademark of Rolls-Royce Corporation

Engine performance data for both the 2025 and 2035 engines were generated using Rolls-Royce's mature and validated in-house engine performance analysis program Turbine Engine Reverse Modeling Aid Program (TERMAP) software. As such, component maps were generated that included Reynolds number effect tables to better model the altitude lapse rates. Additionally, the PT matching was selected to offer a compromise between performance at takeoff and at part speed for cruise conditions.

The Versatile Affordable Advanced Turbine Engine (VAATE) technologies reflected in the PD647 provided a significant weight reduction relative to the 2015 and the 2025 engines. But the variable-geometry power turbine feature that provided the excellent performance also carried a weight penalty.

Additional description of the TERMAP software and more details of the 2035 engine components can be found in Appendix C.

4.3.3 Description of The 2035 Fixed Geometry Engine (FG-VSPT)

NASA Glenn Research Center suggested that the study include 2035 VAATE technologies for a fixed-geometry, variable-speed power turbine (FG-VSPT) in this assessment. The core would be the same as the previous, advanced and high performance EIS 2035 VG-VSPT engine. For a typical aircraft mission, such an engine design would have a 3 stage power turbine, optimized for operation around 90 to 100% rpm and limited capability outside this range (much like the COTS engine). But due to recent VSPT research efforts[11], Rolls-Royce generated performance data for this engine assuming VSPT technology optimized around 90% rpm. This 2035 FG-VSPT design includes an extra power turbine stage that was used in the overall design to improve performance and operability over the variable speed range with only minimal additional weight and complexity. This PD628 FG-VSPT engine was rated at essentially the same max power at 100% RPM and sea level standard (SLS) conditions as the previous three engines. The fixed-geometry PD628 FG-VSPT engine weighs 213 lb less than the 2035 engine with variable geometry – a substantial 20% weight reduction. That was 40% lighter than the 2015 COTS engine.

Midway through the study, it was determined that an additional rotor cruise tip speed was required to better define the best rotor cruise tip speed. A tip speed of 422 fps was selected, between the existing 350 fps and 500 fps tip speeds, or about a 65% cruise RPM. An additional set of engine data was generated for this 2035 FG-VSPT engine at 65% RPM to support the analysis of the additional rotor cruise tip speed.

4.4 Engine Performance

Engine weight and performance characteristics directly affect aircraft sizing and operational costs. Mission fuel is calculated from the Rolls-Royce engine fuel flow data at the power required for each flight segment, including all segments in the mission analysis worksheet. Cruise segments are at the LCTR2 cruise altitude and airspeed (25,000 ft, 310 ktas) for all configurations, unless shown otherwise.

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[11] Ford, A., Bloxham, M., Turner, E. Clemens, E., and Gegg, S., "RTAPS VSPT Contract NNC10BA14B, Design Optimization of Incidence-Tolerant Blading Relevant to Large Civil Tilt-Rotor Power Turbine Applications," NASA/CR-2010-217016, Nov, 2010

Fuel flow collapsed well with altitude for distinct Mach numbers when plotted as referred fuel flow versus referred power, as will be shown later. To use the referred fuel flow curves, actual power required was divided by the product of engine scale factor * number of engines to correct back to a single reference engine, and data was interpolated between Mach number curves. The referred fuel flow returned was then multiplied by that product to estimate total fuel flow of the four scaled engines.

Residual jet thrust from the engine was provided by Rolls-Royce and was accounted for in all mission segments. Data collapsed well with altitude at distinct Mach numbers as a function of referred jet thrust and referred power. These curves were treated like the fuel flow model described above.

4.4.1 2015 Engine Performance

The Rolls-Royce 2015 COTS engine (PD627-MB-8B2-11510) has 8100 SHP static takeoff power available (Max Rated Power, MRP) at SLS. The power available versus altitude and Mach number are shown in Figure 11 through Figure 13. The figures show that only a small amount of power is lost for operations at 77% RPM, but significant power is lost at 54% RPM.

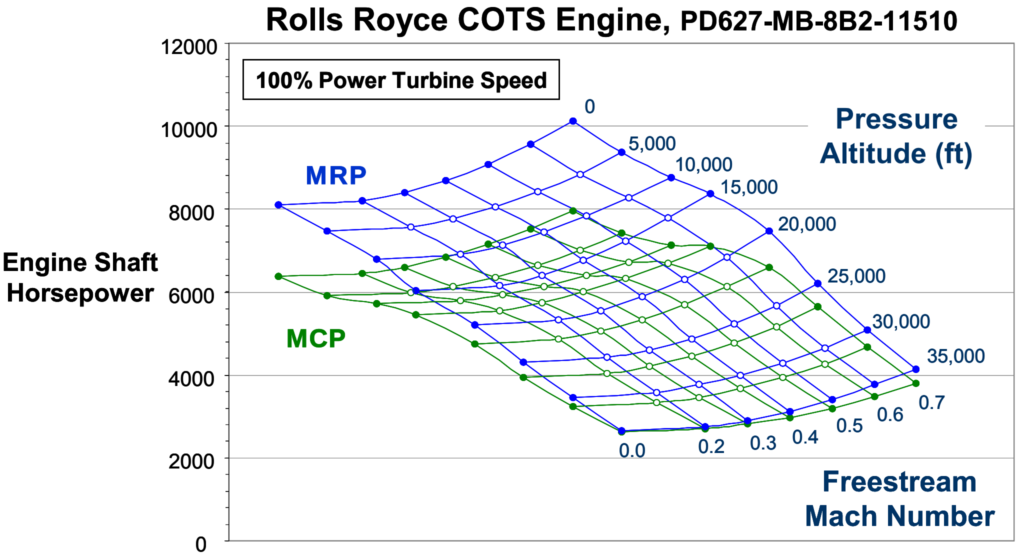

Figure 11. 2015 COTS Engine Power Available at 100% RPM

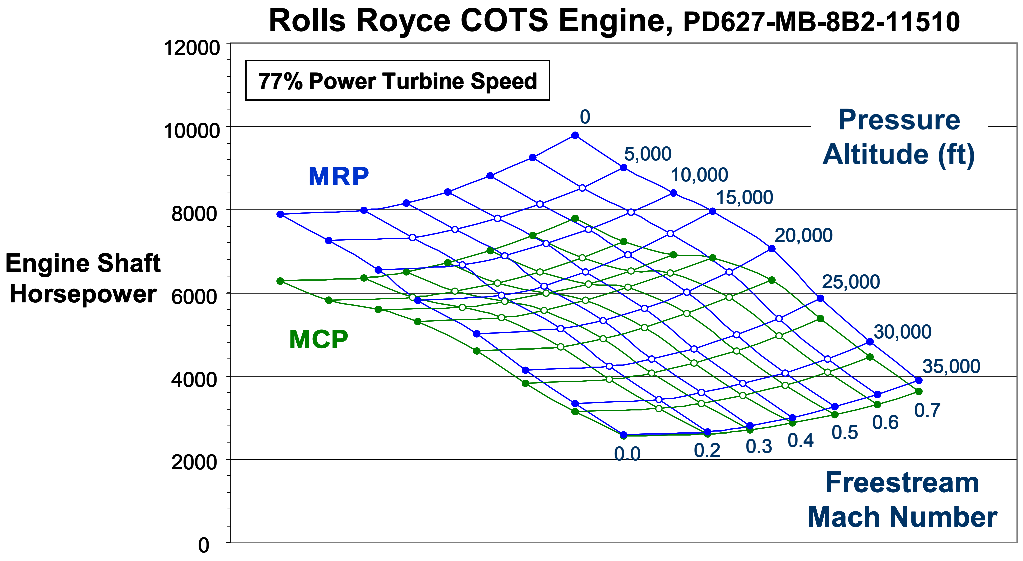

Figure 12. 2015 COTS Engine Power Available at 77% RPM

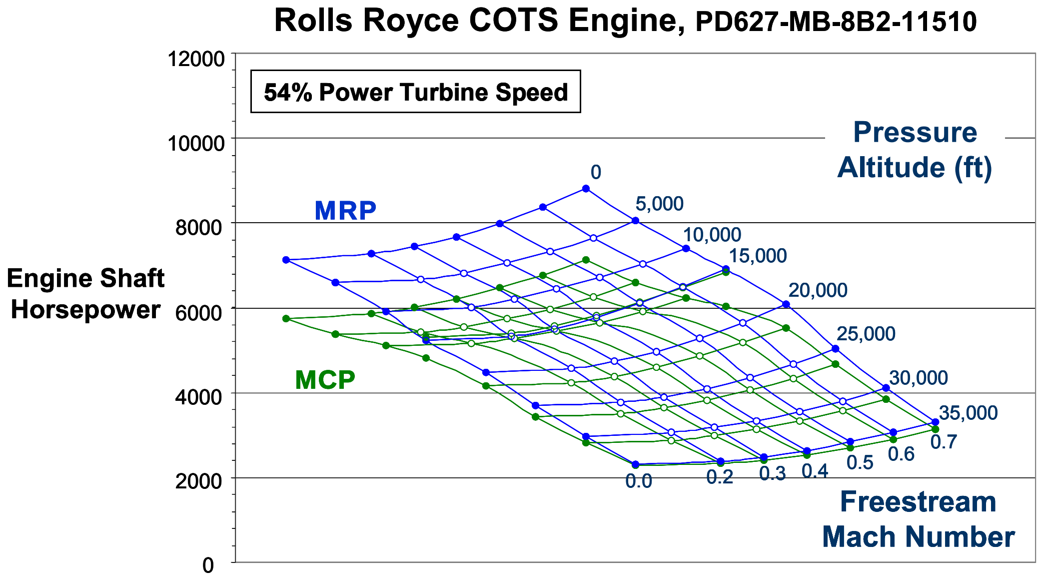

Figure 13. 2015 COTS Engine Power Available at 54% RPM

Fuel flow data collapsed well across all altitudes, for all engines, when expressed as referred fuel flow versus referred SHP, and was therefore easily modeled as functions of referred SHP and Mach number. Figure 14 shows a sample of the collapsed fuel flow data for the 2015 COTS engine at a Mach number of 0.4 and 100% RPM.

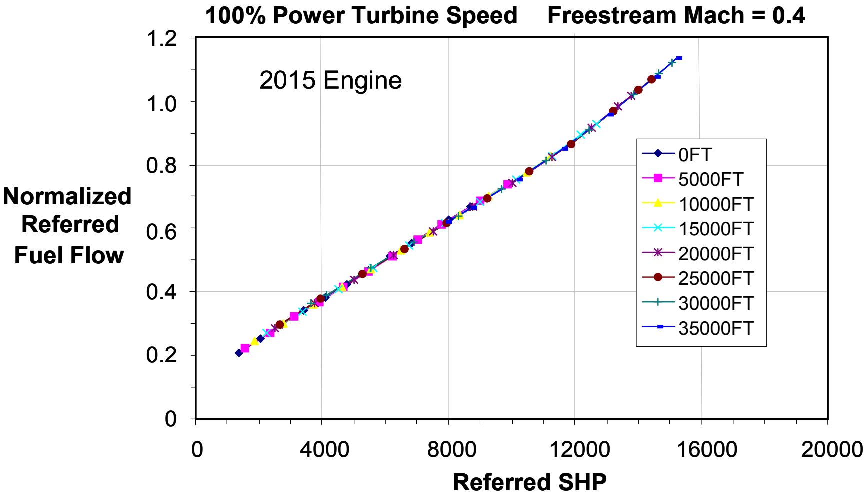

Figure 14. Referred Fuel Flow versus SHP

Residual jet thrust from the engine was also accounted for in all mission segments, using Rolls-Royce data as a function of altitude, Mach, and engine SHP. The engine scale factor from the sizing case was also applied. Figure 15 shows the collapsed net residual jet thrust from the COTS engine for Mach=0 (takeoff) and at Mach=0.3.

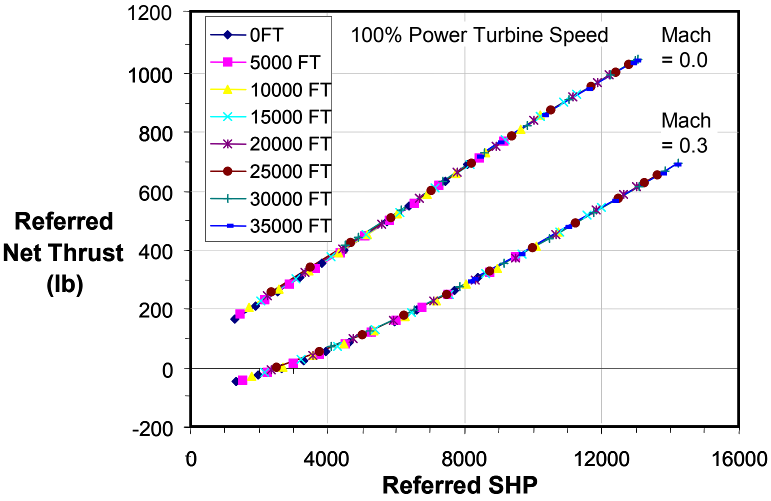

Figure 15. Referred Net Jet Thrust for the COTS Engine At 100% RPM

4.4.2 2025 Engine Performance

The reference takeoff power available from the Rolls-Royce 2025 engine (PD646-11751) was essentially the same as for the 2015 engine (8088 HP vs. 8100 HP MRP at SLS). Graphs of power available versus altitude and Mach number for this engine are shown in Figure 16 through Figure 18. Relatively little difference is seen at 100% RPM MRP, compared to the 2015 engine. However, the 2025 engine provided significantly more power than the 2015 engine at reduced RPM. For instance, at 77% RPM the 2025 engine has 13% more MRP takeoff power than at 100% RPM, but the 2015 engine lost nearly 3% power (at SLS). That is a net gain of nearly 15% in takeoff power (MRP) for the 2025 engine relative to the 2015 engine. At cruise conditions (25,000 ft, Mach 0.5, 77% RPM) the 2025 engine has 10.7% more power available. The performance improvement due to the variable-geometry PT design came at the expense of a 200 lb weight increase per engine (800 lb for the aircraft).

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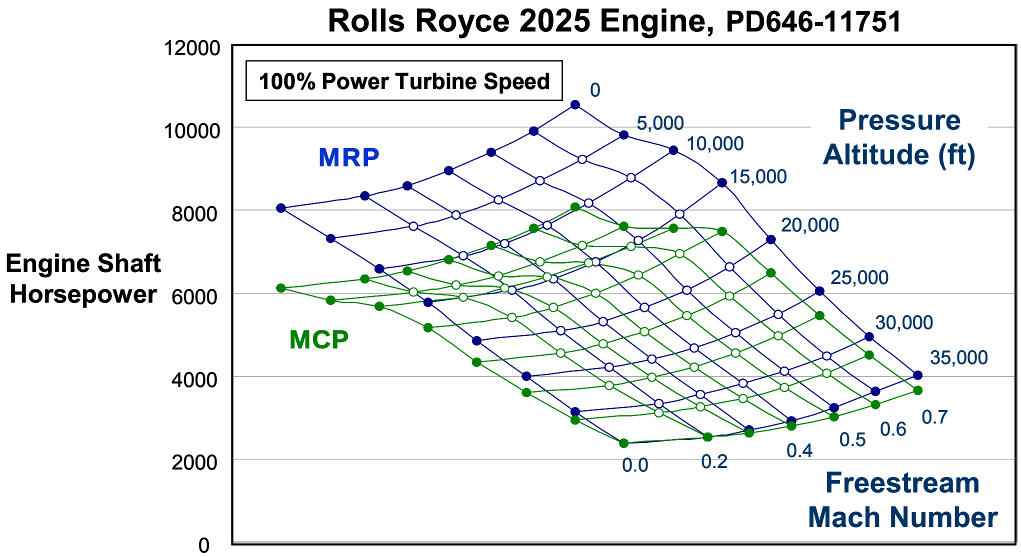

Figure 16. 2025 EIS Engine Power Available at 100% RPM

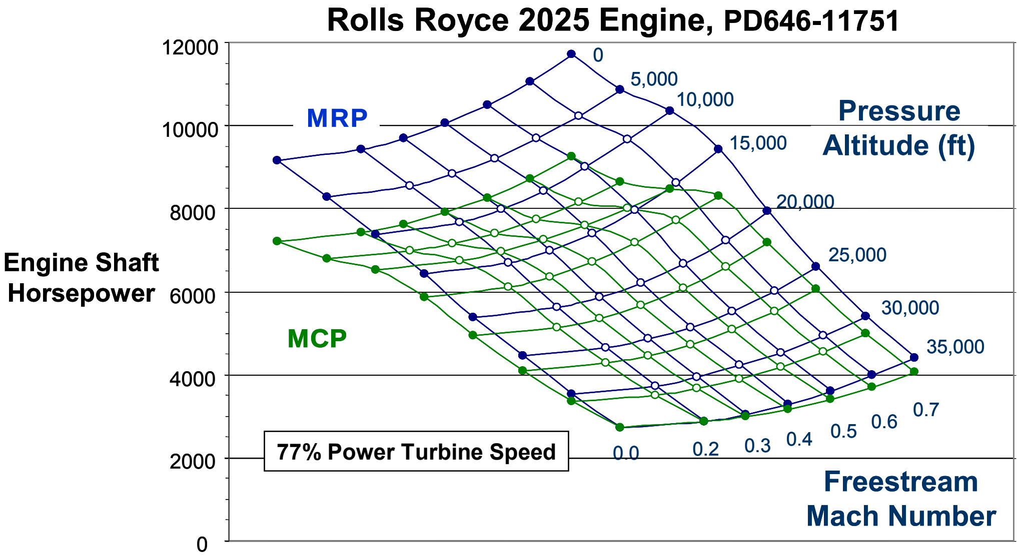

Figure 17. 2025 EIS Engine Power Available at 77% RPM

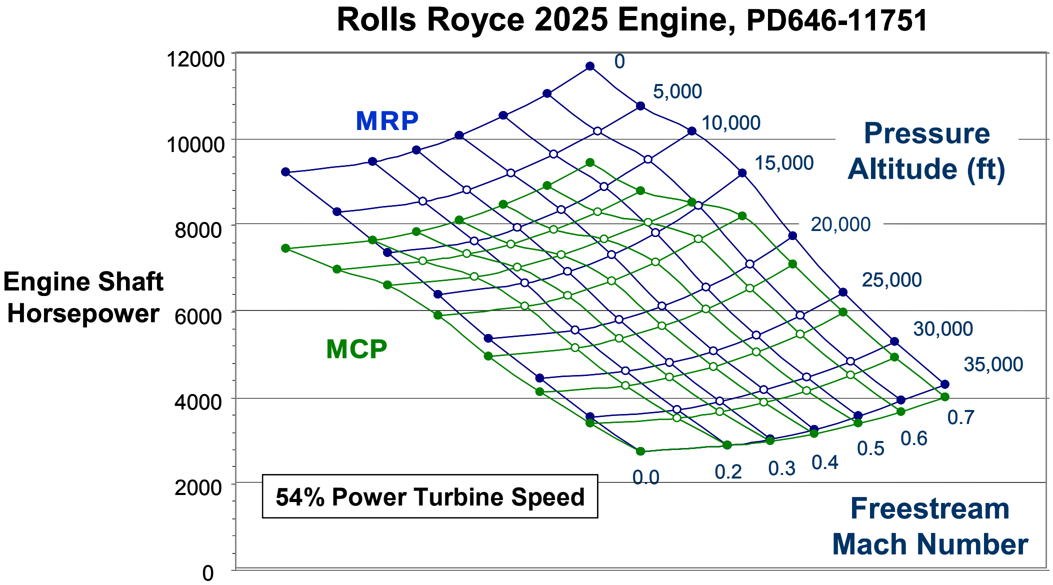

Figure 18. 2025 EIS Engine Power Available at 54% RPM

The 2025 engine provides far more power than the 2015 COTS when operating at 54% RPM. At that cruise condition (25,000 ft, Mach 0.5, 54% RPM) the 2025 engine has 23.6% more power available than the COTS, which was a great advantage when resizing the aircraft.

Furthermore, the 2025 EIS engine had 13.7% more takeoff power (MRP) at 54% RPM than it did at 100% RPM, in contrast to the COTS engine 12% power loss. Thus, at 54% RPM, the 2025 engine MRP takeoff power at SLS was 29% more than the COTS engine, for the same RPM.

4.4.3 2035 VG-VSPT Engine Performance

The Rolls-Royce 2035 EIS variable-geometry, variable-speed engine (PD647-11772) also delivered 8100 SHP MRP at SLS. Advanced Versatile Affordable Advanced Turbine Engines (VAATE) technology was applied to project future capability in this design.

Graphs of power available versus altitude and Mach number for this engine are shown in Figure 19 through Figure 21. At takeoff power, SLS, the 2035 engine has essentially the same SHP as the 2015 engine, 8088 SHP and 8100 SHP respectively. But the 2035 engine has a better lapse rate, such that at 15,000 ft the MRP is about 10% more than the 2015 engine. And the engine performance improves at reduced RPM. At 77% RPM the 2035 engine produces 10.6% more takeoff (MRP) power than at 100% RPM, and at 54% RPM it produces 15% more takeoff power than at 100% RPM. While the study shows more power at these conditions, in an actual application, torque limits may limit the available power at the part-speed conditions to less than the 100% speed cases for hover applications. The degree of that torque limit would depend on the application.

At cruise conditions (25,000 ft cruise altitude, Mach 0.5) the advanced 2035 engine provides 3.6% more MCP power than the COTS engine at 100% RPM , 16% more MCP power at 77% RPM, and 33% more MCP power at 54% RPM. It is 25% lighter than the 2015 COTS engine and 34% lighter than the 2025 EIS engine.

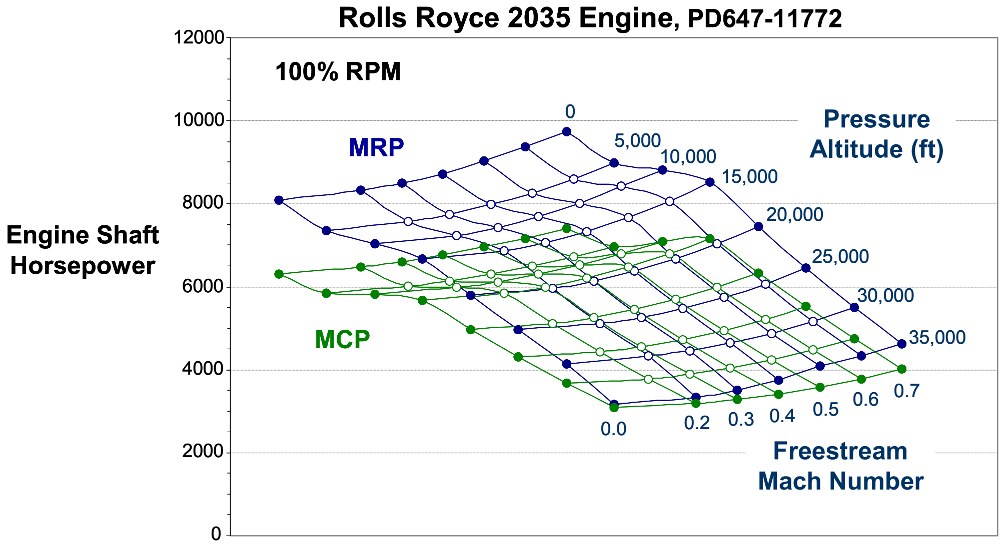

Figure 19. 2035 VG-VSPT Engine Power Available at 100% RPM

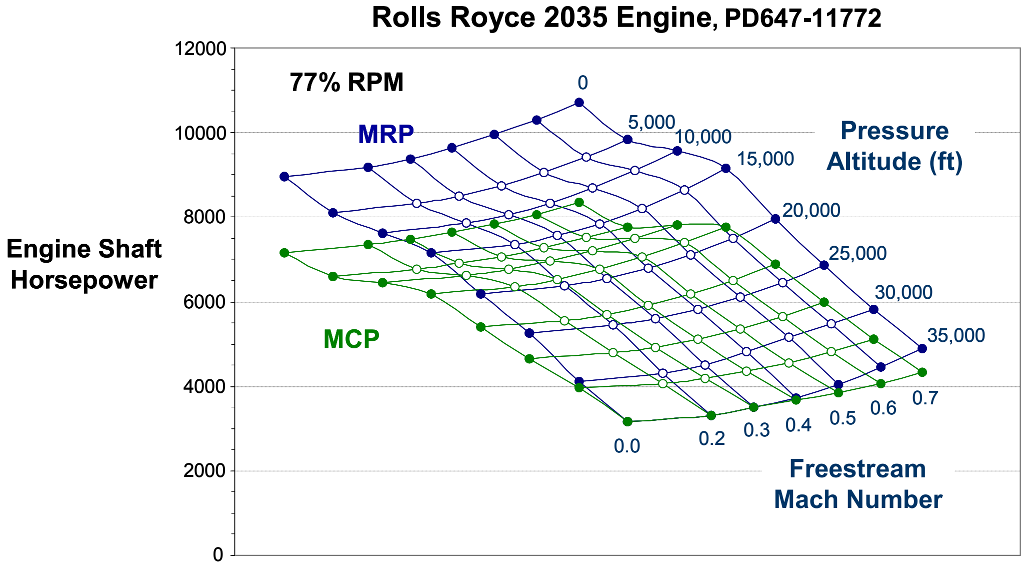

Figure 20. 2035 VG-VSPT Engine Power Available at 77% RPM

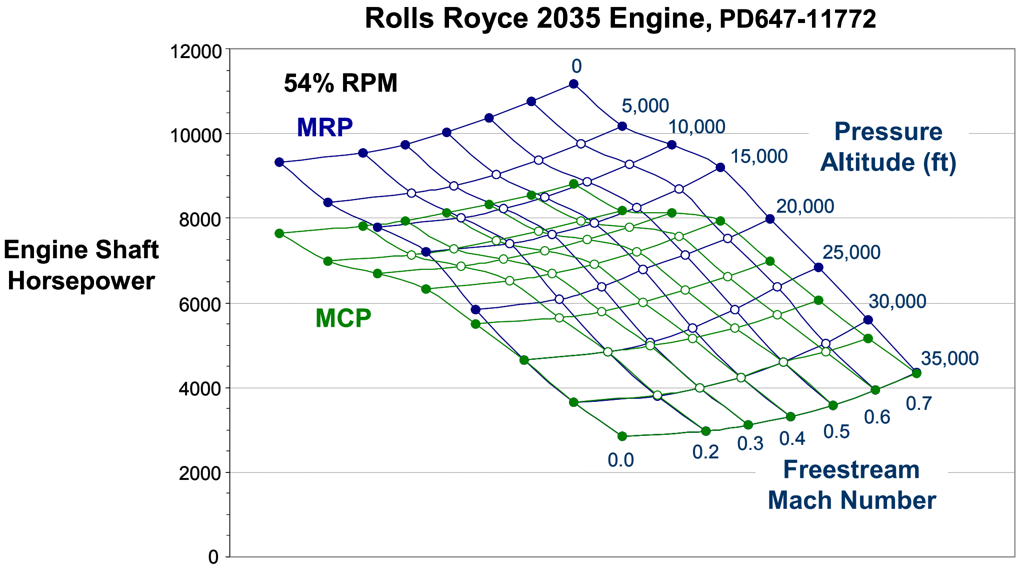

Figure 21. 2035 VG-VSPT Engine Power Available at 54% RPM

4.4.4 2035 FG-VSPT Engine Performance

The Rolls-Royce 2035 fixed-geometry power turbine engine (FG-VSPT), designated PD628-25233, also delivered 8100 SHP MRP at SLS. Advanced Versatile Affordable Advanced Turbine Engines (VAATE) technology was applied to project future capability in this design.

Graphs of power available versus altitude and Mach number for this engine are shown in Figure 22 through Figure 25. This engine was about 20% lighter than the 2035 VG-VSPT, making it the most attractive in terms of aircraft empty weight, but it did not develop as much cruise power as the 2035 VG-VSPT engine, presented above. Available MCP SHP at 54% RPM, Mach 0.5, 25,000 ft was about 4500 HP compared to 5500 HP for the variable geometry version. However, that loss of cruise power did not diminish the benefit of the FG-VSPT, since the LCTR2 engine was sized by hover power demand, not by cruise. That result could be different for a higher airspeed design demanding more cruise horsepower, or for an aircraft with higher cruise drag.

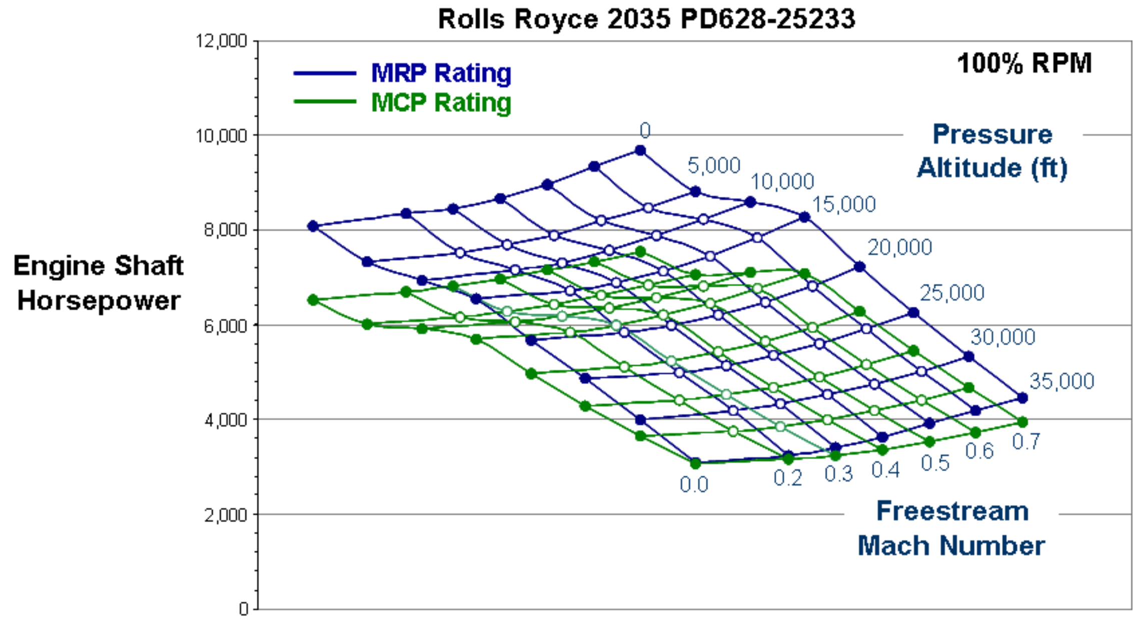

Figure 22. 2035 FG-VSPT Engine Power Available at 100% RPM

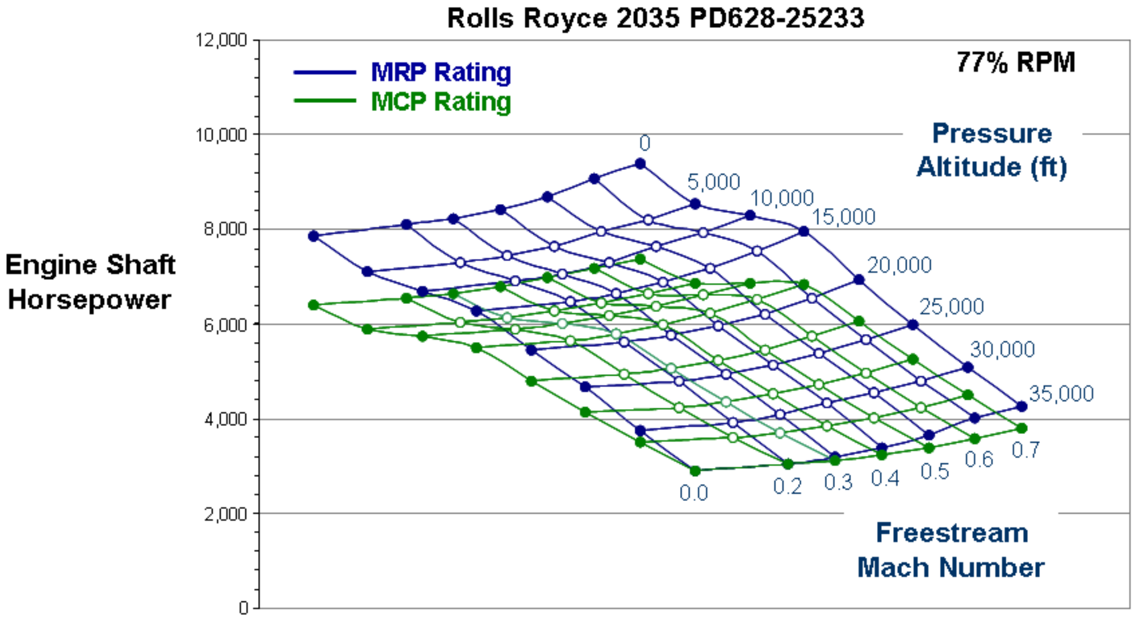

Figure 23. 2035 FG-VSPT Engine Power Available at 77% RPM

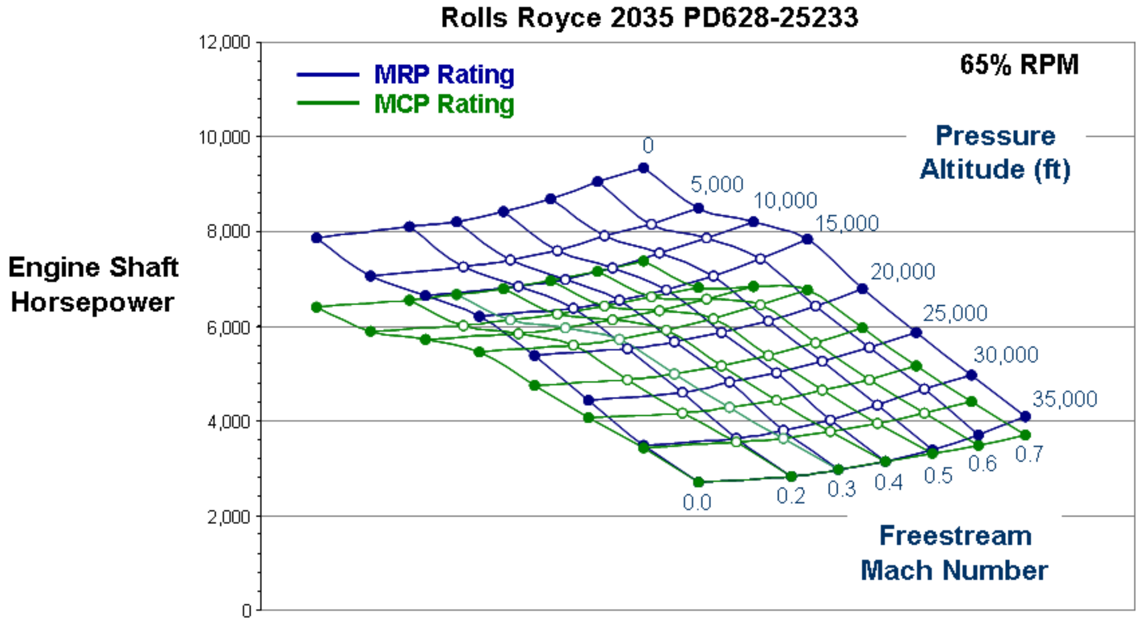

Figure 24. 2035 FG-VSPT Engine Power Available at 65% RPM

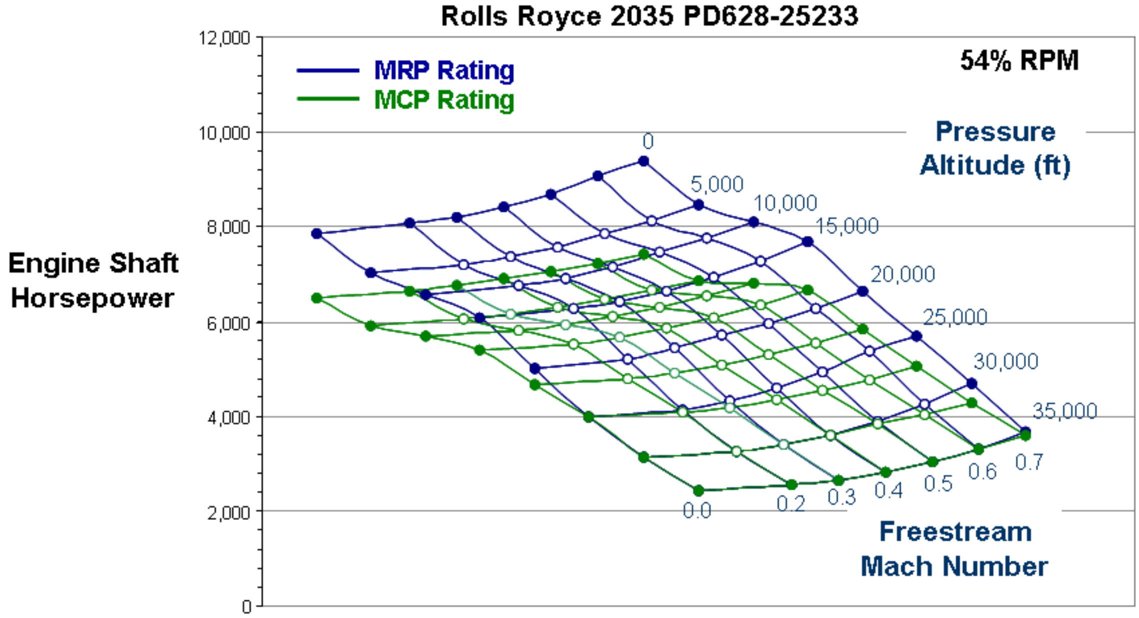

Figure 25. 2035 FG-VSPT Engine Power Available at 54% RPM

4.5 Engine Cruise Power Available

The 2025 and 2035 VG-VSPT engines were intentionally designed to perform better at reduced cruise operating RPM than the reference 2015 engine. They progressively achieved that goal, both in terms of fuel flow and in terms of cruise power available.

Figure 26 graphs the ratio of cruise MCP power available at 25,000 ft and Mach 0.5 (300 ktas) to the MRP power at SLS. At that cruise condition the 2015 engine had only 45% of its MRP at SLS. The 2025 and 2035 VG-VSPT engines regained much of that lost power, actually achieving more power at the 54% RPM cruise condition than at normal 100% RPM. And the 2035 VG-VSPT engine weighed 25% less than the 2015 engine.

Contrarily, the goal of the 2035 FG-VSPT engine was to examine the trade-off of further reduced engine weight while taking a compromise on fuel flow and cruise power available below about 80% RPM. The turned out to be the best match for the LCTR2 aircraft, providing sufficient cruise power with the lightest engine weight. It was near the boundary, where any less cruise power available would have resulted in larger, less optimum engines, being sized by cruise rather than by hover.

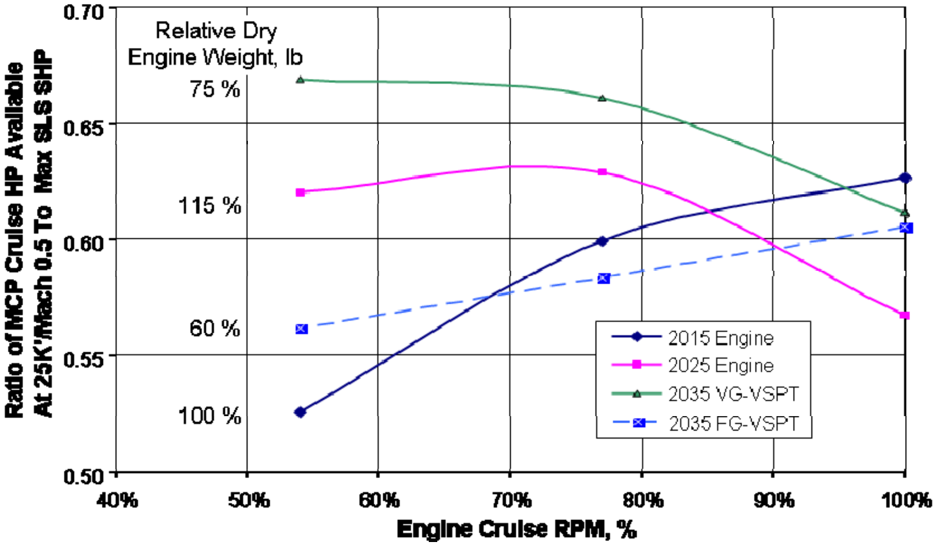

Figure 26. Fraction of Cruise SHP Available

4.6 Propulsion System One-Engine-Inoperative

Initial sizing was conducted with the 2015 COTS engine at the LCTR2 rotor cruise tip speed of 350 fps, achieved by an advanced 2-speed drive system at 100% engine rpm.

The NASA OEI criteria for LCTR2 was adopted for this study, specifically to achieve 90% of the HOGE power required with one engine inoperative and the remaining three engines operating at a 20% contingency power rating. Numerically, this requires;

OEI HP = 0.90 HOGE HP = 1.2*(4-1)/4 * SHPmax

This takeoff condition of 5K/ISA+20°C sized the engine for most sizing cases, so engine power available at that condition sizes the engine and therefore the engine weight.

4.7 Comparison of NASA Engine to Rolls-Royce 2015 Engine

NASA documentation showed the engine MRP takeoff power available at 5K/ISA+20°C to be 77% of max takeoff power available at SLS (see reference 1). Therefore the installed HP at SLS must then be at least 1.30 (1.0/0.77) times the HOGE power required at 5K/ISA+20°C. For comparison, the Rolls-Royce COTS engine takeoff power available at 5K/ISA+20°C is 0.908 of the max SLS takeoff power, and the other three engines had essentially the same ratio. So the installed HP of the Rolls-Royce engines in this Boeing study need only be 1.10 times the power required to hover at 5K/ISA+20°C. Thus, the installed MRP of the engines in this study can be

85% of the NASA installed MRP (1.10/1.30), for the same high/hot takeoff power as the NASA engine, which is an immediate weight savings.

The NASA LCTR2 engine weighed 0.105 lb/max SHP at SLS based on 7500 SHP max power available at SLS, whereas the 2015 COTS engine weighed 0.1674 lb/max SHP, i.e. the 2015 COTS engine weighs nearly 60% more than the NASA LCTR2 engine at the same installed SHP. That difference in dry engine weight is amplified by a factor of 2.3 during sizing since the weight of Engine Systems and the structural Engine Section are both functions of the basic engine weight.

A direct comparison of the NASA LCTR2 engine MCP power available and the COTS engine MCP power available can be seen by comparing Table 3 to Table 4. The COTS engine data in Table 4 was scaled to that of the NASA engine for this comparison; 7500 SHP MRP at SLS. At cruise altitude and airspeed (25K/ISA, 300 ktas), the COTS engine has 7% more MCP power than the NASA engine, nearly the same power at 10K/ISA, and 11% less power at SLS. Obviously, the two engines have significantly different lapse rates.

Table 3. NASA Engine Power Available

MCP Power Available (100% Np)

Airspeed KTAS	SLS	5k/ISA+20	10k/ISA	25k/ISA	30k/ISA
0	5,896	4,420	4,743	3,089	2,605
50	5,922	4,438	4,763	3,103	2,618
100	5,997	4,495	4,824	3,146	2,657
150	6,125	4,590	4,926	3,219	2,723
200	6,307	4,726	5,071	3,323	2,817
250	6,547	4,905	5,263	3,459	2,942
300	6,850	5,130	5,504	3,632	3,100
350	7,220	5,407	5,800	3,843	3,294

Table 4. COTS 2015 Engine Power Available

MCP Power Available per Engine (Scaled to 7500 SHP*)

Airspeed KTAS	SLS	5K/ISA+20C	10K/ISA	25K/ISA	30K/ISA
0	5,900	5,487	5,296	3,657	3,005
50	5,916	5,501	5,311	3,679	3,023
100	5,931	5,514	5,326	3,701	3,041
150	5,947	5,527	5,341	3,722	3,059
200	5,963	5,541	5,356	3,744	3,078
250	6,006	5,575	5,405	3,817	3,143
300	6,072	5,636	5,469	3,894	3,208
350	6,148	5,702	5,546	4,002	3,303

5.0 DRIVE SYSTEM ASSESSMENT

5.1 Evaluation of 2015 (Current) Technology Drive Systems

5.1.1 Concepts

As noted in Section 2.2, the LCTR2 configuration is a high wing, tilting nacelle aircraft that is similar to the V-22 Osprey in many respects. There are obvious differences between the V-22 and the subject LCTR2; the major difference is that the LCTR2 will be a four engine configuration, which affects the complexity and power ratings for OEI operation. Other characteristics of the tilting LCTR2 nacelle that affect the propulsion and drive systems are the rotor load path and the weight distribution. As in the V-22, rotor shaft loads must be reacted into gearbox housing and into efficient structure that is supported from the nacelle pivot axis. The back or base of the Proprotor Gearbox is anchored to structure for the load reaction. Engines are located in back of, and away from the Proprotor box center axis (assume that the nacelle is in a horizontal cruise position for these spatial references). Locating engines aft of the nacelle pivot axis balances some of the rotor system mass and limits CG shift when the nacelle transitions from hover to cruise and back. The effect of these constraints is to limit the number of practical propulsion system arrangements that exist for tilting engine aircraft. The initial investigation considered approximately 10 potential drive system variations. Figure 27 for example, shows an approach to the proprotor gearbox that uses spiral bevel gears instead of helical idlers to transfer engine power to the rotor drive planetary gears.

Figure 28 presents a schematic that appears to be the lightest solution for the LCTR2 configuration from the group of basic arrangements studied. For comparison, a direct drive configuration was developed as shown in Figure 29 that would be used with ‘large speed variation’ engine configurations.

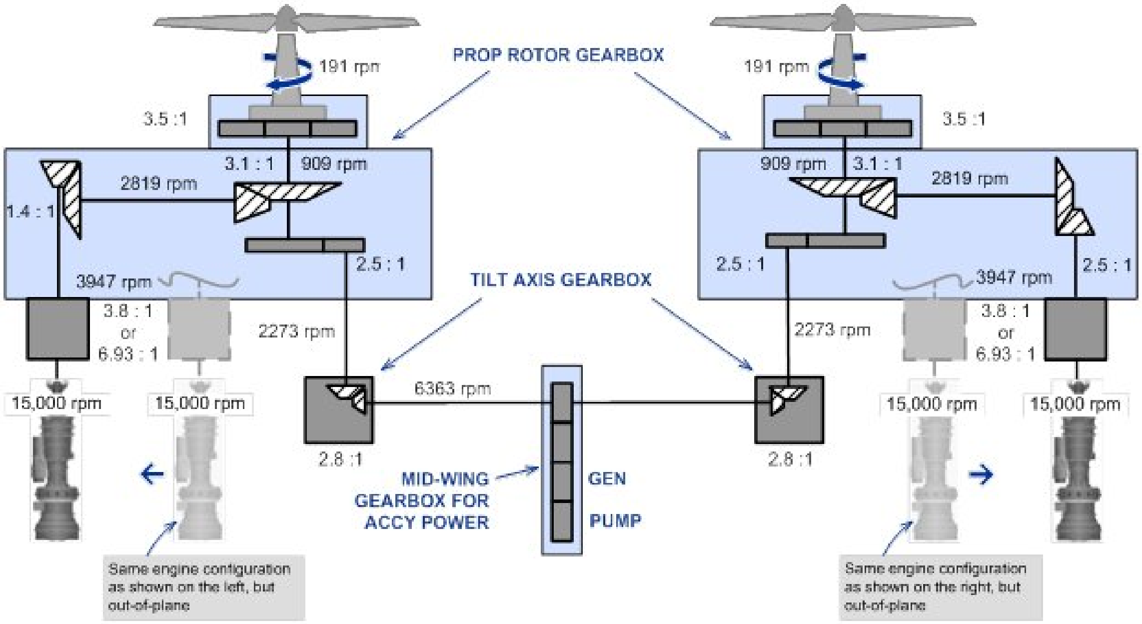

Figure 27. LCTR2 2-Speed Drive System Schematic Diagram with Spiral Bevel gears

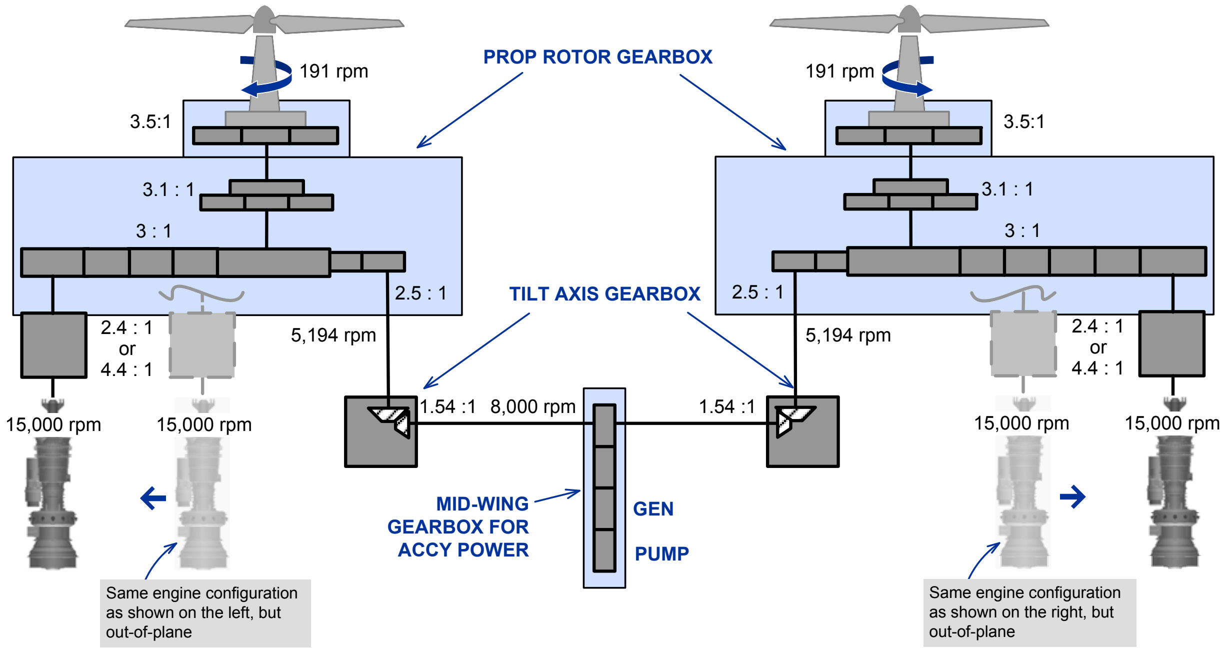

Figure 28. LCTR2 2 Speed Drive System Schematic Diagram with Helical Idler gears

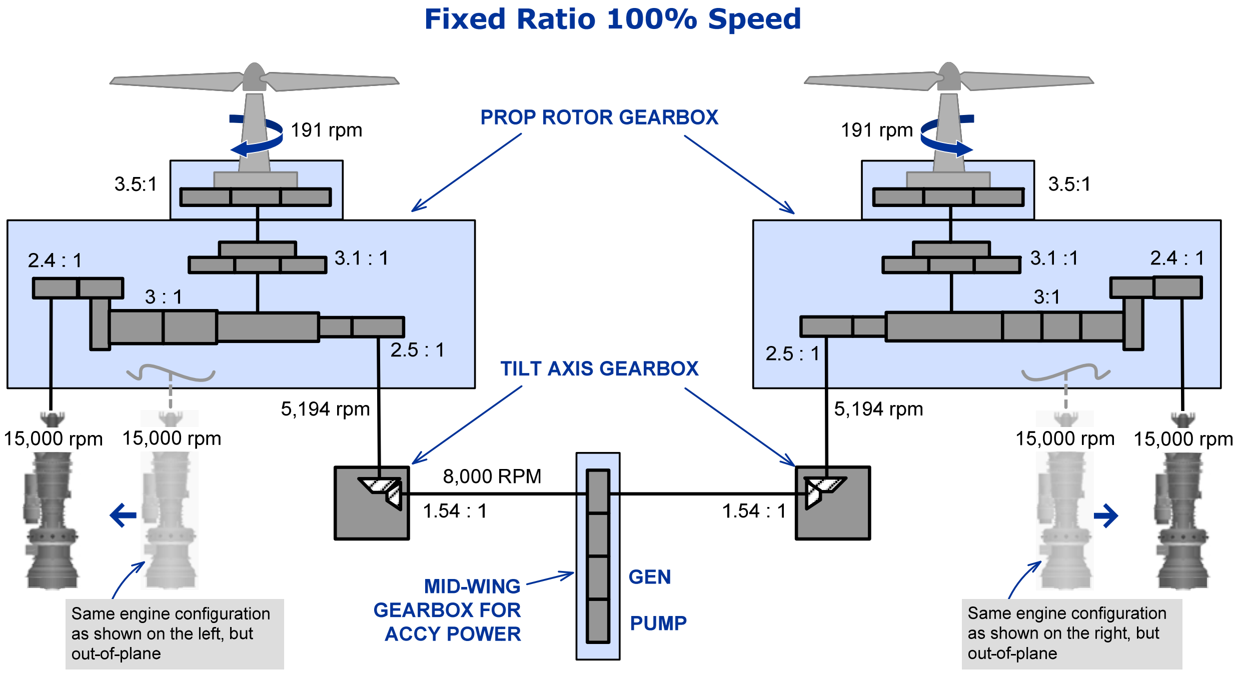

Figure 29. LCTR2 Single Speed Direct Drive System Schematic Diagram with Helical Gears

Characteristics of the study configurations include:

- Speed changing gearboxes are located in the high speed portion of the drive train to minimize weight impacts for those devices. Engine input speed is based on a maximum of 15,000 RPM for all engines.
- Helical Idler geartrain is used to transfer power from engines to Bull Gear, Planetary Systems and Rotor Shaft.
- Output Planetary System reduction ratios are moderate to low to allow for a rotor shaft that extends through the gearbox and is supported by a bearing in the base of the Proprotor Gearbox, similar to the V-22.
- Recognized need for a Mid Wing gearbox to provide auxiliary power to wing and tail control surfaces and cabin environmental and electrical requirements.
- Potential location for the over-running clutch is after the speed changing gearbox so that a failure in the engine or speed changing gearbox can be isolated from the remaining functional propulsion system.

The LCTR2 four-engine configuration may appear to be more complex than a two engine tiltrotor configuration but the four engine configuration has some distinct advantages. In the event of an engine failure, the OEI power available from the remaining engines is only marginally less than with ‘all engines operating’ (AEO) and the power transfer through the wing shafting is assumed to be less in this study. This results in a lighter weight wing shaft system. There are also perceived benefits in the speed changing mechanisms, even though there are more speed changing boxes needed. With this distributed system, it may be easier to implement a (modified) sequential shifting strategy similar to the method described in NASA Report TM 2007-214842 [12].

5.1.2 Changing Gear Ratios

Changing Gear Ratios during operation for a 2-speed discrete ratio device presents some technical challenges that include managing the transient loads during a ratio change. The rotor speed reduction procedure is notionally described as follows:

- At designated conditions (forward flight velocity and altitude) the rotor speed is reduced to near the desired rotor speed condition (54%, or 77%) by varying engine speed (all engines). This presumes that engine configurations can support this flight condition without stall or damage.
- Automated controls reduce the power to engine #1, the first engine to transition to high speed (low gear reduction ratio). Clutch mechanisms actuate the speed changer and the engine speed is raised smoothly to the maximum transition speed as the rotor speed is held constant. This operation is conducted at low power but is also controlled to a speed and clutch pressure profile to minimize heat generation.
- Engine power is raised on this engine and stabilized at the higher engine operating speed.

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[12] Litt, Johathan S. Edwards Jason M, DeCastro, Jonathan A., A Sequential Shifting Algorithm for Variable Speed Control”, NASA Report TM 2007-214842, June 2007

- The sequence is repeated on the remaining engines, one engine at a time until all engines are operating at 100% normal speed while the rotor remains at part speed.

In contrast, to increase the speed of the rotor from a reduced speed, each engine and gearbox pair are sequentially shifted to a lower speed while the rotor speed remains constant. After all engines are shifted to the lower speed, then the rotor speed is increased by raising the engine speeds and entire propulsion system in unison.

A study was conducted to establish a practical approach for the multi-speed mechanism. Literature searches yielded information about variable speed transmission systems that were primarily traction drives. Friction based variable speed transmissions have limitations in load capability, slippage or creep under load, and would be heavier than 2 speed transmissions, and may not be practical for rotorcraft applications. This study will not develop a complete assessment for variable speed transmissions due to budget constraints and scope limitations. Discrete ratio, 2 speed transmissions have been studied for rotorcraft by various groups and a working configuration was recently developed for the A160 Hummingbird, which is currently in development. Numerous speed changes have been accomplished as a part of flight test operations, demonstrating that a multispeed rotorcraft drive system is practical, at least in the UAV size range. The A160 transmission uses a compound planetary arrangement with a wet multi-disc clutch to accomplish speed changes. Similar arrangements were suggested in the NASA sponsored study described in report CR-2002-211564 [13]. Relevant concepts were also discussed in CR-2002-211563 [14], and in TM-2008-215276 [15]. The current study is not intended to be an exhaustive treatise on drive system or propulsion system concepts and technologies, but rather examines the integration and optimization of appropriate configurations for an LCTR2 scaled aircraft. Criteria used to evaluate potential multi-speed transmissions in this study include the following.

- The desired speed shifting range is 54% which corresponds to the rotor tip speed reduction from 650 fps to 350 fps. Additional reduction ranges of 70% and 77% were defined to provide a mid-range data point in the study at 400 fps rotor speed. In this report the ratio between low and high speed reduction ranges will be referred to as the "speed change ratio", which is the 54% or 77% goals noted above.
- Overall reduction ratios for the speed changing unit must be kept low to reduce the weight in the remainder of the drive system components. For example, it is preferable to have a speed changing module that varies between a ratio of 2 and 4 than a module that varies between 4 and 8. This is particularly true with the series of helical idler gears that are located in the PropRotor Gearbox, since a high reduction ratio speed changing module would present a larger torque to this train and each gear weight would increase.
- Configurations must be practical within near term technology advancements, considering typical load and speed capabilities of bearings, gears, and clutch elements.

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[13] Jules Kish, "Vertical Lift Drive System Concept Studies Variable Speed/ Two Speed Transmissions", NASA CR-2002-211564, June 2002

[14] Robert Bossler, "Vertical Lift Drive System Concept Studies", NASA CR-2002-211563, June 2002

[15] Stevens, Mark A., Handschuh, Robert, and Lewicki, David G. "Concepts for Variable/ Multi-Speed Rotorcraft Drive System", TM-2008-215276, September 2008

- Transitions must be able to occur under loaded conditions without exaggerated dynamic effects.
- It is desirable to keep gears and bearings in motion during all modes of operation to generate hydrodynamic film in loaded members, eliminating configurations where gears and bearings get “locked out”, or locked in a static position relative to mating gears, during operation.
- Simplicity of operation and reduced complexity translates into lower weight and higher reliability.
- Heat generation in clutch elements can be mitigated by operational procedures and should not be the most heavily weighted factor in configuration selections.

To meet the above criteria, the speed changing mechanisms considered in this study were based on compound planetary systems that can be enabled with one control input. Either a ring gear or carrier is restrained by an active (multiple disk) clutch, causing the gear ratios to change. Figure 30 shows a schematic arrangement ‘Configuration B’ that proved favorable for weight and operating characteristics. This configuration was practical for a large ratio change while maintaining a lower overall reduction ratio. Planet speeds were considered reasonable and this configuration worked well with the full LCTR2 drive system as shown in previous diagrams.

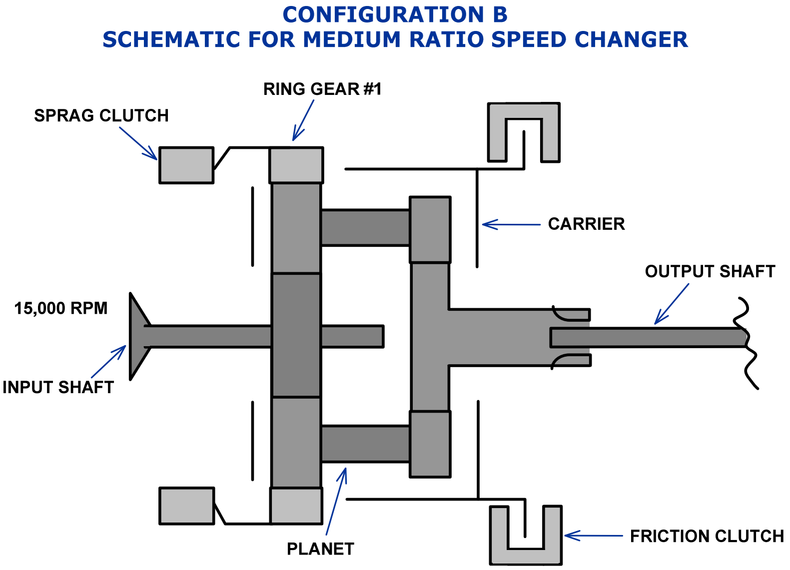

Figure 30. Speed Changing Planetary Schematic.

Characteristics include:

- The direction of load reverses for control input, either the carrier or the ring gear, depending on relative sizing of gear elements, allowing ratio control with one active clutch and a sprag clutch (when the friction clutch is engaged, the sprag is over-running and when the friction clutch is released the sprag clutch engages)
- A portion of the total transmitted torque load is restrained by the clutch elements, which results in smaller clutch sizing
- When transitioning between ratios, this planetary system can carry load and transition smoothly between discrete gear ratios, though the transmitted load influences the clutch sizing

5.2 Analysis and Substantiation

The drive system configurations shown in Figure 27 through Figure 29 represented the different types of tiltrotor drive system architectures evaluated. Other configurations not shown were variations on the basic concepts where different reduction ratios were used at various locations in the drive system or were other combinations of these basic systems. The designs were evaluated with parametric weight analysis as described in appendix D to find the lightest overall configuration. Table 5 summarizes the leading configurations and associated weights which were used as the basis for selecting the configurations, and in the vehicle sizing spreadsheets with appropriate scaling. The table also summarizes mechanical power loss factors used in the sizing process. Weights shown are representative of single speed and variable speed drive system options for the LCTR2 air vehicle rated at approximately 6000 SHP at the input shaft.

Drive System analysis included evaluation of drive system losses for the configurations used in the sizing study as noted above. The drive system power losses were evaluated for the cruise rotor speed condition for each configuration, since cruise segments dominated the defined mission, and differences for hover conditions were considered in the study. Power loss was calculated using empirical methods based on test experience gathered from previous programs. This method assigns a loss factor per mesh based on the type of gearing with an adjustment factor for gear speed. The loss factor includes windage, bearing friction, seals and other losses. Power loss for the high speed (helical idler) portion of the rotor gearbox was studied in greater depth since it is an area of significant power losses for the V-22 drive system. Information was extrapolated from a NASA technical memorandum[16].

Table 5. Summary Drive System Weight and Power Losses

SPEED STUDY FOR CLIMB & CRUISE SEGMENT OR MISSION						TREND WT LBS CURRENT PRODUCTION	2015 WT LBS TECH FACTOR 0.8	2015 PWR LOSS % AT CRUISE SPD PERCENT
CONFIG	SPEEDS %	ENGINE %	DRIVE %	ROTOR RPM	TIP SPEED			
1	100	100	100	191	650.0	11236	8989	4.10
2B	100	100	100	191.0	650.0	11758	9406	4.70
2B	77	100	77	147.1	500.5	11758	9406	4.35
1	77	77	100	147.1	500.5	11236	8989	3.85
2B	77	77	100	147.1	500.5	11872	9497	4.35
3B	54	100	54	103.1	351.0	12086	9669	3.90
1	54	54	100	103.1	351.0	11236	8989	3.40
2B	53.9	77	70	102.9	350.4	11872	9497	3.80

This report describes power losses at various power levels and speeds for a helical geartrain similar to the V-22 high speed gears. Configuration of the helical gears, operating (engine input) speeds and power levels in the referenced report are analogous to the parameters considered in this study, with the exception of the 54% speed condition. This data was used as an approximate guide for the losses in this study by factoring the test data to represent a single gearbox and by extending the test data to a wider power range and a lower speed range.

Two-speed drive systems introduced only marginal increases in drive system losses, which are projected to decrease over the next 20 years through the implementation of new technologies. Figure 31 contains the factored test data and Figure 32 contains the additional projected loss information used in study. The projected high speed gear train data was added to loss estimates for the planetary systems and summarized in Table 5.

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[16] Handschuh, R., and Kilmain, C., "Experimental Study of the Influence of Speed and Load on Thermal Behavior of High-Speed Helical Gear Trains", NASA/TM—2005-213632, ARL–TR–3488, July 2005

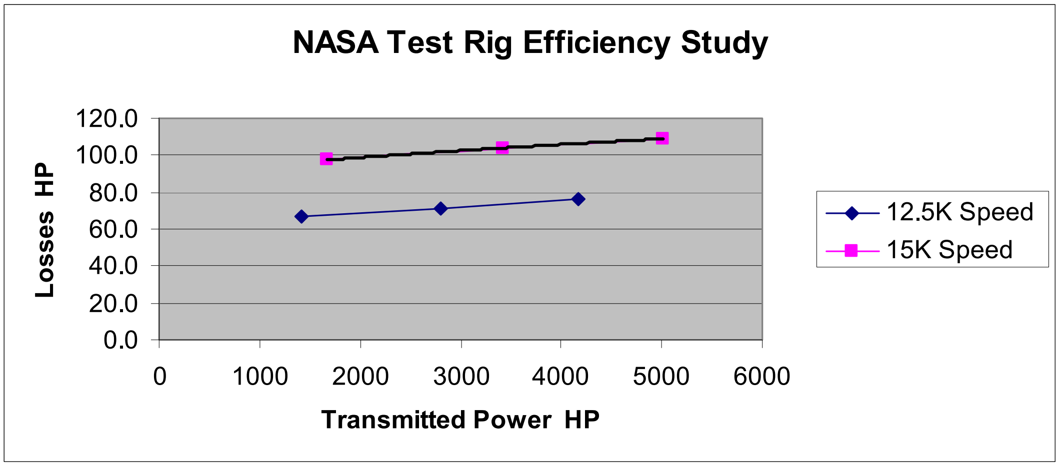

Figure 31. NASA Test Rig Efficiency Test Data from Reference16

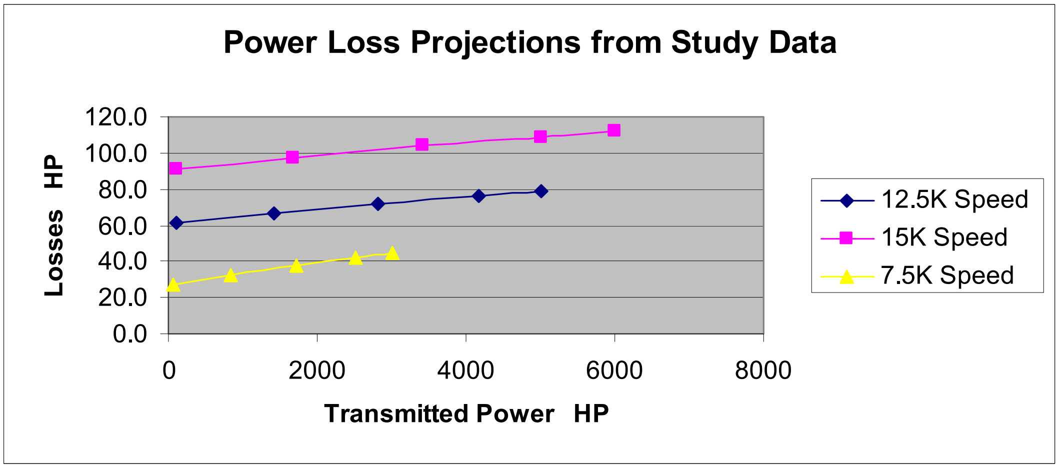

Figure 32. Projected Power Loss for LCTR2 PRGB Helical Idler Gears

In addition to ‘Configuration B’, other compound planetary speed reducer configurations were evaluated during this study. Figure 33 through Figure 37 show the configurations group that had desirable characteristics for the 2 speed application to LCTR2

It was recognized through this study that achieving a 54% speed change ratio was challenging with the stated goals and constraints. The speed change ratio refers to the reduction ratio delta produced by “shifting gears” in the 2-speed module. The overall ratio refers to the inherent minimum ratio through the shifting module. Providing a (near) 54% speed change ratio with an overall reduction ratio varying from around 2.5 to 5 was possible only with ‘Configuration B’ planetary system. Many of the configurations could achieve the 54% speed change ratio but required a higher overall reduction as a consequence. As an example, ‘Configuration A’ planetary system shown in Figure 33 had many desirable characteristics but had an overall reduction ratio that varied from 3.8 to 6.9 to achieve the 54% speed change ratio. Similarly, ‘Configuration E’ shown in Figure 37 had a low overall reduction ratio but could not attain the desired 54% speed change ratio in a single compound planetary stage.

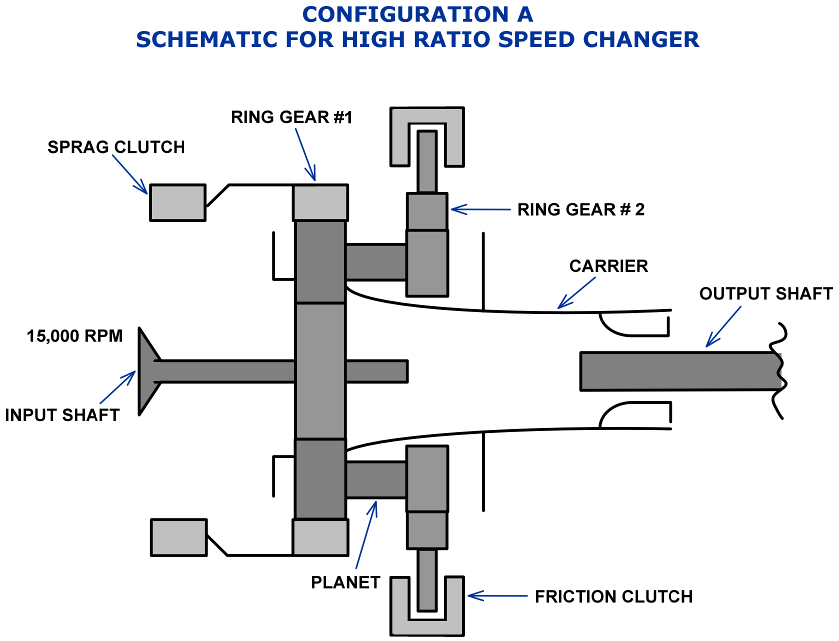

Figure 33. Speed Changing Planetary Gearbox Schematic A

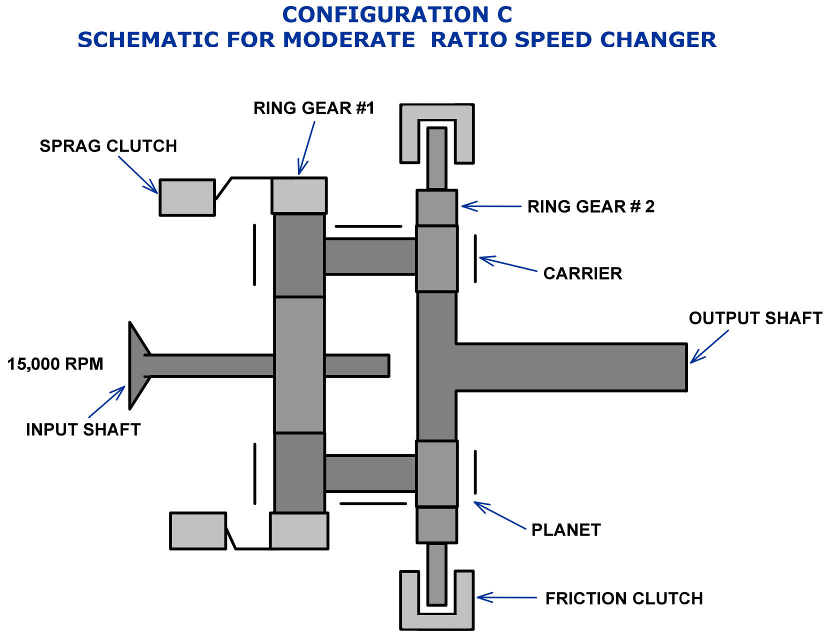

Figure 34. Speed Changing Planetary Gearbox Schematic C

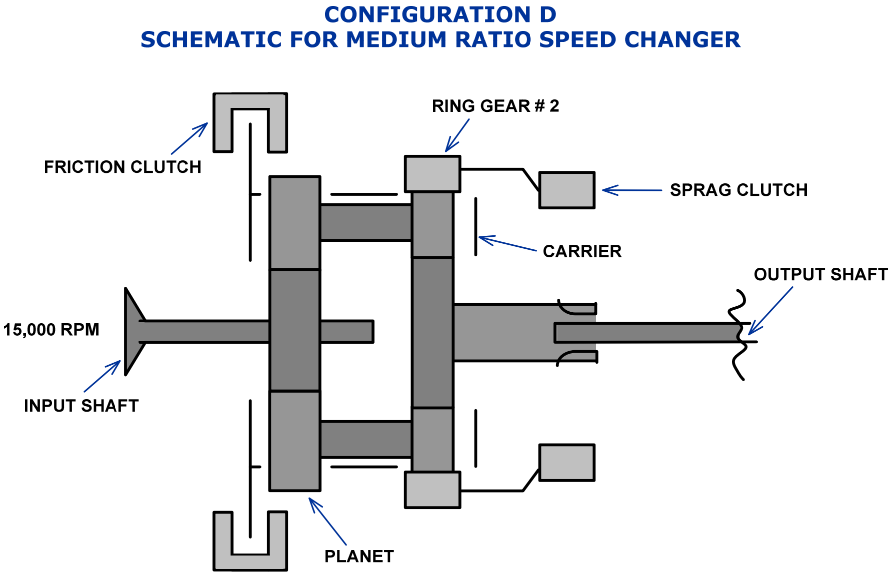

Figure 35. Speed Changing Planetary Gearbox Schematic D

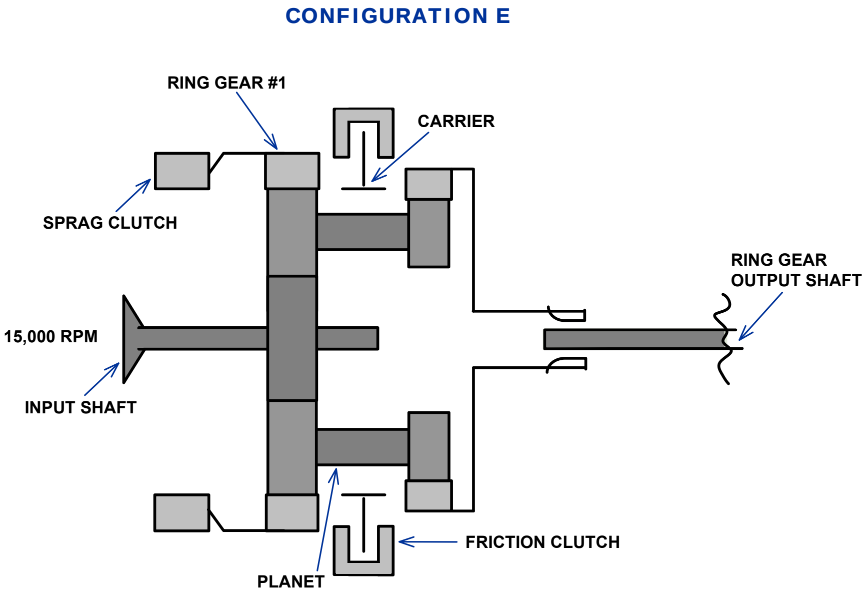

Figure 36. Speed Changing Planetary Gearbox Schematic E

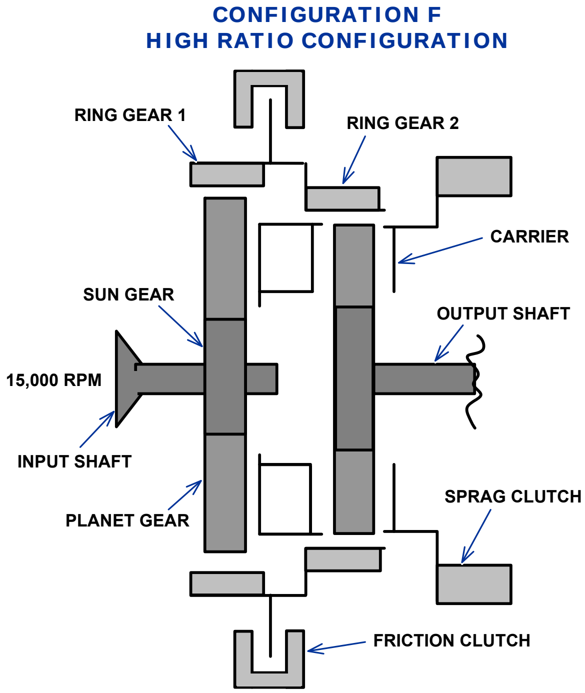

Figure 37. Speed Changing Planetary Gearbox Schematic F

Summary results of the planetary system evaluation are contained in Table 6 where the notional gear tooth numbers are listed and a calculated ratio for each of the 2 possible ratios. The lightest configurations for 77% and 54% reduction are highlighted in the table. Configuration E is not represented in the table because no practical ratios for this study were found but is an interesting configuration because the speed change ratios tended to be greater than 3. Formulas to calculate output speeds and other component speeds were taken from a NASA report [17] for configurations A through D. Formulas for the output speed of configurations E and F are presented below. Output Speeds for Configuration E (Similar to Configuration B, No 6 in NASA report but with Ring Gear #2 output)

Carrier fixed Ring 1 free

$$\text{REout1} := \text{Nr2} \cdot \frac{\text{Np1x}}{\text{Np2x} \cdot \text{Ns1}}$$

Carrier free Ring 1 fixed

$$\text{REout2} := \frac{1}{\left(\frac{\text{Ns1} \cdot \text{Np2x} - \text{Ns1} \cdot \text{Np1x}}{2 \cdot \text{Np1x} \cdot \text{Nr2}}\right)}$$

Where Ns1 = Number of sun teeth, sun #1

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[17] Jules Kish, “Vertical Lift Drive System Concept Studies Variable Speed/ Two Speed Transmissions”, NASA CR-2002-211564, June 2002

Np1x = Number of planet teeth, planet #1

Np2x = Number of planet teeth, planet #2

Nr2 = Number of ring gear teeth, ring #2

Output Speeds for Configuration F (Joined Ring Gears and Carriers, Sun 2 output)

Ring Gear 1 and 2 fixed

$$FRy1 := \frac{Nsy2 \cdot (Nry1 + Nsy1)}{Nsy1 \cdot (Nry2 + Nsy2)}$$

Carrier fixed Ring gear 1 and 2 free

$$FRy2 := \frac{Nsy2 \cdot Nry1}{Nry2 \cdot Nsy1}$$

Where Nsy1 = Number of sun teeth, sun #1

Nsy2 = Number of sun teeth, sun #2

Nry1 = Number of ring gear teeth, ring #1

Nry2 = Number of ring gear teeth, ring #2

Table 6. Summary of Planetary System Reduction Ratios

COMPOUND PLANETARY SPEED CHANGER CONFIGURATIONS, WEIGHT DATA											
Config	**Planetary**	**S_1**	**S2**	**P_1**	**P_2**	**R_1**	**R_2**	**RATIO 1**	**RATIO 2**	**2015 WT ^{1}**	**Comments**
1	**n/a**									8989	Baseline, no speed changer
2	**B**							77%		9406	**config factor=1.046**
		32	48	42	26	116	-	2.400	1.850		
2	**B**							70%		9497	**config factor=1.057**
		28	48	44	24	116	-	3.140	2.220		
3	**B**							54%		9993	**config factor=1.112**
		30	60	48	18	126	-	2.910	5.330		
4	**A**							77%		9881	**config factor=1.099**
		50	-	37	23	124	110	3.480	4.540		
4	**A**							70%		10051	**config factor=1.118**
		50	-	39	21	128	112	3.560	5.090		
5	**A**							54%		10262	**config factor=1.142**
		50	-	45	17	140	112	3.800	6.930		
6	**A**							54%		11199	**config factor=1.246**
		50	-	45	17	140	112	3.800	6.930		
7	**A**							54%		12347	**config factor=1.374**
		50	-	45	17	140	112	3.800	6.930		

Configuration B as used in this study was sized to provide a speed change ratio of 54% with the low reduction ratio as 2.91:1 and the high reduction ratio as 5.33:1. The presumption is that an additional bit (3%) of speed reduction can be provided by engine RPM variation without impacting any of the sizing, weight or performance calculations presented. For simplicity in the planetary system sizing and calculations, the assumption was made that diametral pitch remained the same throughout the system and that the system would have 6 planets (B only). Preliminary sizing indicates that the planetary system could be packaged in approximately a 14.5 inch diameter cylindrical housing, and would have a pitch line velocity of less than 12,500 fpm. Other parameters such as stress limits appear to be within practical limits.

5.3 Two-Speed Gearbox Module Simulation

A two-speed transmission is used to shift the rotor speed for the concept drive systems. This additional gearbox module increases the weight and complexity of the drive system layout but allows the engine to operate at higher efficiency. The engagement and disengagement of the clutch system generates heat and transient torque loads which were explored using MATLAB's SimDriveline program, as shown in Figure 38. The block diagrams in this dynamic model replicated the drive systems from the engine to the speed changer to the rotor. The blue blocks are the actual models representing each portion of the vehicle from engine input to gearboxes and rotors. The pink blocks provide the inertias from each component.

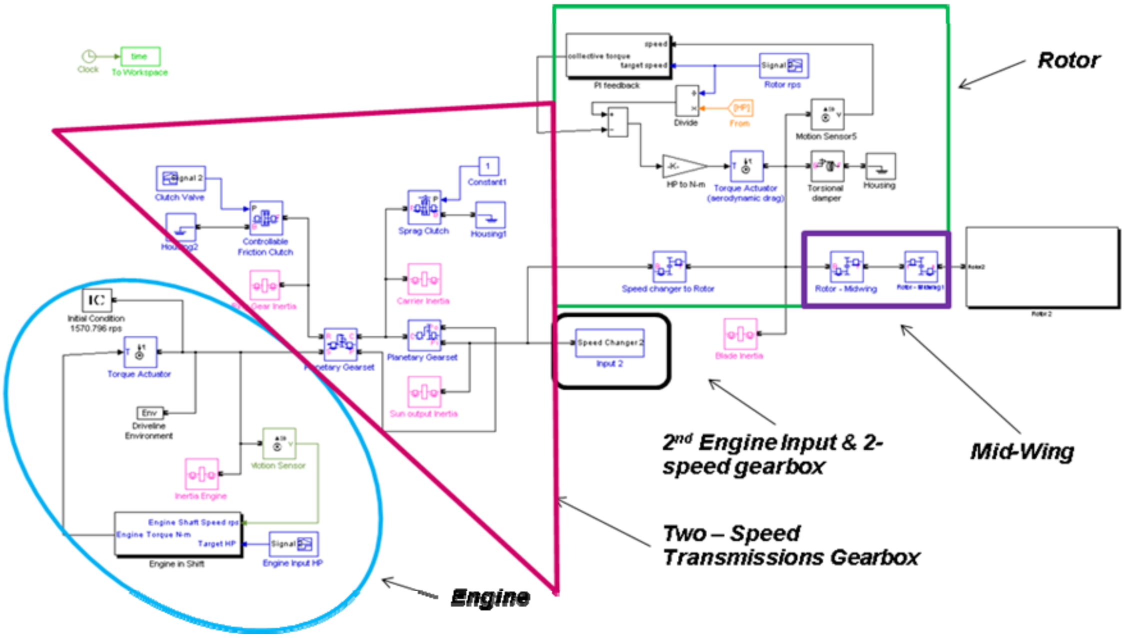
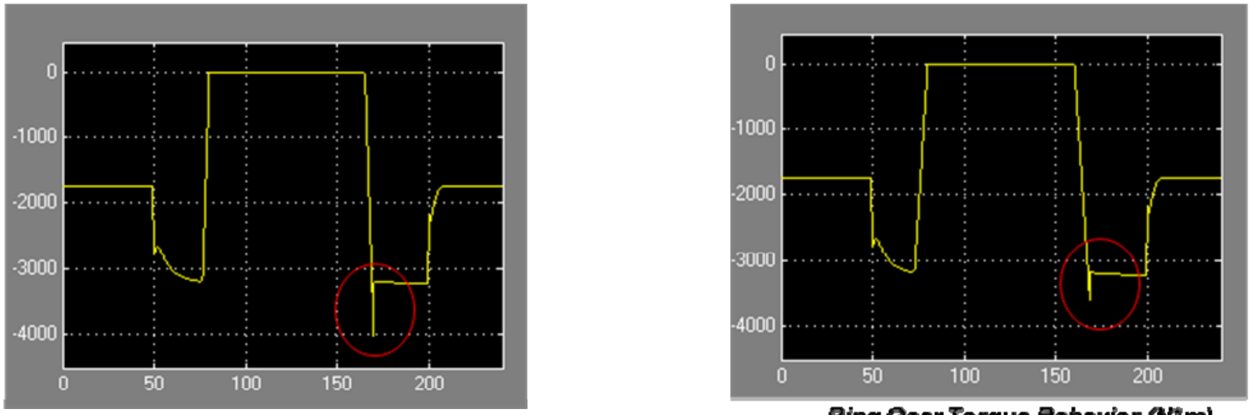


Figure 38. Matlab Model of the Drive Train

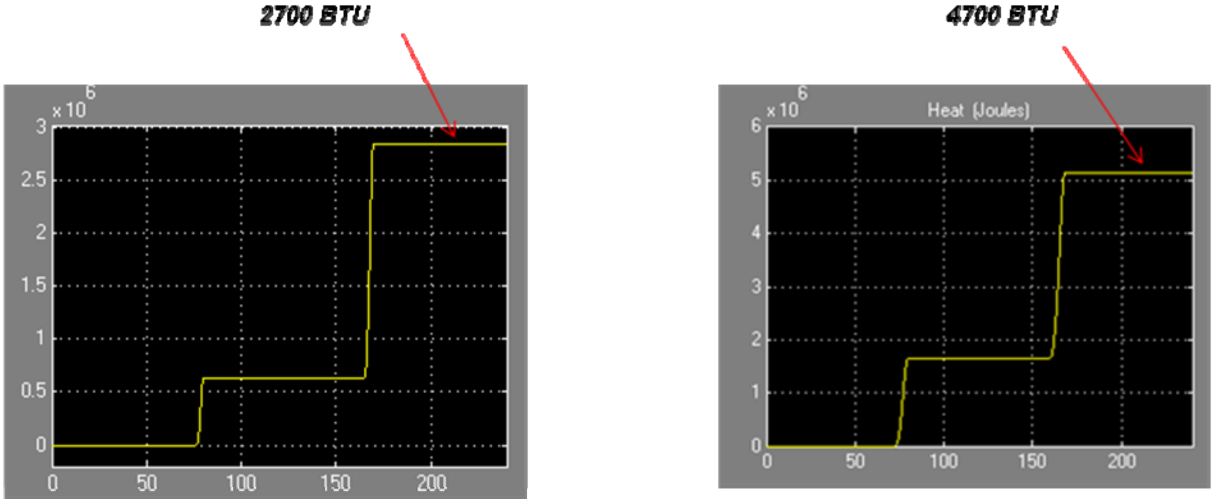
The individual shifting engine power is lowered to 30% to start the shifting process while the other three engines take on more power to maintain level flight. The clutch system was built to meet the loads generated as the clutch engages/disengages. Maximum temperature of the whole system should not exceed 400°F to ensure proper functioning of the gearbox. These two criteria dominated the sizing of the speed changer gearbox as well as the time each of the shifting process takes place. The dynamic model was configured to run the shifting process for 5 and 10 seconds. Results are show in Figure 39 and Figure 40. For a 5 second shifting process, the torque spike is roughly 35,000 in-lbs vs. 31,000 in-lbs with a 10 second shifting process. However, the heat generated from the two is 2700 BTU and 4700 BTU, respectively. The 5 second shifting process was selected for this two-speed transmission as heat dissipation played a more dominate role for this case.



Ring Gear Torque Behavior (N*m)
T=5s

Ring Gear Torque Behavior (N*m)
T=10s

Figure 39. Ring Gear Torque Behavior



Energy Dissipation from Shifting in Joules
T=5s

Energy Dissipation from Shifting in Joules
T=10s

Figure 40. Energy Dissipation

Transient dynamic analysis results and torque calculations from above determined the size of this gearbox, as shown in Figure 41 and Figure 42. This speed changer gearbox is a three dimensional model of Configuration B. It consists of Sun Gear # 1 as the input and Sun Gear # 2 as the output. Speed changing is accomplished by holding either Ring Gear # 1 or the Carrier stationary with clutches while the other rotates freely. In this case, a (spring apply, hydraulic pressure release) friction clutch is used to stop and hold the ring gear during hover while a sprag clutch is used to hold the carrier stationary for cruise condition. The envelope dimension of this gearbox is 17 inches in diameter and 21 inches in length. Weight is estimated to be 270 lbs.

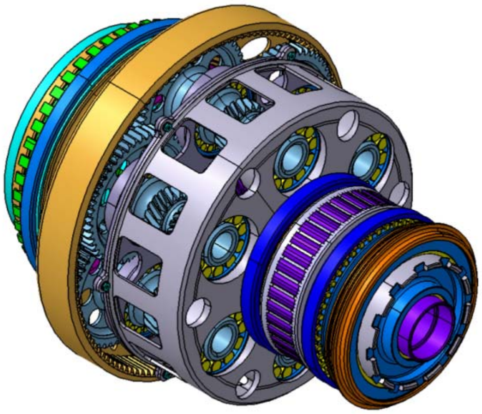


Figure 41. Speed Changer Gearbox: Isometric View

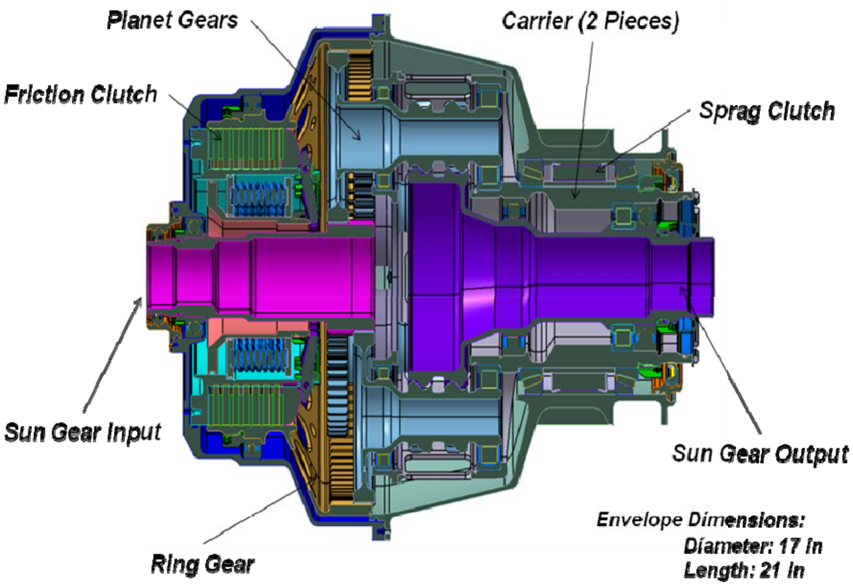


Figure 42. Speed Changer Gearbox: Section View

6.0 ROTOR DESIGN AND PERFORMANCE

Boeing designed four rotors for the 310 ktas LCTR2 cruise airspeed, based on the NASA LCTR2 rotor airfoils and blade planform. Twist distributions were modified to align blade sections with the helical inflow angle for 650 fps, 500 fps, 422 fps and 350 fps cruise tip speeds. These four rotor designs were examined during the trade-off of reduced engine rpm versus variable speed drive system technology to achieve the objective rotor cruise tip speeds.

Two additional rotors were designed to evaluate the impact of higher cruise airspeeds on the LCTR2 size, gross weight, and cost; one for 350 ktas cruise and the other for 375 ktas cruise. Both rotor designs applied the 350 fps rotor tip speed, partially since that corresponded to 54% RPM, where existing engine data was available. The helical blade tip Mach number is 0.71 at 25,000 ft, 375 ktas cruise airspeed, so this design required thinner airfoils over the blade radius to avoid adverse drag divergence.

6.1 Rotor Designs for 310 KTAS

NASA airfoil data was applied with the LCTR2 radial distribution of airfoils and blade planform for the 310 ktas cruise airspeed. The LCTR2 geometric twist distribution was maintained for the 350 fps cruise tip speed, as that was the NASA design point. Blade twist was modified for the other cruise tip speeds (422 fps, 500 fps, 650 fps) with the goal of locally aligning the blade element in cruise to the oncoming flow at the nominal design cruise airspeed of 310 ktas. Boeing's B-08 program was used to calculate rotor hover efficiency (FM) and cruise propulsive efficiency (η). The rotor solidity (σ) matches the NASA LCTR2 design because the LCTR2 values of Ct/σ, disc loading, and hover tip speed were preserved. In accordance with the statement of work, no blade optimization was performed to further refine the resulting twist distributions for the cruise condition or to balance the design for hover performance.

NASA supplied 'C81' format airfoil data for the LCTR2 rotor design, which Boeing converted to a format required for the Boeing B-08 rotor performance analysis. Boeing applied the NASA blade airfoil performance characteristics and definition of relative chord throughout this study, and as previously mentioned the LCTR2 rotor thrust-weighted solidity of 0.133 was preserved. Absolute chord lengths changed with the rotor radius as a result of resizing the aircraft. The reference LCTR2 rotor is a four-bladed, 65 ft diameter rotor, with an overall taper ratio of 0.70 and a bi-linear blade twist of -38°/-30°.

A comparison of the twist distributions for the four rotor designs is shown in Figure 43, and compared to the distribution of helical inflow angle for each rotor operating at 310 ktas. The NASA bi-linear twist for the LCTR2 rotor with the 350 fps cruise tip speed closely agrees with the helical inflow angle ($\theta_{TWIST} \cong \arctan(\mu/x)$). Boeing applied a bi-linear twist distribution for tip speed of 500 fps, similar to the NASA twist parameterization. A bi-linear twist distribution proved to be inadequate to properly align the blade for the 650fps cruise tip speed and a tri-linear twist was used instead. A tri-linear twist distribution was later employed for the tip speed of 422 fps, when this operating condition was introduced into the study under Task Order 5.

- The Boeing rotor design for 650 fps cruise tip speed had a tri-linear twist (-63° / -42°/ -33°) for improved cruise efficiency, but otherwise had the same solidity, reference blade planform and airfoil distribution as the baseline LCTR2 rotor. The breakpoints in the piecewise linear twist distribution were located at r/R = 0.50 and 0.75.

- The Boeing 500 fps cruise tip speed rotor design had a bi-linear twist (-50°/-34°) to closely match the helical inflow distribution at 300 ktas, with the LCTR2 solidity, reference blade planform and airfoil distribution. The breakpoint in the piecewise linear twist distribution was located at r/R = 0.60.
- The Boeing rotor design for 422 fps cruise tip speed had a tri-linear twist (-48°/-39/-32°) with the LCTR2 solidity, reference blade planform and airfoil distribution. The breakpoints in the piecewise linear twist distribution were located at r/R = 0.40 and 0.70.
- The NASA LCTR2 rotor design for 350 fps cruise tip speed had a bi-linear twist (-38°/-30°). The breakpoint in the piecewise linear twist distribution was located at r/R = 0.50.

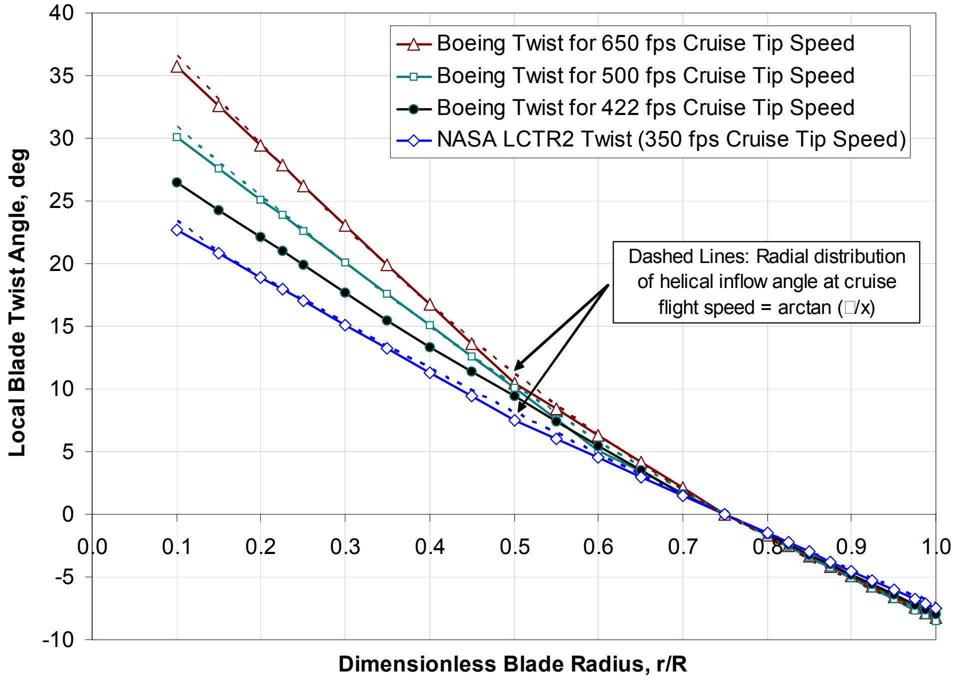


Figure 43. Comparison of Rotor Blade Twist Distributions

6.1.1 Hover Performance

Boeing applied the in-house B-08 rotor performance analysis in this study. B-08 is a local blade-element / momentum theory analysis for static and axial flight proprotor performance. The method incorporates the effect of tip loss associated with a finite number of blades through Prandtl's tip loss correction. Tip compressibility relief associated with three-dimensional flow effects near the tips is treated using the Lenard correction. The B-08 analysis was applied to evaluate rotor performance in both hover and cruise.

Calculated hover performance for each rotor design is shown in Figure 44 for the LCTR2 takeoff condition at 5,000'/ISA+20°C and 650 fps hover tip speed. Hover performance from B-08 is for an isolated rotor. The isolated performance was adjusted for installation effects by taking a 4% reduction in the hover thrust.

The hover Ct/σ was 0.150 for all vehicle sizing cases, a fallout of using fixed LCTR2 values for disk loading and solidity at the prescribed takeoff condition of 5,000’, ISA+20°C.

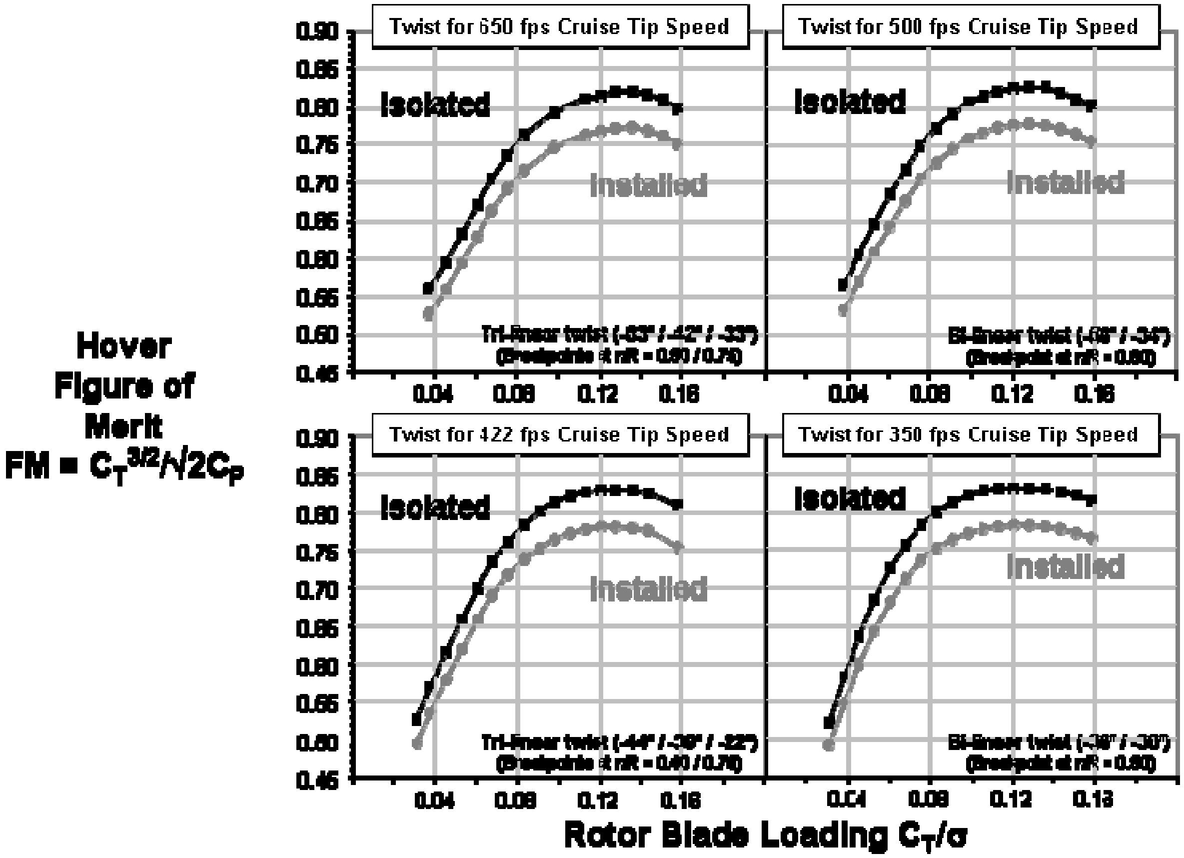


Figure 44. Rotor Hover Figure of Merit for 310 ktas cruise rotor designs

6.1.2 Cruise Propulsive Efficiency

Maps of rotor cruise efficiency from the B-08 analysis are presented below in Figure 45 through Figure 48. Cruise propulsive efficiency for the 650 fps rotor at 310 ktas is low in general, only 0.74 at the nominal cruise C_T. The relatively low propulsive efficiency for the 650 fps rotor is certainly one contributing factor leading to the heavier Gross Weights during vehicular sizing cases that applied this rotor performance. To the contrary, cruise efficiency of the 500 fps rotor design and 350 fps rotor designs were much better at 310 ktas, 0.835 and 0.84 respectively. In the figures, the cruise operating point is marked by a blue star.

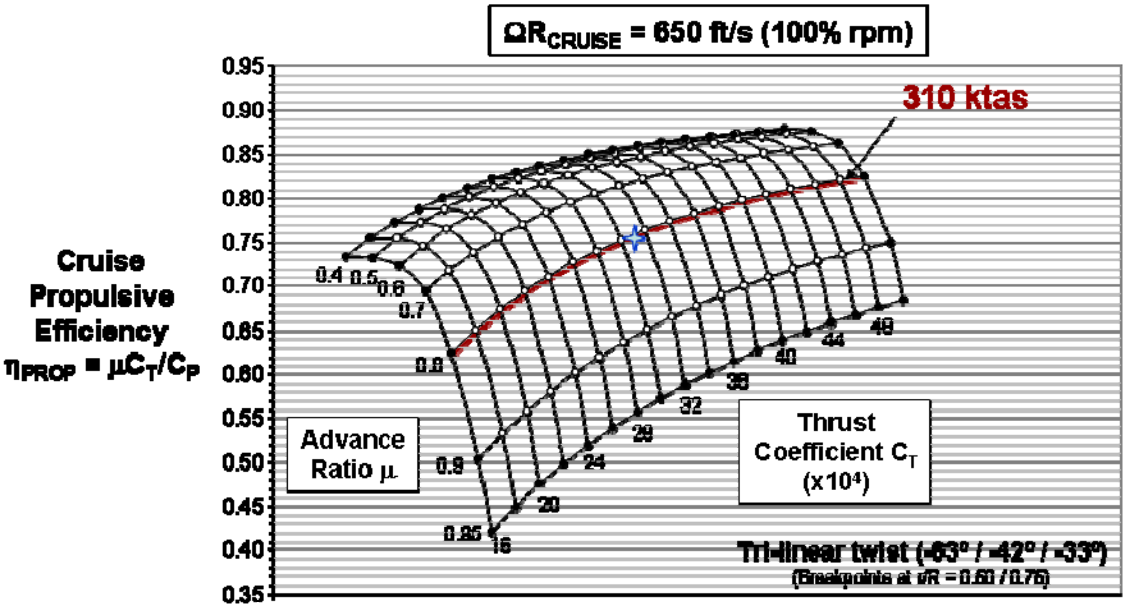


Figure 45. Rotor Cruise Propulsive Efficiency for 650 fps Cruise Tip Speed Design

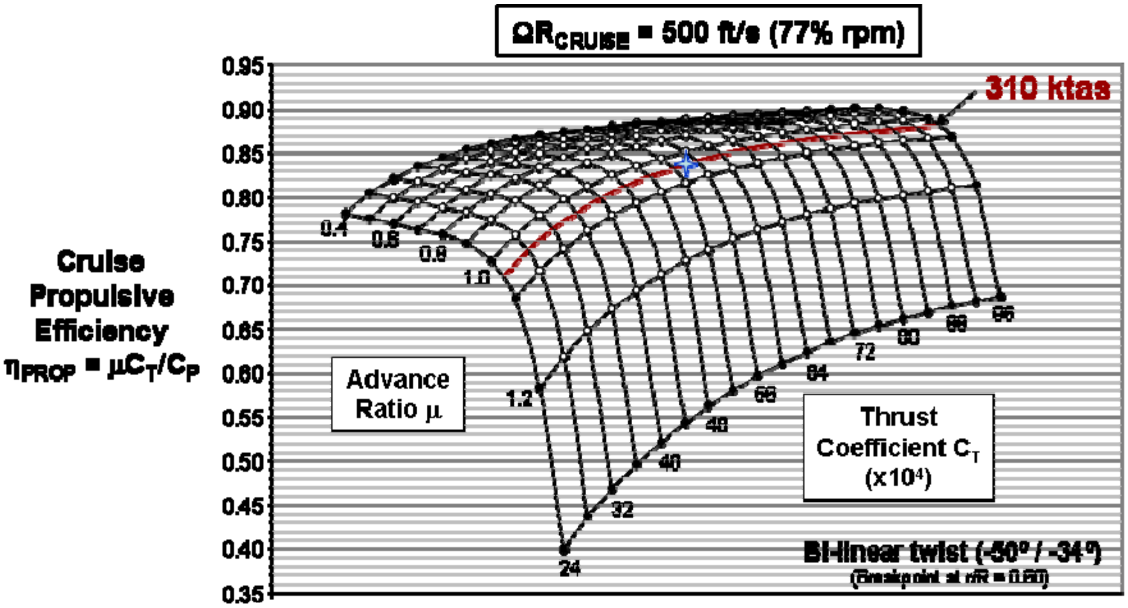


Figure 46. Rotor Cruise Propulsive Efficiency for 500 fps Cruise Tip Speed Design

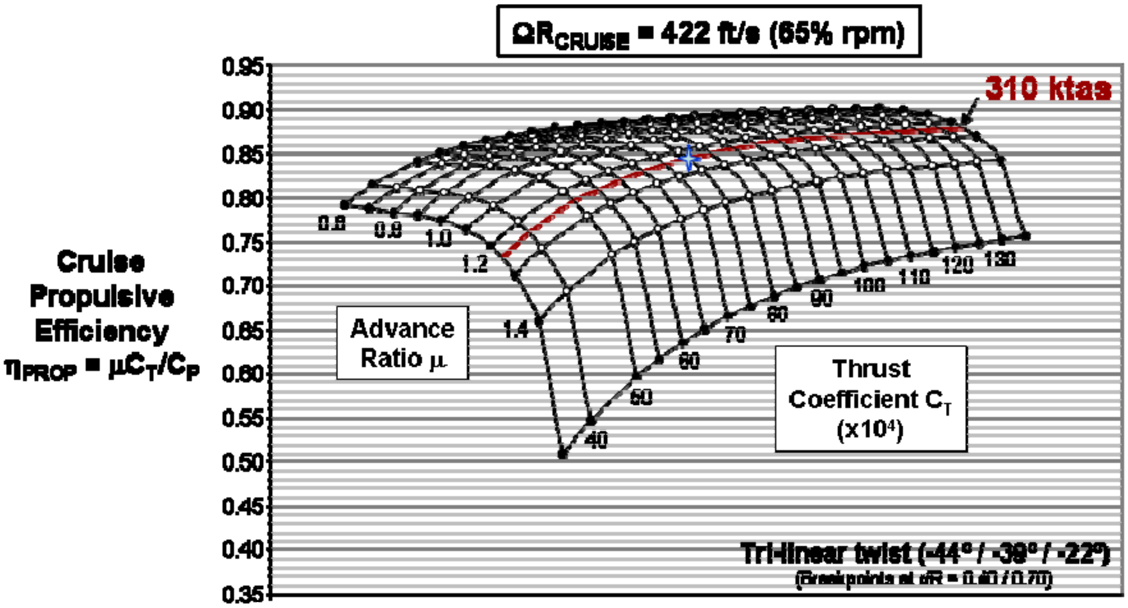


Figure 47. Rotor Cruise Propulsive Efficiency for 422 fps Cruise Tip Speed Design

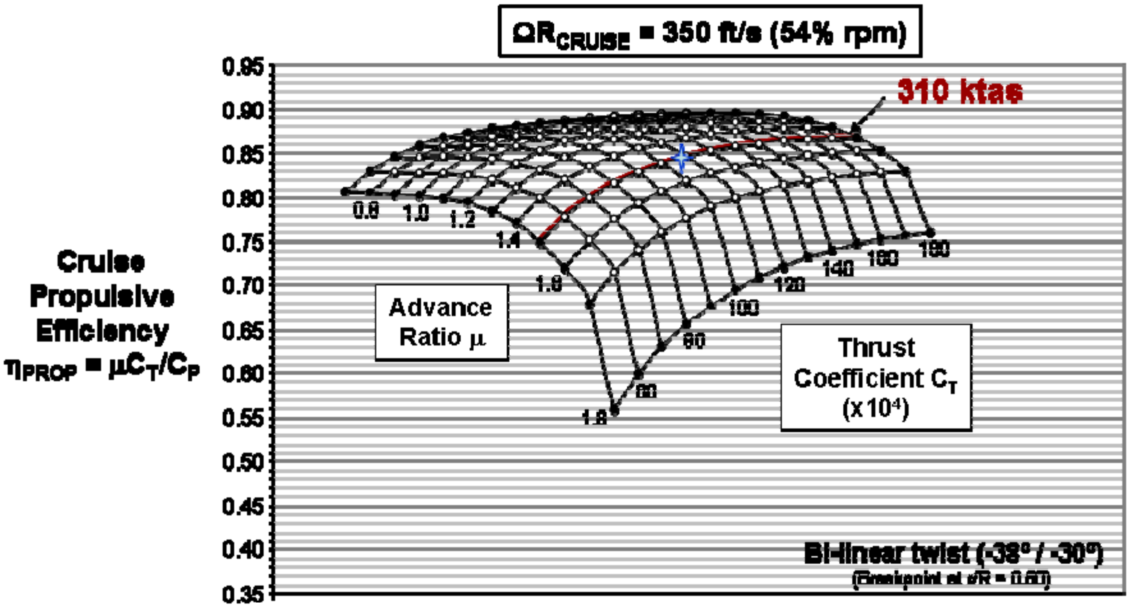


Figure 48. Rotor Cruise Propulsive Efficiency for 350 fps Cruise Tip Speed Design

6.2 Rotor Design for 350 KTAS Cruise Airspeed

Boeing employed a similar approach in development of the two additional rotors for increased cruise airspeeds of 350 ktas and 375 ktas. While maintaining the NASA LCTR2 cruise tip speed of 350 fps and its relative chord distribution, blade geometric twist was modified to better align local airfoil sections with helical inflow angle at the two higher flight speeds. During this process, additional consideration was given to the attendant increase in local blade Mach number, especially over the inboard portion of the rotor blade. As flight speed is raised from 310 ktas to 350 ktas and beyond to 375 ktas, the local Mach number at the blade root station (r/R = 0.10) increases from $M_{HELICAL} = 0.51$ to 0.58 and 0.63, respectively. (Note – a maximum cruise airspeed of 385 ktas was initially considered for this additional task. Reference to this flight condition appears later in this discussion and was ultimately used to evaluate airfoil placement along the blade span. Any conservatism associated with this assumption is likely offset by the fact that consideration of installation effects, such as the presence of the spinner, on local velocity distribution at the plane of the proprotor near the root is not given in the present study.)

The drag characteristics provided by NASA for the LCTR2 28% thick blade root airfoil are plotted in Figure 49. Inspection of these properties indicates that this airfoil cannot operate above Mach 0.60 at any angle-of-attack without incurring significant compressibility penalties. Comparison of this limit with the local Mach number conditions at the blade root suggests that at 350 ktas this airfoil will operate close to its drag divergence boundary, while at 375 ktas this airfoil will operate entirely beyond this limit and unduly penalize rotor performance at this operating condition. For the purpose of this study, the original NASA LCTR2 airfoil placement was retained for the 350 ktas rotor design, but was modified for the 375 ktas design by eliminating the 28% thick airfoil from the blade root and re-distributing the remaining airfoils along the inner portion of the span[18].

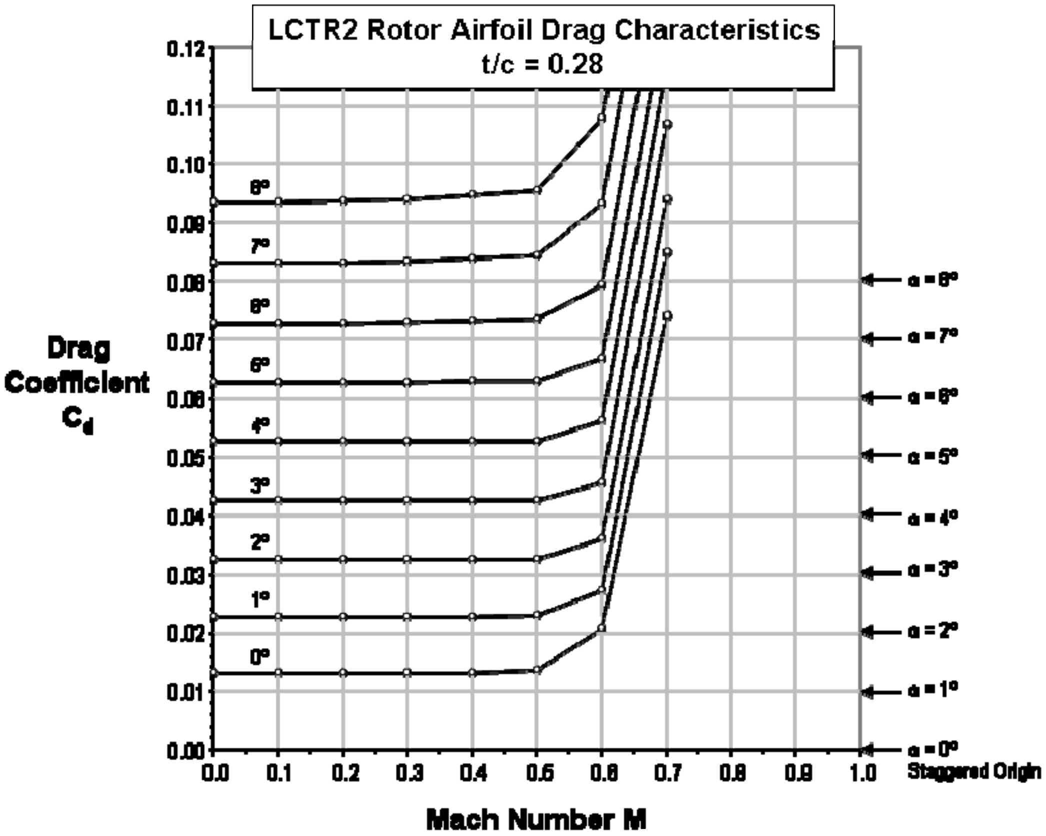


Figure 49. Drag Characteristics of 28% thick NASA LCTR2 Airfoil

To identify the appropriate spanwise placement of the remaining LCTR2 airfoils for the 375 ktas rotor, their maximum lift-to-drag ratio and drag divergence boundaries were also identified

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[18] A similar design approach was taken during a NASA Contractor Design Trade Study performed by Boeing to investigate a 400 knot tilt-rotor design (NAS2-13607, authored by Joe Wilkerson and Leo Dadone, 1993).

through inspection of the airfoil tables provided by NASA. These airfoil performance boundaries are compared graphically in Figure 50 to the distribution of local helical Mach over the LCTR2 blade at various cruise airspeeds.

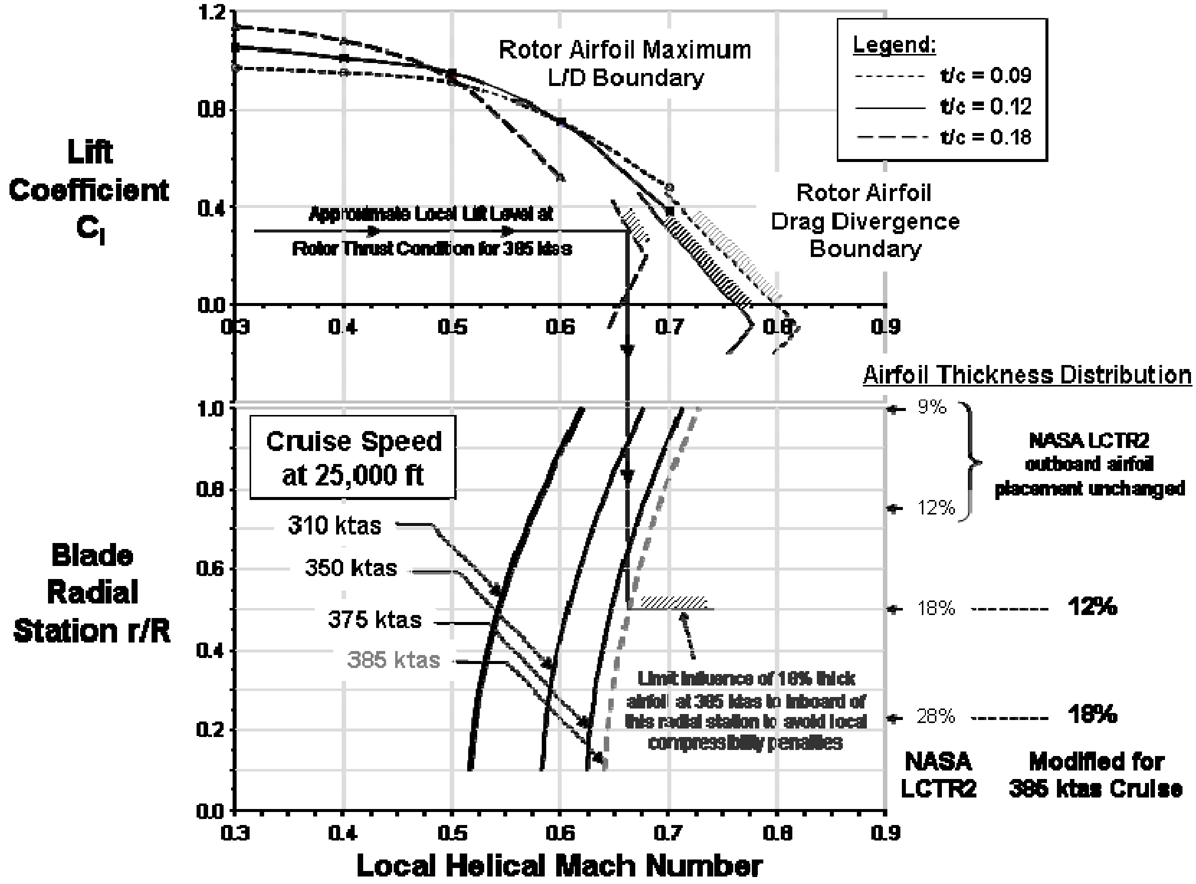


Figure 50. Rotor Airfoil Performance Boundaries and LCTR2 Blade Operating Conditions

Upon re-twisting the blade to align the local airfoil sections with helical inflow angle, rotor cruise predictions were made with the B-08 rotor performance program at representative thrust conditions to identify the associated blade lift coefficient levels. From these calculations, a representative value of $C_l = 0.30$ was identified, and this value was used as shown in Figure 50 to determine the limiting outboard radial station at which the 18% thick LCTR2 airfoil could be tolerated without exceeding its performance limits. A limit of r/R = 0.50 was identified, and the blade thickness distribution of the 375 ktas rotor was tapered from 18% at r/R=0.225 to 12% at r/R=0.50.

In summarizing the geometric attributes of the 350 ktas and 375 ktas rotor designs:

- The Boeing 350 ktas cruise airspeed rotor design had a tri-linear twist (-33.1°/-30.5 / -27°) to closely match the helical inflow distribution with a 350 fps tip speed. The LCTR2 solidity, reference blade planform and airfoil distribution were maintained. Breakpoints in the piecewise linear twist distribution were located at r/R = 0.45 and 0.70.
- The Boeing rotor design for 375 ktas cruise airspeed had a tri-linear twist (-30.8°/ -29° /-25.8°) with the LCTR2 solidity and reference blade planform. Breakpoints in the piecewise linear twist distribution were located at r/R = 0.40 and 0.70. The

LCTR2 28% thick root airfoil was eliminated and the remaining LCTR2 airfoils were re-distributed along the blade span with the placement tabulated below (NASA LCTR2 shown for reference):

Blade Airfoil Thickness-to-chord (t/c) Ratio Distribution		
r/R	**Boeing 375 ktas Rotor**	**NASA LCTR2 (Reference)**
0.10 – 0.225	0.18	0.28
0.50	0.12	0.18
0.75	0.12	0.12
1.0	0.09	0.09

6.2.1 Hover Performance

The B-08 analysis was applied to evaluate rotor performance in both hover and cruise. Calculated hover performance for each rotor design is shown in Figure 51 for the LCTR2 takeoff condition at 5,000'/ISA+20°C and 650 fps hover tip speed. The isolated hover performance from B-08 was adjusted for installation effects by taking a 4% reduction in the hover thrust. Consistent with the 310 ktas designs, the hover Ct/σ was 0.150 for all vehicle sizing cases, a fallout of using fixed LCTR2 values for disk loading and solidity at the prescribed takeoff condition of 5,000', ISA+20°C.

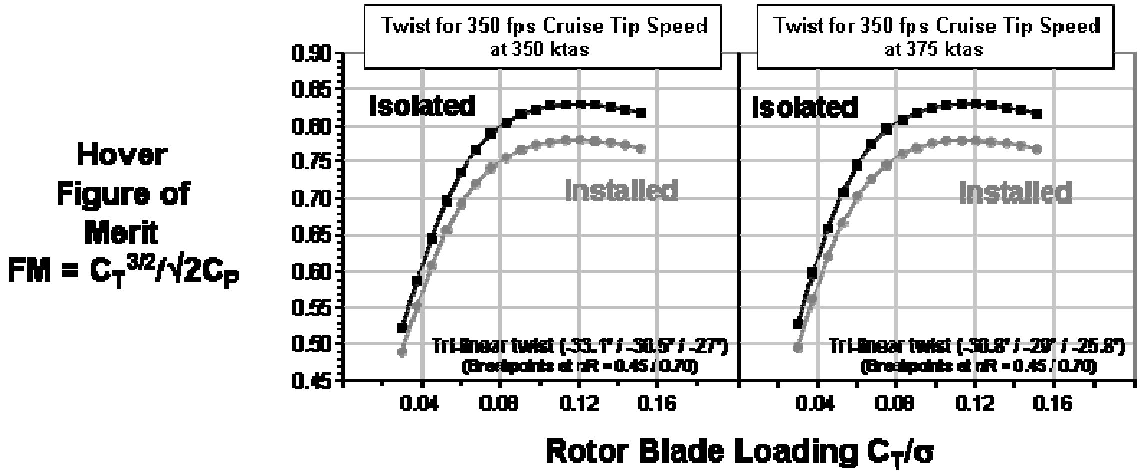


Figure 51. Rotor Hover Figure of Merit for 350 ktas and 375 ktas Rotor Designs

6.2.2 Cruise Performance

Maps of rotor cruise efficiency from the B-08 analysis are presented in Figure 52 and Figure 53, respectively, for the 350 ktas rotor and 375 ktas rotor.

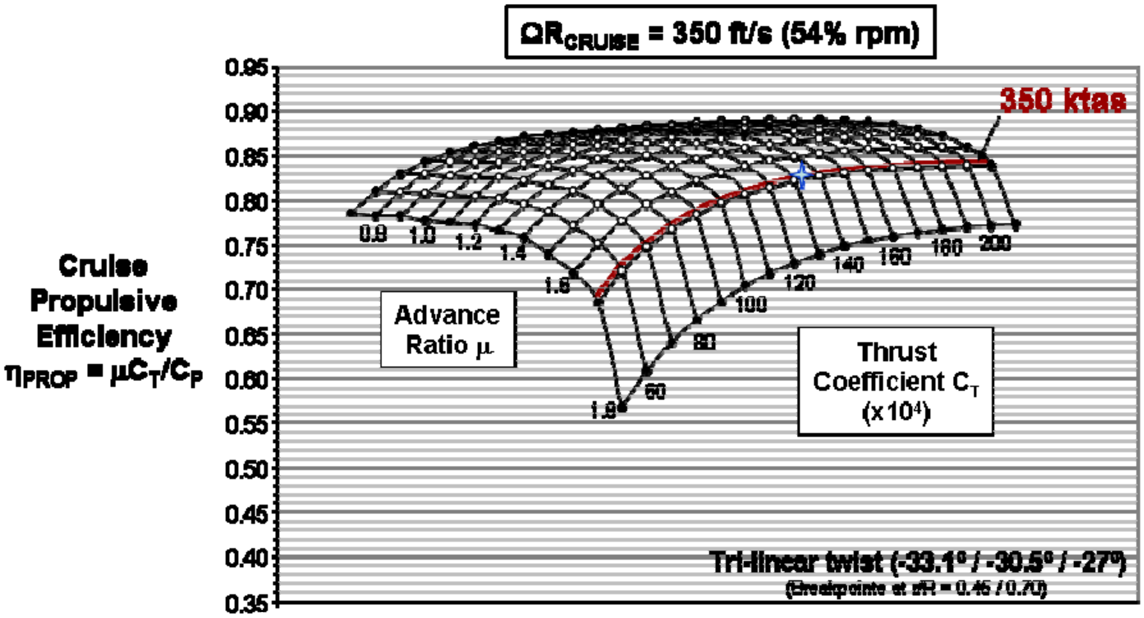


Figure 52. Rotor Cruise Propulsive Efficiency for 350 ktas Cruise Airspeed Design

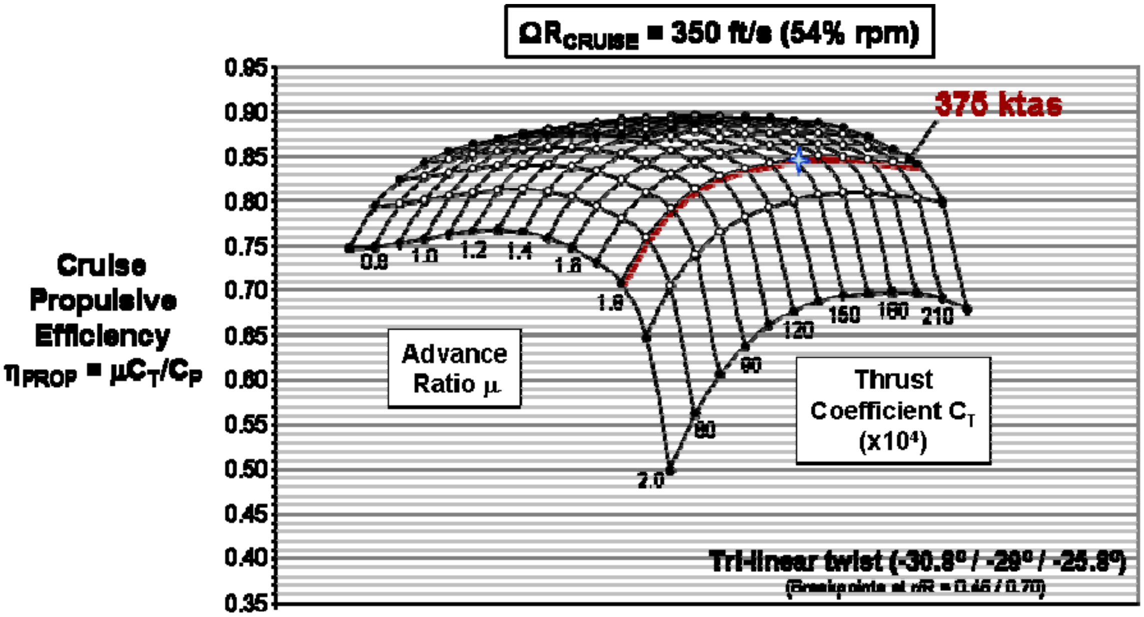


Figure 53. Rotor Cruise Propulsive Efficiency for 375 ktas Cruise Airspeed Design

7.0 LCTR2 VEHICLE RESIZING AND PERFORMANCE

7.1 Aircraft Sizing To LCTR2 Mission

An initial evaluation was made to quantify the overall effects of Boeing component weights, the Rolls-Royce engine fuel flow, and consequences of the COTS engine weight and takeoff power at the 5K/ISA+20°C takeoff condition. Rules and assumptions for all resized cases were detailed in Section 3.2.1. Initial cases were run using the COTS engine fuel flow, retaining the NASA LCTR2 drag (both parasite and induced), the NASA engine takeoff power fraction (0.77) and engine weight (0.105 lb/maxSHP) to calibrate the model without complications of differences in engine weight or performance.

The 2015 COTS engine weight is about 160% of the NASA engine lb/shp. But it sized down to about 67% of the NASA engine installed power due to (1) more power available at the 5K/ISA+20°C takeoff condition and (2) being sized only to the takeoff condition versus NASA's selected 7500 SHP size. These compensating differences resulted in the Boeing analysis with the COTS engine weight having only about 7% more engine weight than the reference NASA LCTR2. Overall, the effect of the 2015 COTS engine with the Boeing weights gave a 4% increase in OWE with nearly 19% decrease in mission fuel relative to the NASA LCTR2, or about a 3% change in GW.

The NASA LCTR2 design was modeled using Boeing weight estimates and rotor performance estimates, with the Rolls-Royce COTS engine (2015 technology). Many features of the LCTR2 are retained, such as the fuselage size, rotor disc loading and design Ct/sigma, wing loading and wing tip extensions. The wing area and rotor diameter were allowed to vary as the vehicle was resized to the three rotor cruise tip speeds, via different combinations of engine speed and drive system speed reduction. Engine performance (power available, fuel flow, and residual jet thrust) is modeled for each specific operating RPM in cruise. Rotor performance is calculated for each of the three rotor tip speeds as a function of advance ratio and thrust coefficient. Boeing weight estimates are based on empirical weight trends and experience with tiltrotor aircraft, modified to reflect a 2025 technology level. Dry engine weights were provided by Rolls-Royce, scaled during the sizing using a constant lb/SHP ratio. Further explanation of some component weight estimates are provided in Appendix D-Boeing Approach to LCTR2 Vehicle Weight Estimates.

7.2 LCTR2 Sized With The 2015 COTS Engine

Table 7 shows aircraft sizing results for six combinations: three engine RPMs for the 350 fps rotor cruise tip speed, two engine RPMs for the 500 fps cruise tip speed, and one case for the 650 fps rotor cruise tip speed. Three cases were run at the 350 fps rotor cruise tip speed (54% of hover RPM), examining the effect of engine RPM reduction versus drive system RPM reduction. The highlighted cells indicate whether hover or cruise power requirements sized the engine. The engine is sized by hover for all cases, except for the one with the engine operating at 54% RPM, pointing to the need for an engine design with improved performance at low cruise RPM.

The Gross Weight at 54% engine RPM (350 fps rotor cruise tip speed) is driven up by an 11% increase in required fuel relative to the 100% engine RPM case. Notably the engine is sized by the cruise power required at the 54% engine RPM, and requires more installed SHP than either the 100% or the 77% engine RPM cases.

Table 7. Summary of Six LCTR2 Aircraft Sized with COTS engine

Sizing Summary for Study of LCTR2 Rotor Tip Speed and Drive System RPM with COTS Engine

CONDITION							
ROTOR Cruise Tip Speed, fps		**350**	**350**	**350**	**500**	**500**	**650**
Engine Cruise RPM / Hover RPM		100%	77%	54%	100%	77%	100%
Drive System Cruise RPM / Hover RPM		54%	70%	100%	77%	100%	100%
Drive System Type		2-speed	2-speed	single speed	2-speed	single speed	single speed
GROSS WEIGHT		108,325	107,882	110,571	106,132	105,687	108,569
Wing Weight		6,850	6,852	7,063	6,797	6,775	7,092
Rotor Weight		9,529	9,477	9,641	9,049	9,011	9,261
Engine Weight		3,473	3,455	3,697	3,460	3,428	3,534
Drive System Weight		9,640	9,131	8,712	8,296	7,857	8,138
Empty Weight		70,380	69,775	70,720	68,260	67,677	69,181
OWE		71,830	71,225	72,170	69,710	69,127	70,631
FUEL		16,710	16,882	18,628	16,624	16,767	18,141
DIMENSIONS							
FUSELAGE	Equivalent Diameter	9.0	9.0	9.0	9.0	9.0	9.0
WING	Span, Overall	107.4	107.4	108.7	106.5	106.3	107.7
	Area Exposed	1008.6	1008.0	1033.1	991.6	987.5	1014.4
	Aspect Ratio, geometric	11.44	11.44	11.44	11.44	11.44	11.44
MAIN ROTOR	Diameter	65.36	65.23	66.04	64.70	64.56	65.44
	Solidity	0.1432	0.1432	0.1432	0.1432	0.1432	0.1432
	Hover Tip Speed	650	650	650	650	650	650
	Disc Loading, W/A	16.1	16.1	16.1	16.1	16.1	16.1
	Thrust Coefficient, CT/s	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
PROPULSION							
ENGINE RATING (Max SHP, SLS)							
	Installed max SHP (SLS) per Engine	5,186	5,159	5,521	5,168	5,120	5,278
	Engine Scale Factor for Hover	0.640	0.637	0.650	0.638	0.632	0.652
	Engine Cruise Scale Factor for 310 kt @ 25K'	0.585	0.603	0.682	0.583	0.599	0.644
TRANSMISSION							
	Transmission Rating (Hover)	21,974	21,795	21,835	19,616	19,536	20,090
	Transmission Rating (Cruise)	11,832	11,736	11,757	15,089	15,028	20,090
	Losses	3.90%	3.80%	3.40%	4.35%	3.85%	4.10%
PERFORMANCE							
ROTOR HOVER TAKEOFF FM		0.775	0.774	0.775	0.769	0.766	0.765
AIRCRAFT CRUISE ALTITUDE, ft		25,000	25,000	25,000	25,000	25,000	25,000
AIRCRAFT CRUISE AIRSPEED, ktas		**310.0**	**310.0**	**310.0**	**310.0**	**310.0**	**310.0**
HELICAL M TIP @ 25K'		0.620	0.620	0.620	0.713	0.713	0.822
ROTOR CRUISE EFFICIENCY		0.846	0.845	0.844	0.839	0.839	0.754
AIRFRAME CRUISE L/D (max)		11.02	11.04	11.13	10.98	10.96	11.08
AIRFRAME CRUISE L/D (1st cruise)		10.91	10.90	10.99	10.85	10.83	10.93
CRUISE SHP / AVAILABLE SHP (1st cruise)		90%	94%	99%	90%	94%	99%

The least takeoff GW for the 350 fps rotor cruise tip speed is at the intermediate condition of 77% engine RPM, although that is not very different from the 100% engine RPM. The 54% engine cruise RPM is the worst of all six cases, and the only one where the engine is sized by cruise rather than by the hover takeoff condition, a clear indication of reduced engine performance.

The right-hand column shows LCTR2 GW is not severely affected by the 650 fps rotor cruise tip speed, where the engine is operating its best at 100% RPM, even though the helical tip speed was 840 fps (M 0.82) at the 310 ktas cruise airspeed. Installed SHP is still determined by the hover condition for this case, with a simple single-speed transmission. Not surprisingly, it has the lowest rotor cruise efficiency and therefore required more mission fuel than most other cases.

Table 7 shows the minimum GW solution is for the 500 fps rotor cruise tip speed, not for the 350 fps cruise tip speed. Both of the 500 fps cruise tip speed cases result in a lighter overall GW than the other four cases. While the 500 fps cruise tip speed has slightly lower rotor propulsive efficiency than the 350 fps cases, it is the best overall solution of the 2015 options. Power required for cruise is correspondingly reduced from the 650 fps rotor case, to the 350 fps cases. The 500 fps rotor cases resulted in the lowest transmission ratings, and associated drive system weights. The lightest GW solution is a 500 fps rotor cruise tip speed, 77% engine RPM, and no drive system reduction (100%RPM). It is 3,000 lb lighter than the 350 fps rotor cruise tip speed case at 100% engine RPM.

In general, the following may be concluded from the study with the COTS engine.

- Gross Weight variation was less than expected for different rotor cruise tip speeds.
- The engines were sized to meet the highest power demand in either hover or cruise, with a result where most cases were sized to hover requirements. This produced smaller engines than the original NASA LCTR2 design for comparable conditions (350 fps tip speed).
- Boeing transmission weights and rotor weights were generally higher than NASA LCTR2.
- Sensitivity to design cruise airspeed was found to have as much effect on GW as rotor cruise tip speed. As a consequence, additional work was done to size the LCTR2 configuration for a range of design airspeeds.
- Two-Speed Transmissions were a more efficient means of obtaining the 350 fps rotor tip speed than reducing the engine RPM due to a reduction in engine performance at the 54% reduced speed (350 fps)
- Reduced Engine RPM was equally as efficient as a 2-speed transmission for the 500 fps Vtip.
- The 500 fps rotor tip speed resulted in lower GW than the 350 fps rotor tip speed, suggesting that the optimum tip speed may lie between 350 and 500 fps for a 310 ktas cruise airspeed.

Figure 54 shows that both the 350 fps and 500 fps rotor tip speeds result in lower GW than the 650 fps Vtip. The COTS engine operating at 54% RPM with a single-speed transmission is not competitive.

Much of the weight sensitivity for the LCTR2 comes from the dynamic system components, consisting of the rotor weight, drive system weight, engine weight and weight of fuel. These four elements are graphed in Figure 55 for the 350 fps cruise tip speed. Fuel is obviously the dominant element, representing 15.4% of Gross Weight. The combination of rotor group weight and drive system group weight constitute 17.7% of Gross Weight.

Variation of component weights at different engine RPMs tracks the GW trend. It is often difficult to determine what elements are driving factors and which are simply responding. But the figure shows the fuel/GW ratio is higher at 54% engine RPM, identifying it as the factor that drove up the GW for this case. If GW had been driven by an EW element, the fuel/GW fraction would have been similar to the other two cases.

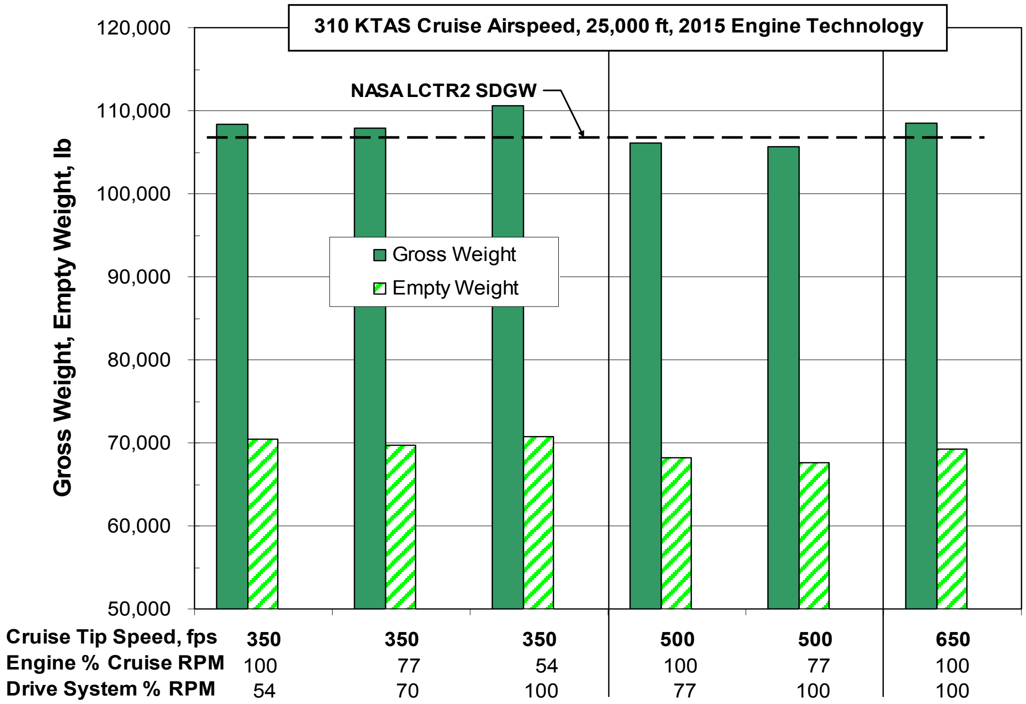


Figure 54. 2015 Engine: Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

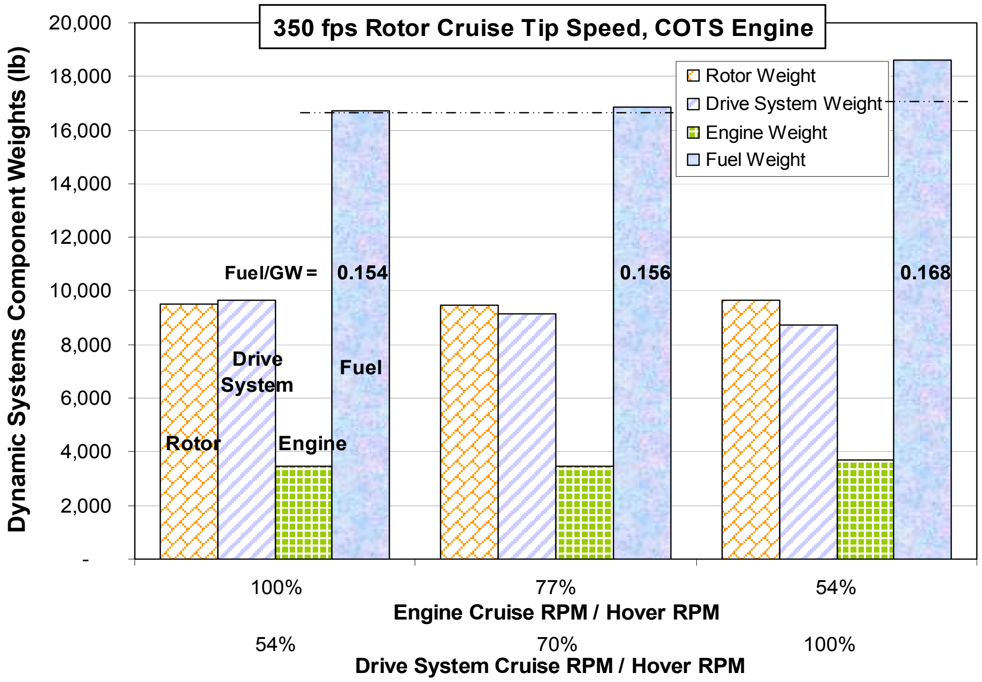


Figure 55. Changes in Dynamic System Weight at 350 fps Rotor Tip Speed

Installed SHP and engine weights are graphed in Figure 56 for all six cases. The engine inefficiency at 54% engine RPM (for the 350 fps / 100% drive system RPM), stands out as a primary cause for the highest GW.

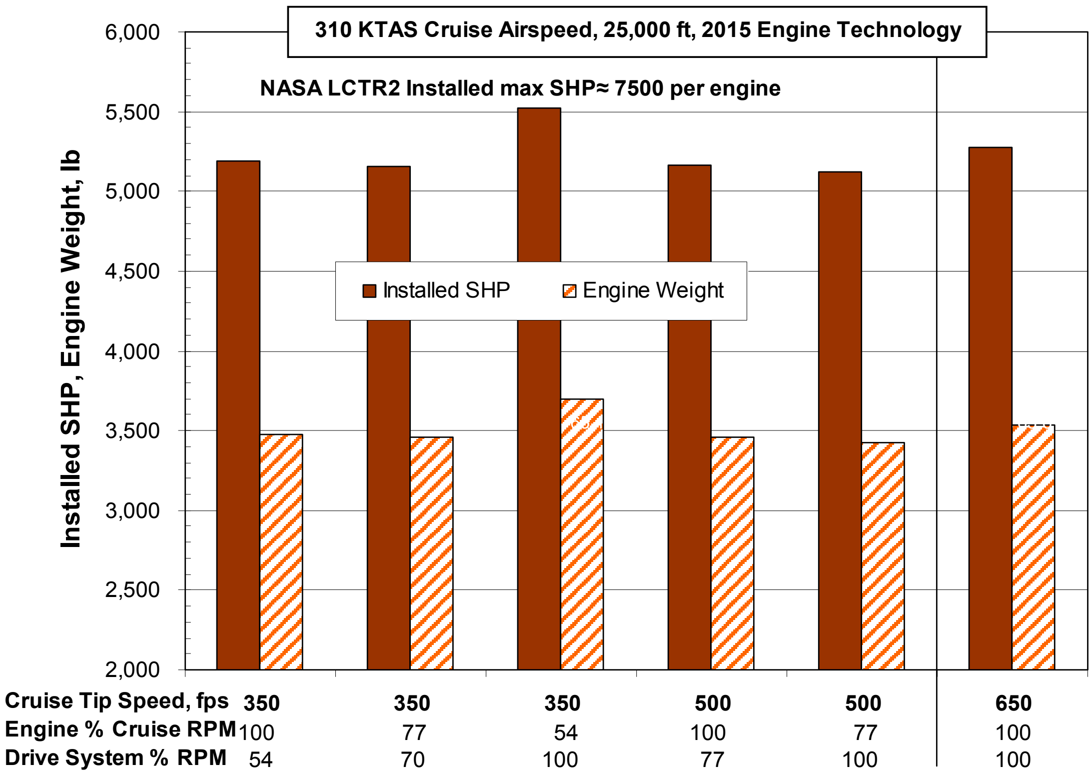


Figure 56. COTS Engine Installed SHP and Weight

Finally, Figure 57 compares the rotor cruise efficiency for all six cases. It is interesting that the two 500 fps cruise tip speed cases have slightly lower cruise efficiency than the 350 fps tip speed, but still result in a lower GW than the 350 fps cases. Table 7 shows the drive system weights for the 500 fps cases as significantly lighter than those of the 350 fps cases, suggesting that higher output torque required for a 350 fps rotor is a significant factor.

The 650 fps cruise tip speed has the lowest rotor cruise efficiency, but the GW is competitive to the 350 fps rotor tip speeds. Again, a compensating factor for the 650 fps rotor may be a lower drive system weight, 600 to 1500 lb lighter than the drive system weight for the 350 fps rotor cases.

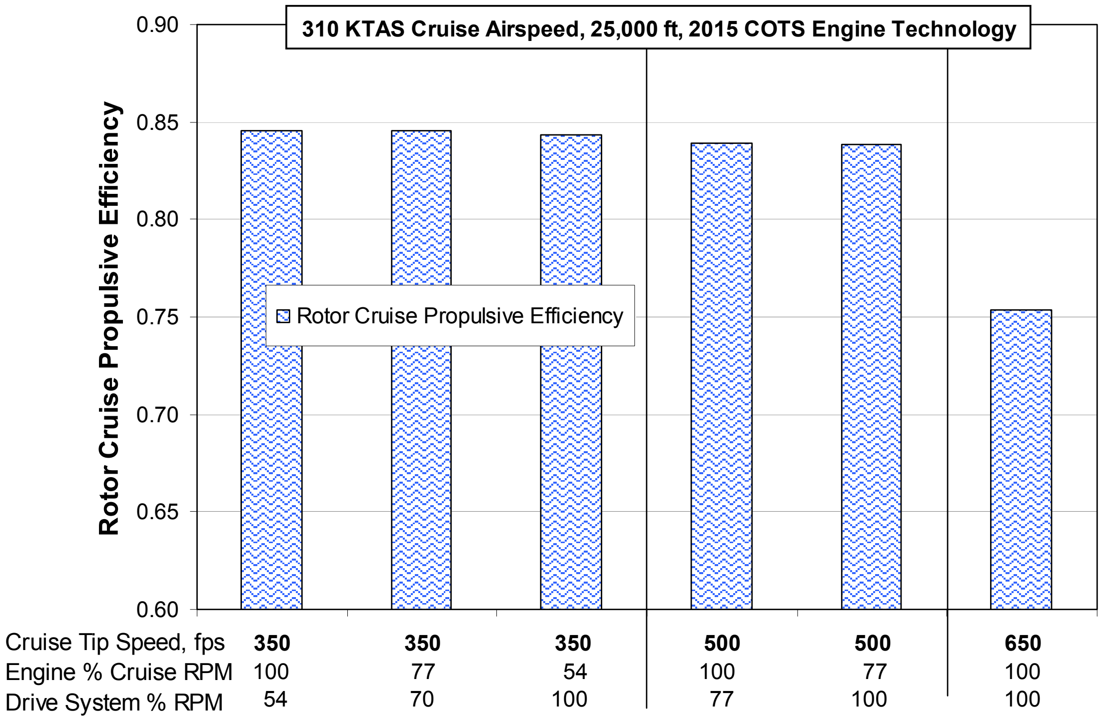


Figure 57. Rotor Cruise Propulsive Efficiency (2015 Engine Cases)

7.2.1 2015 Model Sensitivity To Cruise Airspeed

To highlight sensitivity to off-design conditions (using 2015 technology), this section shows results when the aircraft is resized over a range of airspeeds, applying the same 310 ktas rotor designs and cruise performance maps at other airspeeds. The LCTR2 rotor solidity and disc loading were maintained, as in the previously sized cases, allowing the rotor diameter to change with the sized gross weight.

The six combinations of rotor cruise tip speed and engine/drive system RPM were resized for design cruise airspeeds of 270 ktas up to 350 ktas, all at 25,000 ft altitude. The engine size was determined by the greater of hover takeoff power required or the newly specified cruise power required, and the aircraft cruised at the newly specified design cruise airspeed, i.e. increasing the mission fuel and installed SHP for higher design airspeeds.

Figure 58 shows the expected overall effect, that gross weight increases as design airspeed increases. The data at 310 ktas is the same as previously shown. Beyond that, there are some interesting observations.

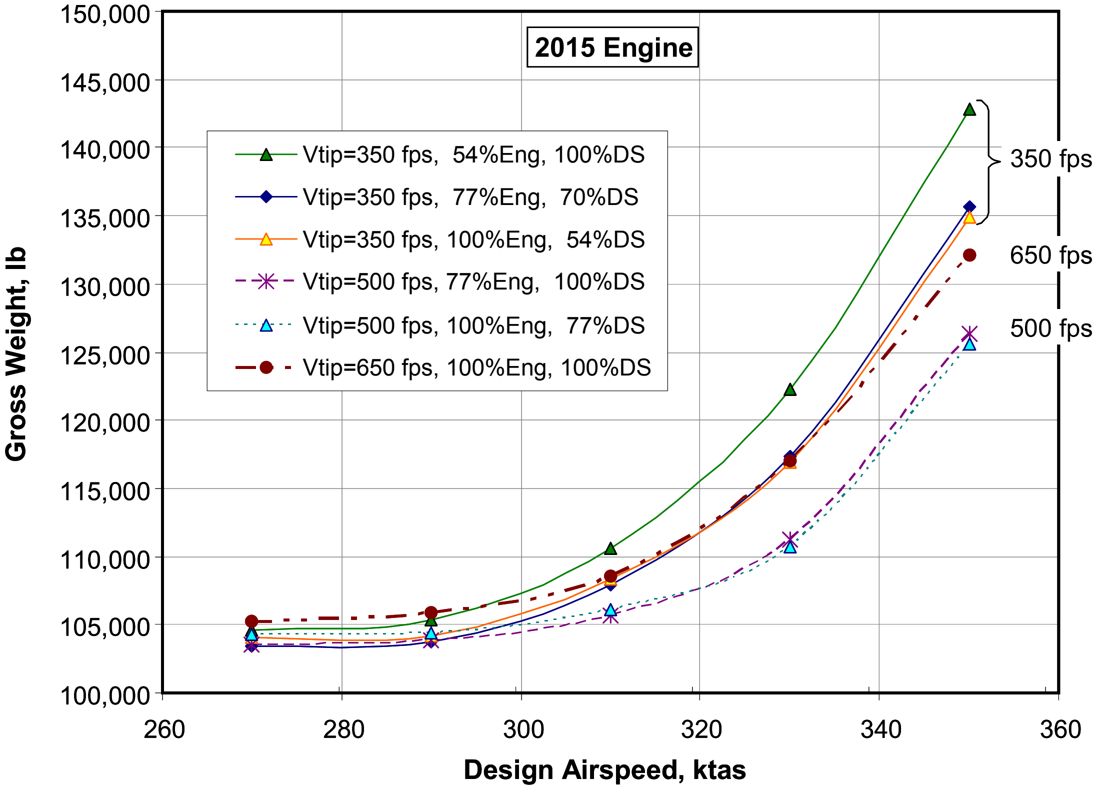


Figure 58. Gross Weight Variation with New Design Airspeeds

The rotor design for 500 fps cruise tip speed was previously shown to provide the lowest GW solution at 310 ktas design airspeed. Figure 58 shows it continues to provide the lowest GW solution up to 350 ktas airspeed, significantly below that of the 350 fps rotor cruise tip speed. Degraded engine performance is the cause of high GW solutions for the 350 fps tip speed with 54% engine RPM.

The helical Mach number at the rotor tip is shown in Figure 59 for the three rotor cruise tip speeds. The 650 fps rotor tip speed reaches 0.86 tip helical tip Mach number at 350 ktas, which is certain to degrade performance. The 500 fps and the 350 fps tip speed rotors are viable over wider operational conditions.

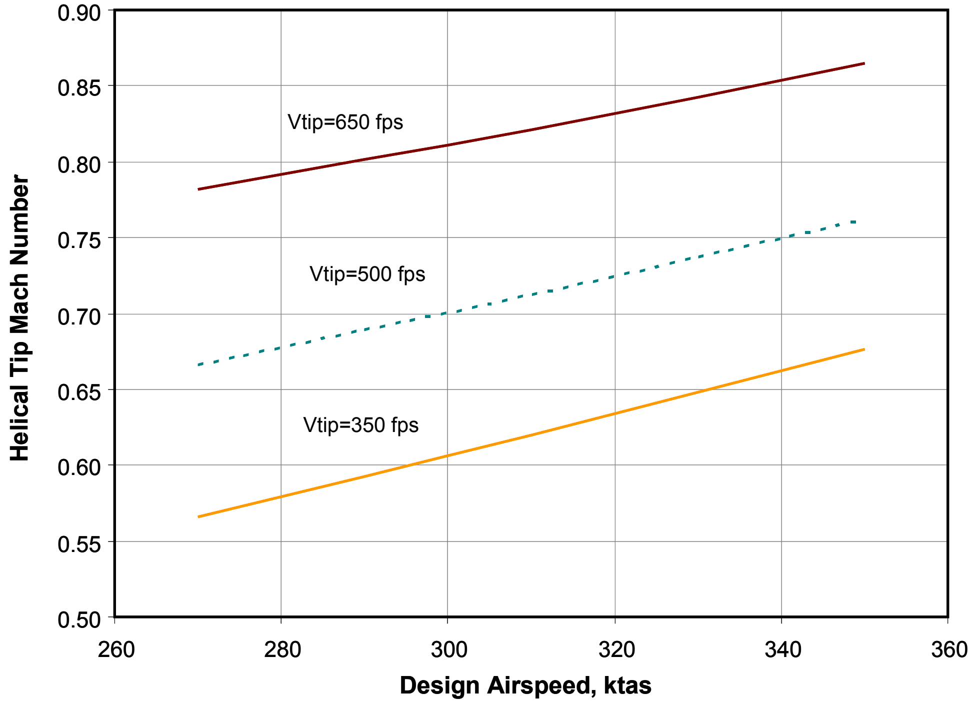


Figure 59. Rotor Blade Tip Helical Mach Number Versus Design Airspeed

Finally, the sensitivity of mission fuel requirement to design airspeed, shown in Figure 60, reflects increased GW with design airspeed and reduced rotor propulsion efficiency at higher airspeeds.

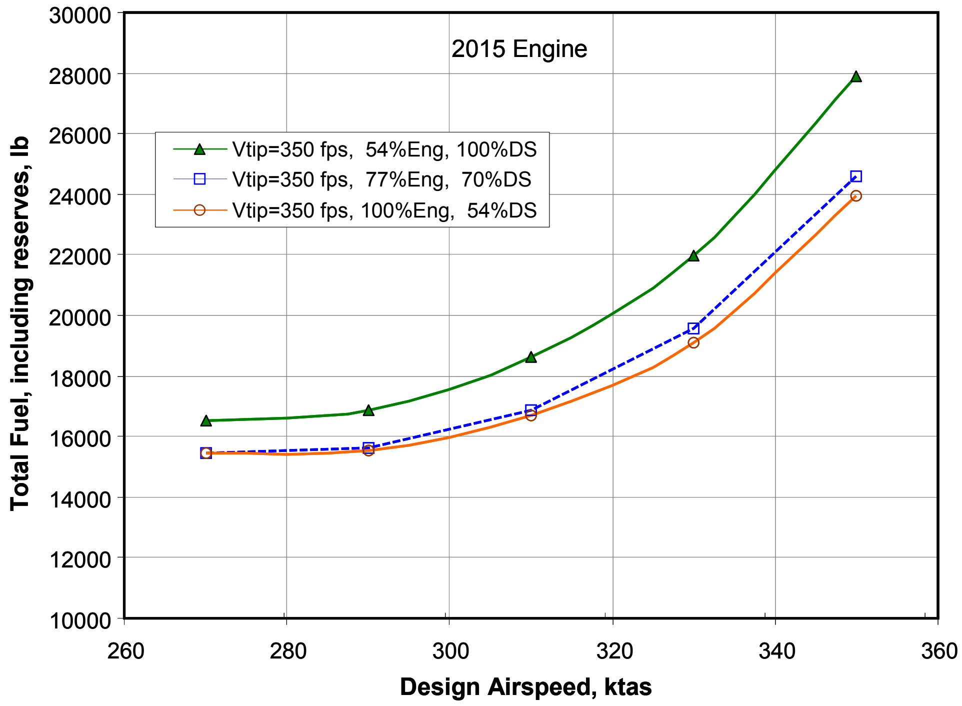


Figure 60. Mission Fuel Required Versus Design Airspeed

7.3 Vehicle Sizing with Advanced Engines

Sizing results for the 2025 and 2035 engines are significantly different from the 2015 COTS engine. Improved fuel flow at reduced engine RPM and dry engine weight have very notable effects on the aircraft GW. The impact on engine power available was shown in section 3.3.1 and engine weight was discussed in section 3.2.5.1. An overall comparison of fuel flow from the three engine technologies is discussed below.

Rolls-Royce generated fuel flow as a function of airspeed and altitude for each of the three engine technologies. Figure 61 shows relative fuel flow of the three engines at 100% RPM, 77% RPM and at 54% RPM at Mach 0.5 cruise, 25,000’/ISA. The 2015 COTS engine has substantially higher fuel flow at 54% RPM, and a reduction in available power, as expected from current engine designs. In contrast, the 2025 engine with its variable-geometry power turbine has the highest fuel flow at 100% RPM, with substantially lower fuel flow at 77% and at 54%RPM, giving it a valuable advantage for operations at reduced cruise RPM. Furthermore, the available horsepower increases at reduced RPM, although that represents a large increase in torque. The increased output shaft horsepower at reduced operating RPM is an advantage for any concept targeting a high-speed cruise condition at MCP. But the advantage may be limited by the imposition a flat rating at MRP (takeoff) in a production engine.

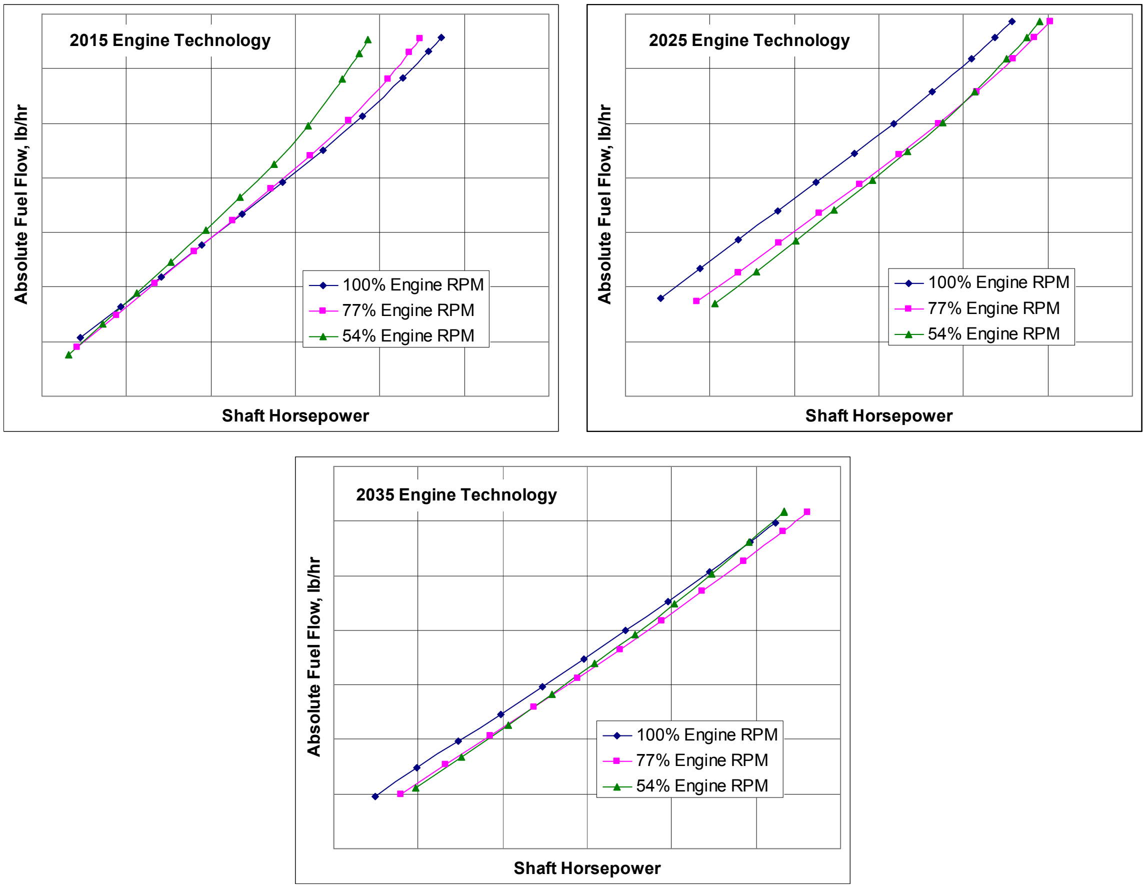


Figure 61. Relative Fuel Flow Versus Engine RPM For The COTS, 2025 And 2035 Engines

The 2035 engine offers further reductions in specific fuel consumption, where the SFC is much less sensitive to changes in its operating RPM. This high technology engine promises over a 25% reduction in SFC, and at a lighter weight (lb/shp).

7.4 LCTR2 Sized With The 2025 Technology Engine (Variable Geometry Variable Speed Power Turbine Engine)

Sizing results for LCTR2 with the 2025 EIS engine (PD646_11751) reflect increased engine weights, reduced drive system weights with lower drive system losses, and very different engine fuel flow characteristics. Structural weights were based on 2025 technology throughout this study to avoid confusing the results by introducing another variable.

Table 8 shows sizing results for the 2025 engine. They are more easily understood by re-examining the fuel flow of the 2025 engine relative to the COTS engine. The 2025 engine is clearly a major improvement over the COTS engine when operating at reduced RPM. It displays a lower SFC at reduced RPM, whereas the COTS engine lost power and suffered increased SFC at reduced RPM.

The 2025 dry engine weighs 200 lbs more than the 2015 engine, 0.1674 lb/shp versus 0.1427 lb/shp for the 2015 engine. The four-engine LCTR2 with 2025 engines added 800 lb per aircraft and, as previously noted, the dry engine weight is amplified by corresponding increases in related propulsion system weights. However, the 2025 engine has lower fuel burn, tailored for best performance at the desired reduced operating RPM. The concept was then to accept a relatively small increase in engine weight to gain a large expected benefit from more efficient fuel burn.

Applying the 2025 engine results in as much as a 7% increase in aircraft gross weight. Table 8 shows data from sizing the six combinations of rotor tip speed and engine-drive system RPM reductions. This table can be compared directly to Table 7 for the 2015 engine cases.

Three cases at 350 fps tip speed (54% of hover RPM) examined the effect of engine RPM reduction versus drive system RPM reduction. Highlighted cells in the table indicate which condition sized the engine; hover or cruise. The engine was sized by hover for all cases except for the 650 fps cruise tip speed case. Trends from the 2025 engine have some similarity to the 2015 engine results, i.e. at 100% engine RPM the GW for 650 fps cruise tip speed is nearly the same as the 350 fps cruise tip speed. However, fuel flow for the 2025 engine is significantly higher than the 2015 engine at 100% engine RPM, which increases GW for all three cases at 100% RPM.

Aircraft Gross Weight trend at 350 fps rotor cruise tip speed is drastically different from that of the COTS engine. GW from the COTS engine cases increased with reduced engine RPM (refer to Figure 48), but GW actually decreases with reduced engine RPM for the 2025 engine, owing to the significant fuel efficiency from the 2025 engine’s variable-geometry power turbine. A single-speed transmission for the 54% engine RPM is lighter than 2-speed solutions, contributing further to a lighter GW at 54% engine RPM and 100% drive system RPM. Improved engine fuel efficiency at 54% engine RPM combined with a single-speed transmission yields the lowest GW solutions for this group, one at 350 fps tip speed and the other at 500 fps tip speed.

Table 8. Summary of Six LCTR2 Aircraft Sized with 2025 EIS Engine

Sizing Summary for LCTR2 Rotor Tip Speed and Drive System RPM with 2025 EIS Engine

CONDITION						
ROTOR Cruise Tip Speed	350	350	350	500	500	650
Engine Cruise RPM / Hover RPM	100%	77%	54%	100%	77%	100%
Drive System Cruise RPM / Hover RPM	54%	70%	100%	77%	100%	100%
Drive System Type	2-speed	2-speed	Single speed	2-speed	Single speed	Single speed
GROSS WEIGHT	113,264	109,028	107,205	111,883	106,656	115,394
Wing Weight	7,147	6,897	6,798	7,155	6,842	7,505
Rotor Weight	9,897	9,591	9,439	9,521	9,074	9,832
Engine Weight	4,139	3,981	3,900	4,148	3,937	4,373
Drive System Weight	9,112	8,685	8,047	8,229	7,397	8,165
EMPTY WEIGHT	72,758	70,784	69,499	71,385	68,572	73,030
OWE	74,208	72,234	70,949	72,835	70,022	74,480
FUEL	19,258	17,005	16,465	19,266	16,839	21,149
DIMENSIONS						
FUSELAGE Equivalent Diameter	9.0	9.0	9.0	9.0	9.0	9.0
WING Span, Overall	108.8	107.6	107.0	108.4	106.9	109.5
Area Exposed	1054.6	1018.7	1001.6	1045.4	996.5	1078.2
Aspect Ratio, geometric	11.23	11.36	11.44	11.25	11.46	11.11
MAIN ROTOR Diameter	66.84	65.58	65.02	66.43	64.86	67.46
Solidity	0.1432	0.1432	0.1432	0.1432	0.1432	0.1432
Hover Tip Speed	650	650	650	650	650	650
Disc Loading, W/A	16.1	16.1	16.1	16.1	16.1	16.1
Thrust Coefficient, CT/σ	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
PROPULSION						
ENGINE RATING (Max SHP, SLS)						
Installed max SHP (SLS) per Engine	5,379	5,174	5,069	5,390	5,116	5,682
Engine Scale Factor for Hover	0.665	0.640	0.627	0.666	0.633	0.688
Engine Cruise Scale Factor for 310 kt @ 25K'	0.621	0.551	0.549	0.623	0.546	0.703
TRANSMISSION						
Transmission Rating (Hover)	22,506	22,116	21,806	20,546	19,588	21,256
Transmission Rating (Cruise)	12,119	11,909	11,741	15,804	15,068	21,256
Losses	3.71%	3.61%	3.23%	4.13%	3.66%	3.90%
PERFORMANCE						
ROTOR HOVER TAKEOFF FM	0.775	0.775	0.775	0.768	0.768	0.765
AIRCRAFT CRUISE ALTITUDE, ft	25,000	25,000	25,000	25,000	25,000	25,000
AIRCRAFT DESIGN & CRUISE AIRSPEED, ktas	310.0	310.0	310.0	310.0	310.0	310.0
HELICAL MTIP @ 25K'	0.62	0.62	0.62	0.71	0.71	0.82
ROTOR CRUISE EFFICIENCY	0.844	0.846	0.846	0.836	0.839	0.751
CRUISE SHP / AVAILABLE SHP (1st cruise)	92%	85%	86%	92%	85%	99%

The 2025 engine was tailored to provide lower fuel consumption than the COTS engine when operating at reduced RPM. However, fuel consumption is roughly 10% higher at normal 100% RPM. This is evident in the results for the 350 fps rotor tip speeds. GW consistently increased by 6.5% to 7% over the COTS engine with the 2025 engine at 100% RPM in cruise. The impact on mission fuel is obvious.

Conversely, the one case with the 2025 engine cruising at its optimum 54% RPM results in a 2% drop in GW, and the mission fuel is less than that from the 2015 engine case. As noted, it is difficult at times to distinguish what parameter is driving a trend versus following a trend. It is reasonably clear in this case by examining the ratio of mission fuel / GW. That fuel ratio was 16.8% from the 2015 engine case, but dropped to 15.3% in the 2025 engine for the case of 350 fps cruise tip speed, 100% drive system RPM, and 54% engine RPM. And that is the only case out of the six where the aircraft GW was lighter than the corresponding 2015 engine case.

The graph of GW and EW in Figure 62 displays higher resulting GW for engine operation at 100% RPM, and lower GW for engine operation at 77% and 54% RPM, all deriving from the variable-geometry power turbine and higher dry weight of the 2025 engine. This figure can be compared to Figure 54 for the COTS engine.

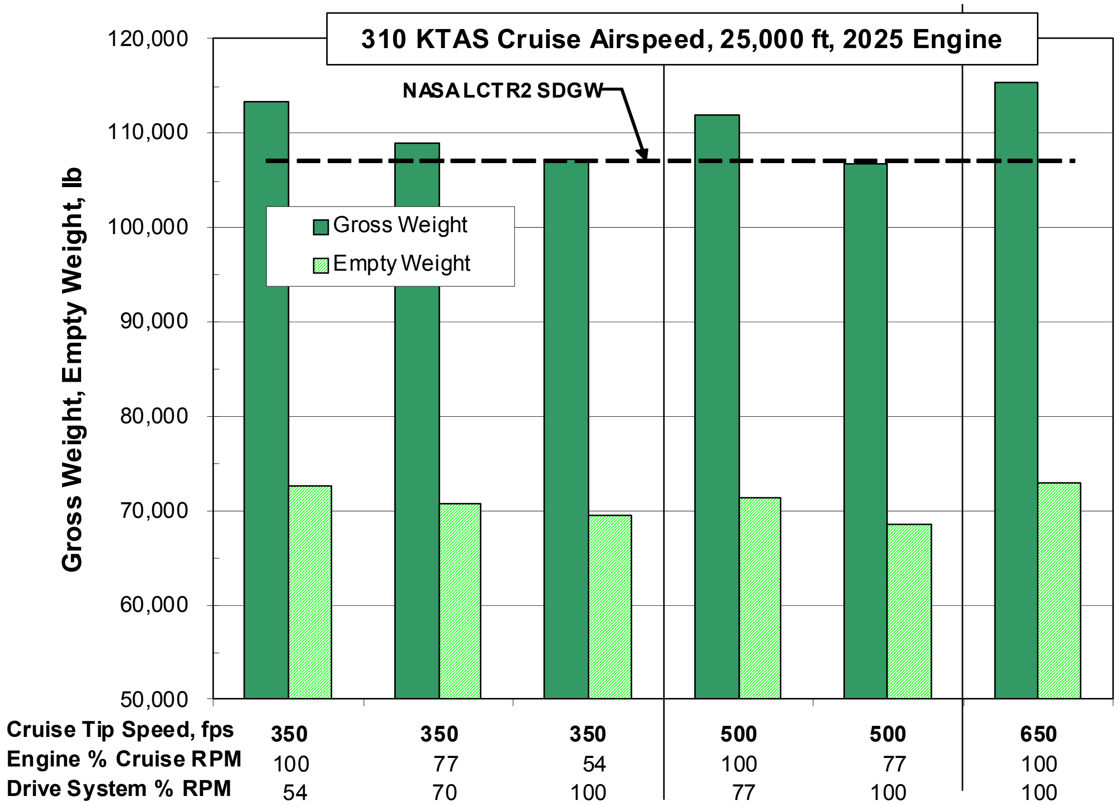


Figure 62. 2025 Engine: Effect of Rotor Tip Speed and Engine/Drive System RPM on GW

Results identify that propulsion system weights (fuel, drive system, engines, engine system, and engine structure) drive the GW, making up 31% of aircraft empty weight as shown in Figure 63. The pattern is very similar to the preceding GW chart, verifying these were the primary terms that drove the GW pattern. Drive system and rotor weight far outweigh the engine system weights.

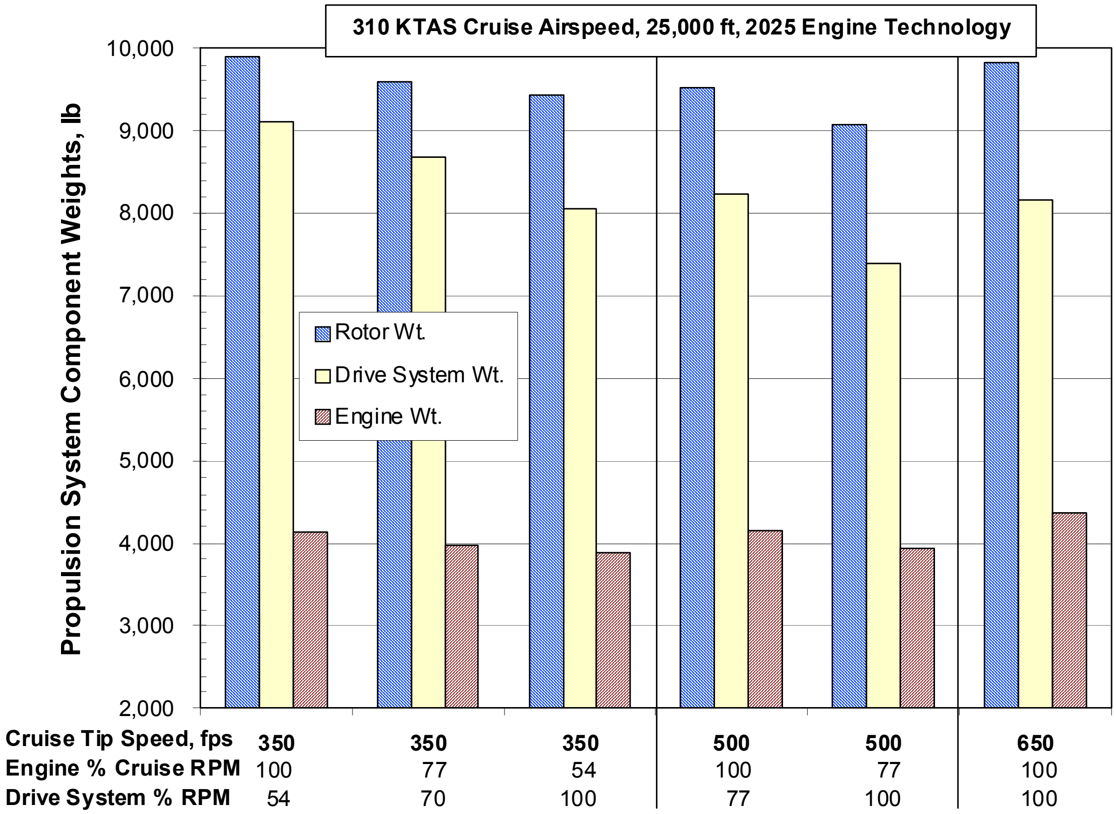


Figure 63. Propulsion System Component Weights for 2025 Engine

The breakdown of component weights in Figure 64 shows that Fuel is the dominant part, constituting 50% of the group's weight. The combined weight of the engine weight, the engine systems, and the engine section make up another 26%.

Engine installed SHP naturally follows the aircraft GW trend since installed SHP was determined by the hover condition for all but the 650 fps case, as shown in Figure 65.

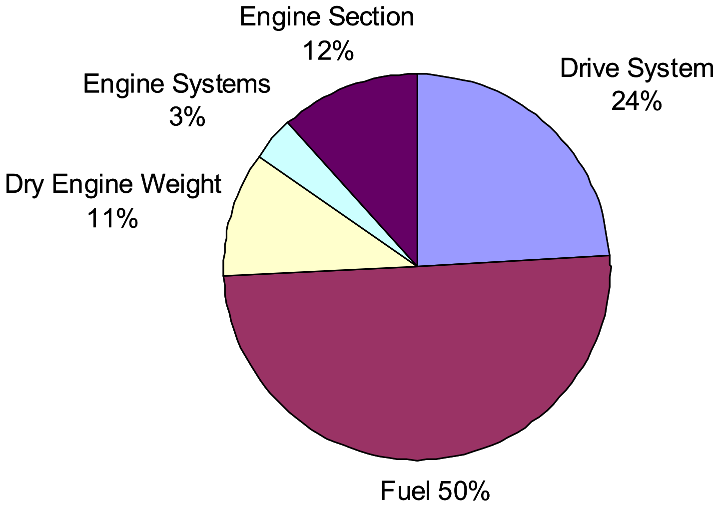


Figure 64 Breakdown of Component Weights.

The 2025 engine required much more fuel than the COTS engine when operating at 100% RPM, but gave significant reductions in mission fuel operating at 54% RPM. Mission fuel at the 77% RPM condition was about the same as the 2015 engine.

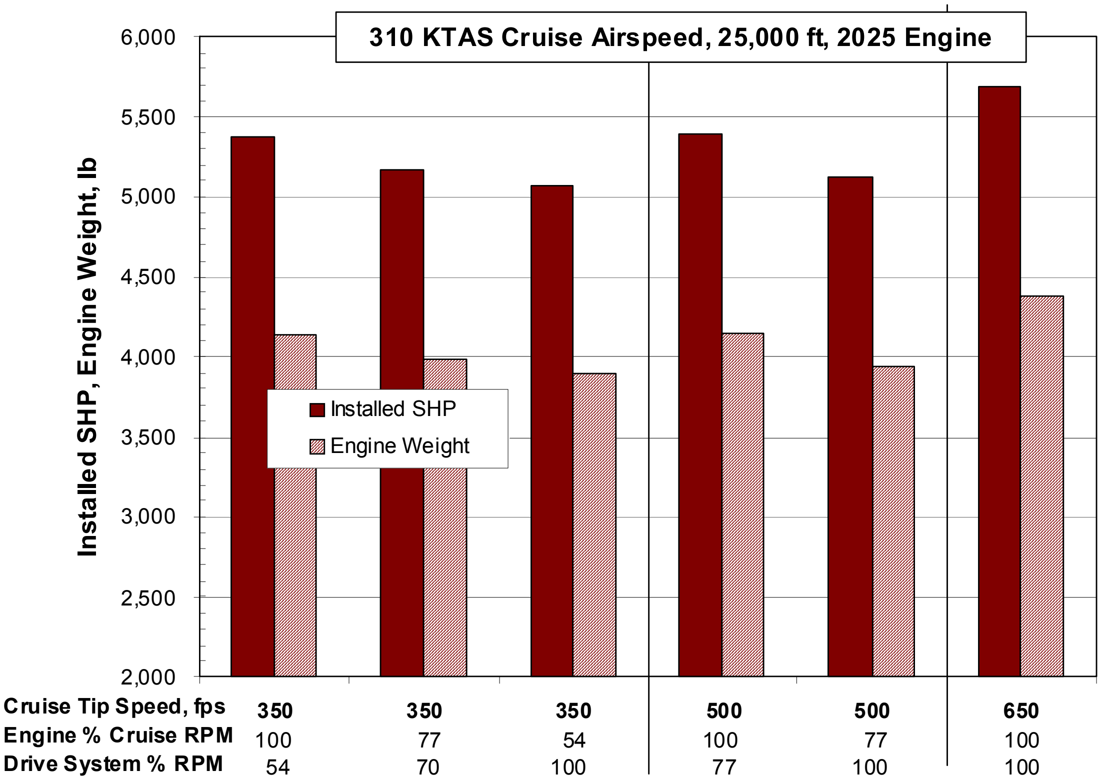


Figure 65. 2025 EIS Engine Installed SHP and Weight

A comparison was made of the aircraft gross weight with the 2015 engine to that with the 2025 engine.. Not surprisingly, the great reduction in 2025 fuel flow at reduced RPM drastically reduced the 2025 GW at 350 fps tip speed, 54% engine RPM and 100% drive system RPM. Similarly, the higher fuel flow of the 2025 engine at 100% RPM drove GW up for the three cases at 100% RPM.

7.5 LCTR2 Sized With The 2035 Variable Geometry Power Turbine Engine

The LCTR2 was resized using the Rolls-Royce 2035 VG-VSPT engine (PD647-11772) performance and weight, and estimated weight and efficiency for a 2035 drive system. Structural weights were based on 2025 technology as in the previous sizing studies.

As observed in the 2025 engine study, mission fuel has a dominant effect on LCTR2 sizing for the constrained parameters in this study. Figure 61 showed fuel flow versus shaft horsepower for each of the three operating RPM's, for each engine. That data is plotted below with all three engines on the same graph at a selected RPM, Figure 66, providing a direct comparison of engine technologies on fuel flow at a given RPM.

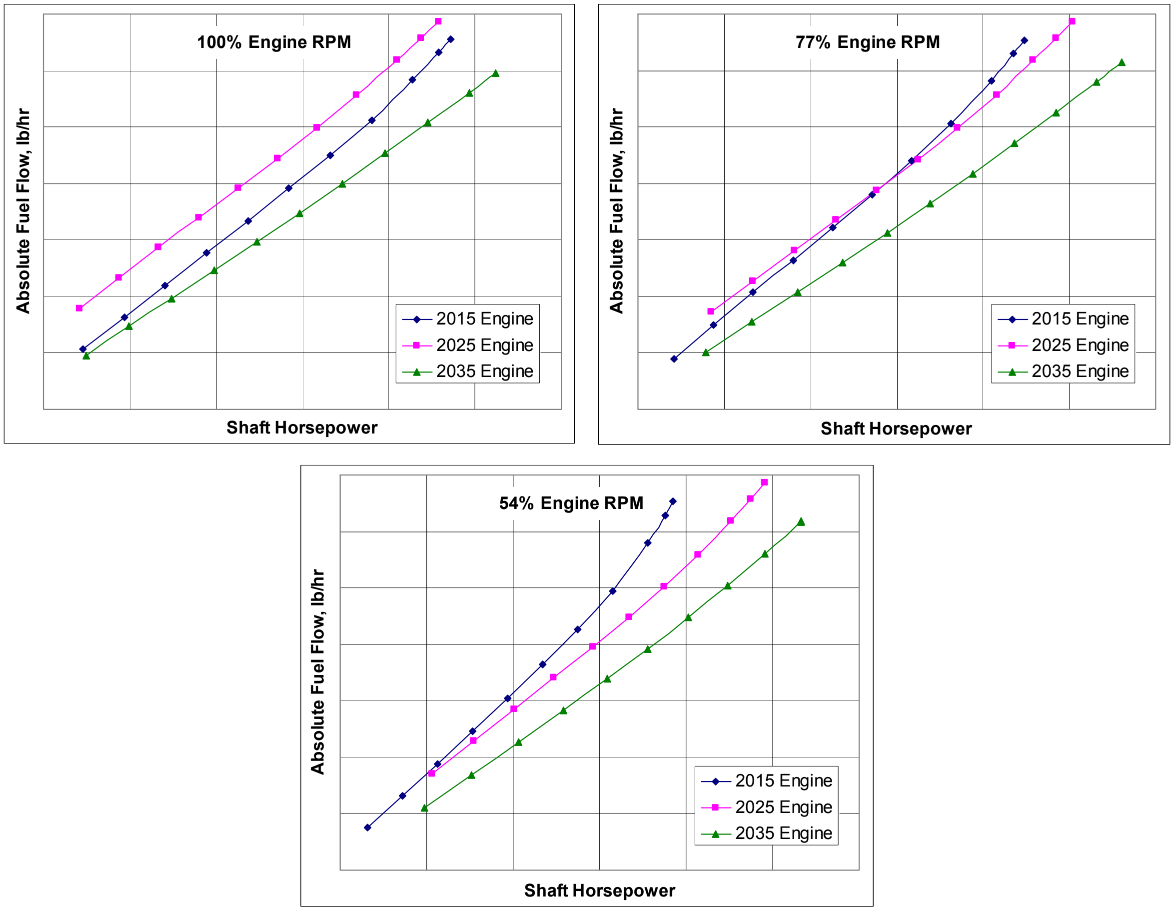


Figure 66. Relative Fuel Flow for the COTS, 2025 and 2035 Engines At Specific RPMs

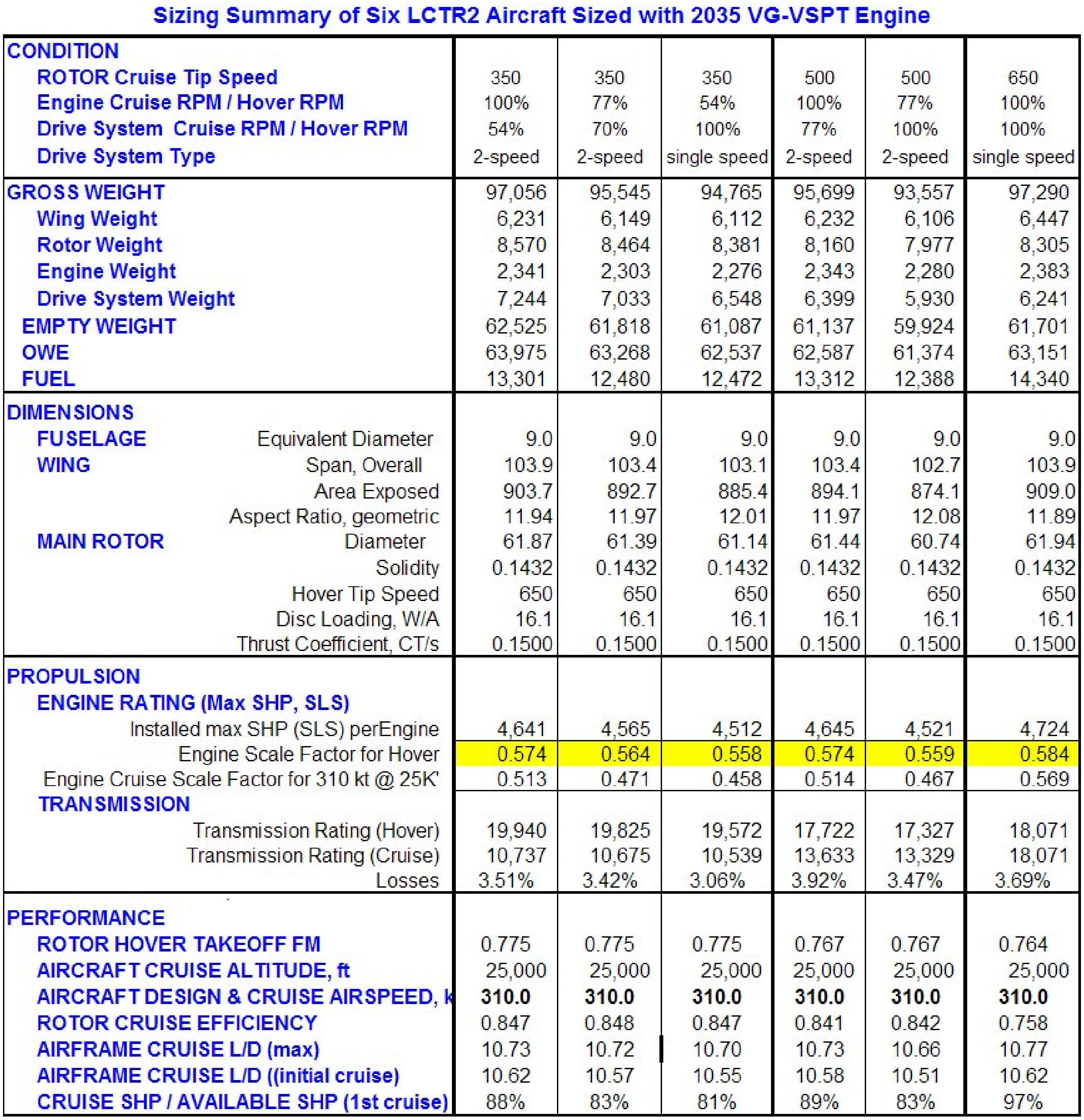
Fuel flow of the 2035 engine is significantly less than either the COTS engine or the 2025 engine at all operating RPMs. And the 2035 engine is significantly lighter; weighing 25% less than the COTS engine (per shp), and 34% less than the 2025 engine (per shp).

This double benefit of reduced fuel and reduced engine weight provides a substantial reduction in aircraft GW for all combinations of drive system and engine operating RPM, at all three rotor cruise tip speeds. A summary of the six sized cases are shown in Table 9. Fuel flow penalties of the 2025 engine are nearly eliminated at 100% RPM. Overall, the 2035 engine results in a remarkable 14% average reduction in GW.

Gross weight of the 350 fps tip speed operating at 77% engine RPM is reduced by 2,000 lb, relative to the 100% engine RPM. Overall, the 2035 engine fuel flow is much less sensitive to operating RPM than either of the previous engines, resulting in very little variation in GW across the combinations of engine and drive system RPM. The engine is sized by hover for all cases.

The 500 fps rotor tip speed with a 77% engine RPM and the lighter weight single-speed drive system again provided the lowest GW and EW as well as the lowest fuel consumption.

Table 9. Summary of Six LCTR2 Aircraft Sized with 2035 VG-VSPT Engine



Sizing Summary of Six LCTR2 Aircraft Sized with 2035 VG-VSPT Engine

CONDITION							
ROTOR Cruise Tip Speed		350	350	350	500	500	650
Engine Cruise RPM / Hover RPM		100%	77%	54%	100%	77%	100%
Drive System Cruise RPM / Hover RPM		54%	70%	100%	77%	100%	100%
Drive System Type		2-speed	2-speed	single speed	2-speed	2-speed	single speed
GROSS WEIGHT		97,056	95,545	94,765	95,699	93,557	97,290
Wing Weight		6,231	6,149	6,112	6,232	6,106	6,447
Rotor Weight		8,570	8,464	8,381	8,160	7,977	8,305
Engine Weight		2,341	2,303	2,276	2,343	2,280	2,383
Drive System Weight		7,244	7,033	6,548	6,399	5,930	6,241
EMPTY WEIGHT		62,525	61,818	61,087	61,137	59,924	61,701
OWE		63,975	63,268	62,537	62,587	61,374	63,151
FUEL		13,301	12,480	12,472	13,312	12,388	14,340
DIMENSIONS							
FUSELAGE	Equivalent Diameter	9.0	9.0	9.0	9.0	9.0	9.0
WING	Span, Overall	103.9	103.4	103.1	103.4	102.7	103.9
	Area Exposed	903.7	892.7	885.4	894.1	874.1	909.0
	Aspect Ratio, geometric	11.94	11.97	12.01	11.97	12.08	11.89
MAIN ROTOR	Diameter	61.87	61.39	61.14	61.44	60.74	61.94
	Solidity	0.1432	0.1432	0.1432	0.1432	0.1432	0.1432
	Hover Tip Speed	650	650	650	650	650	650
	Disc Loading, W/A	16.1	16.1	16.1	16.1	16.1	16.1
	Thrust Coefficient, CT/s	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
PROPULSION							
ENGINE RATING (Max SHP, SLS)							
	Installed max SHP (SLS) perEngine	4,641	4,565	4,512	4,645	4,521	4,724
	Engine Scale Factor for Hover	0.574	0.564	0.558	0.574	0.559	0.584
	Engine Cruise Scale Factor for 310 kt @ 25K'	0.513	0.471	0.458	0.514	0.467	0.569
TRANSMISSION							
	Transmission Rating (Hover)	19,940	19,825	19,572	17,722	17,327	18,071
	Transmission Rating (Cruise)	10,737	10,675	10,539	13,633	13,329	18,071
	Losses	3.51%	3.42%	3.06%	3.92%	3.47%	3.69%
PERFORMANCE							
ROTOR HOVER TAKEOFF FM		0.775	0.775	0.775	0.767	0.767	0.764
AIRCRAFT CRUISE ALTITUDE, ft		25,000	25,000	25,000	25,000	25,000	25,000
AIRCRAFT DESIGN & CRUISE AIRSPEED, k		**310.0**	**310.0**	**310.0**	**310.0**	**310.0**	**310.0**
ROTOR CRUISE EFFICIENCY		0.847	0.848	0.847	0.841	0.842	0.758
AIRFRAME CRUISE L/D (max)		10.73	10.72	10.70	10.73	10.66	10.77
AIRFRAME CRUISE L/D ((initial cruise)		10.62	10.57	10.55	10.58	10.51	10.62
CRUISE SHP / AVAILABLE SHP (1st cruise)		88%	83%	81%	89%	83%	97%

The worst case (highest GW and EW) continued to be the 650 fps rotor tip speed case, about 11% higher than the average of the other two 2035 cases.

As with the other engine technologies, the installed SHP follows the GW, where both are affected by the combination of fuel flow sensitivity to engine RPM, rotor propulsive efficiency dependency on tip speed, and drive system weight and efficiency. The trend of Gross Weight in Figure 67 is similar to that of installed SHP in Figure 68.

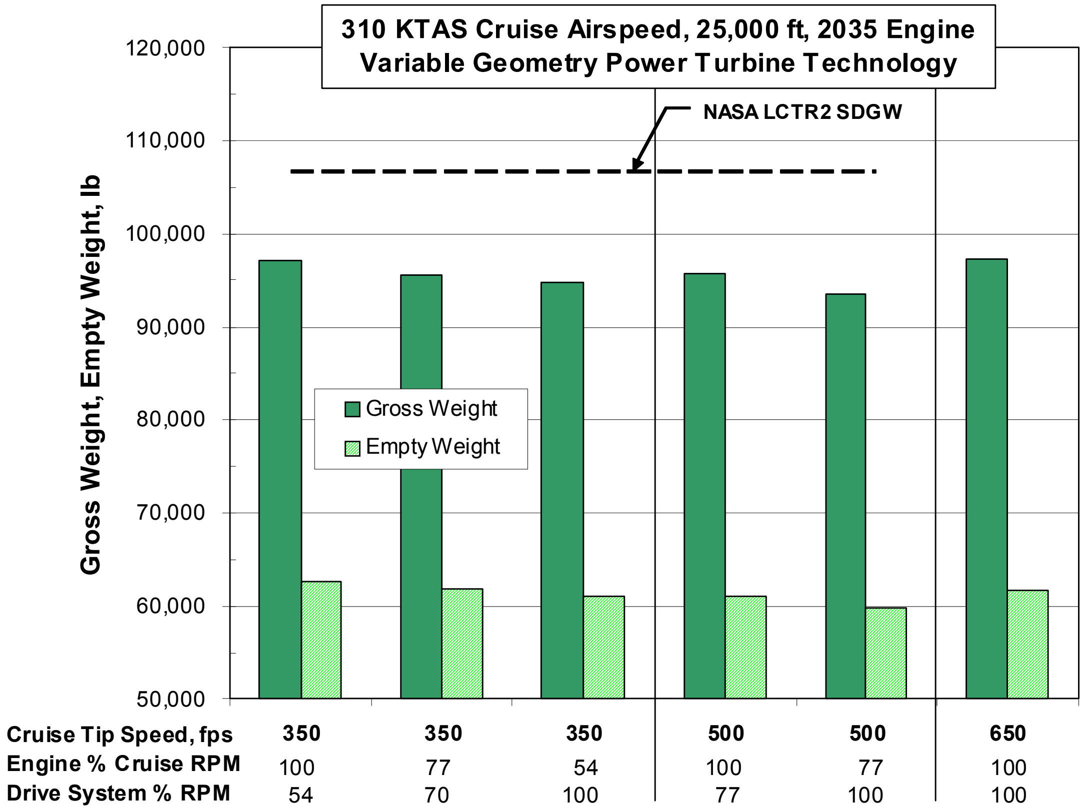


Figure 67. 2035 VG VSPT Engine: Rotor Tip Speed and Engine/Drive System RPM Effect on GW

The discriminating propulsion system weights are the rotors, the drive system, and the engines, displayed in Figure 69.

The ratio of Fuel/GW is a meaningful metric, as it reflects the combination of rotor cruise efficiency, drive system efficiency and engine weight and fuel consumption. Figure 70 shows the Fuel/GW fraction for all three engine technologies and all rotor cruise tip speeds. The following observations are readily made from this chart.

- Mission Fuel/GW ratio for the 2025 engine was worse than the 2015 engine at 100% engine RPM, essentially the same at 77% engine RPM, and was better at the single case with 54% engine RPM.
- Mission Fuel/GW ratio for the 2035 engine was better than the other two engine technologies for all combinations of engine and drive system RPMs for reduced rotor cruise tip speed. The 2035 engine had a slightly higher Fuel/GW ratio at 100% RPM.
- A 500 fps rotor cruise tip speed with a single-speed drive system and 77% engine RPM is as good a solution as the 350 fps rotor tip speed for the 310 ktas cruise condition.

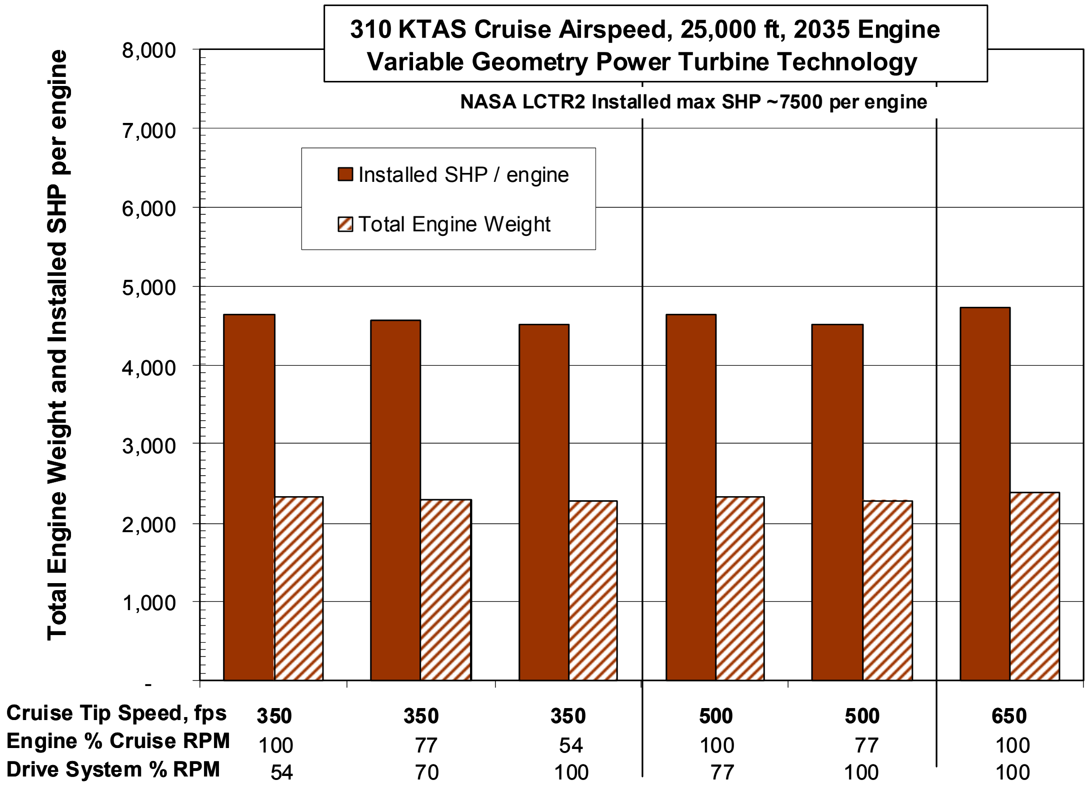


Figure 68. 2035 VG-VSPT Engine Installed SHP and Weight

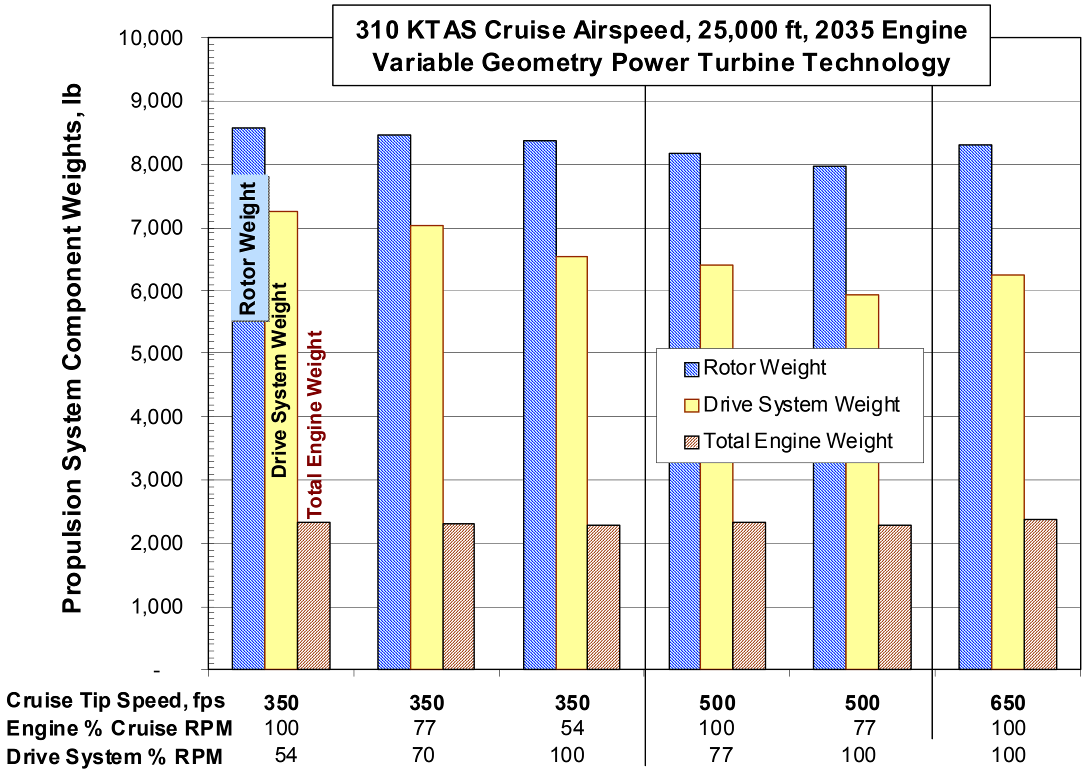


Figure 69. Propulsion System Component Weights for 2035 VG-VSPT Engine

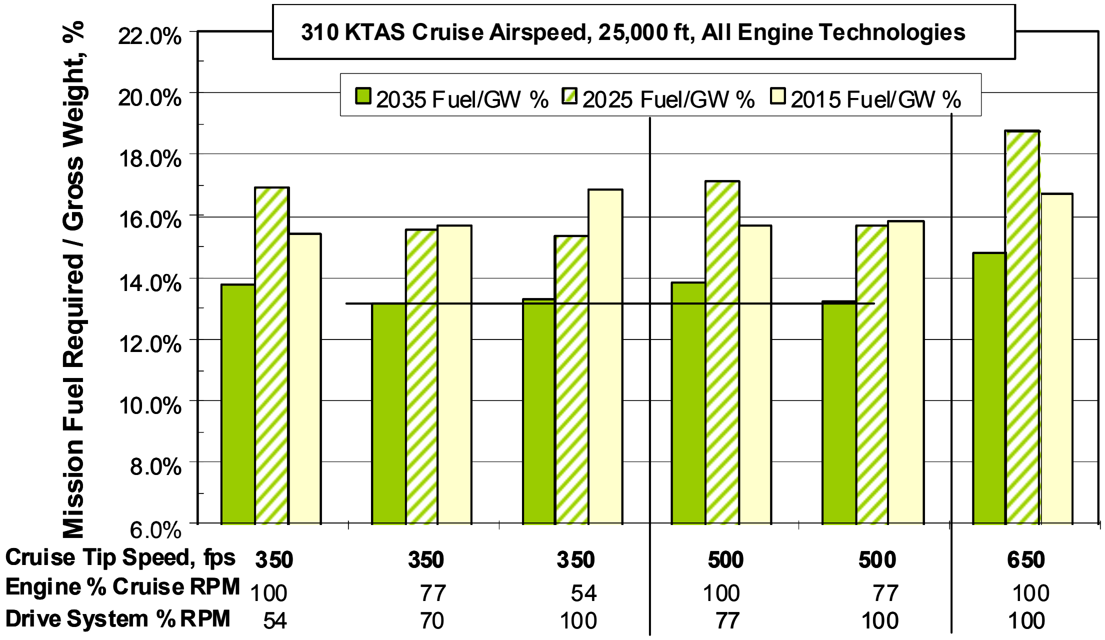


Figure 70. Ratio of Mission Fuel / GW for All Engine Technologies and Rotor Tip Speeds

Interestingly, the 500 fps rotor tip speed requires only 2% more fuel than the lowest fuel case at 350 fps cruise tip speed, 16,994 lb versus 16,647 lb.

7.6 LCTR2 Sized With The 2035 Fixed Geometry Power Turbine Engine

The LCTR2 was resized with the 2035 FG-VSPT engine for the same three rotor cruise tip speeds evaluated before with the 2035 VG-VSPT. The additional rotor design with a 422 fps cruise tip speed (65% of hover rpm) was also evaluated with this engine to better define the optimum rotor cruise tip speed.

Results from the 2035 FG-VSPT engine gave an average 2400 lb lower GW than the 2035 VG-VSPT engine for all combinations of tip speed and engine-drive system RPM, as shown in Table 10. The previous minimum GW of 93,557 with the VG-VSPT engine and 500 fps tip speed drops down to 91,612 with the FG-VSPT and 422 fps tip speed, a 1,945 lb drop in GW. In contrast to previous results in this study, the lowest weight option at the 422 fps tip speed is obtained with a 2 speed drive system used to obtain the 65% reduction, and engine operating at 100% speed.

The 422 fps and 500 fps rotor tip speeds clearly showed the lowest GW, with a small spread of only 648 lb between them, rather clearly showing that the optimum rotor cruise tip speed is in this 422 fps to 500 fps range.

The closest result for 350 fps was 1912 lb heavier. There was a very small spread of rotor cruise propulsive efficiency from 350 fps, 422 fps and 500 fps rotors, 0.841 to 0.848 at the 310 ktas design cruise airspeed. Cruise propulsive efficiency for the 650 fps case was notably lower, 0.76.

Table 10. Summary of Eight LCTR2 Aircraft with 2035 FG-VSPT Engine

Sizing Summary of Eight LCTR2 Aircraft with 2035 FG-VSPT Engine

CONDITION									
ROTOR Cruise Tip Speed		350	350	350	422	422	500	500	650
Engine Cruise RPM / Hover RPM		100%	77%	54%	100%	65%	100%	77%	100%
Drive System Cruise RPM / Hover RPM		54%	70%	100%	65%	100%	77%	100%	100%
Drive System Type		2-speed	2-speed	single speed	2-speed	single speed	2-speed	single speed	single speed
GROSS WEIGHT		93,524	93,779	94,403	91,612	92,260	92,025	92,012	93,705
Wing Weight		6,046	6,066	6,118	5,974	6,023	6,026	6,033	6,244
Rotor Weight		8,289	8,289	8,286	7,798	7,853	7,850	7,849	8,002
Engine Weight		1,796	1,799	1,804	1,770	1,775	1,793	1,785	1,827
Drive System Weight		6,994	6,844	6,401	6,066	5,799	6,114	5,820	5,974
EMPTY WEIGHT		60,158	60,098	59,877	58,393	58,388	58,654	58,385	59,246
OWE		61,608	61,548	61,327	59,843	59,838	60,104	59,835	60,696
FUEL		12,117	12,431	13,276	11,970	12,623	12,122	12,377	13,209
DIMENSIONS									
FUSELAGE	Equivalent Diameter	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
WING	Span, Overall	102.7	102.8	103.0	102.1	102.3	102.2	102.2	102.8
	Area Exposed	873.8	876.2	882.0	856.0	862.0	859.8	859.7	875.5
	Aspect Ratio, geometric	12.08	12.06	12.03	12.18	12.15	12.16	12.16	12.07
MAIN ROTOR	Diameter	60.73	60.82	61.02	60.11	60.32	60.25	60.24	60.79
	Solidity	0.1432	0.1432	0.1432	0.1432	0.1432	0.1432	0.1432	0.1432
	Hover Tip Speed	650	650	650	650	650	650	650	650
	Disc Loading, W/A	16.1	16.1	16.1	16.1	16.1	16.1	16.1	16.1
	Thrust Coefficient, CT/s	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500	0.1500
PROPULSION									
ENGINE RATING (Max SHP, SLS)									
	Installed max SHP (SLS) per Engine	4,498	4,506	4,520	4,433	4,446	4,493	4,472	4,577
	Engine Scale Factor for Hover	0.556	0.557	0.559	0.548	0.550	0.556	0.553	0.566
	Engine Cruise Scale Factor for 310 kt @ 25K'	0.506	0.521	0.532	0.499	0.520	0.505	0.518	0.559
TRANSMISSION									
	Transmission Rating (Hover)	19,441	19,339	19,059	16,885	17,006	17,069	17,069	17,433
	Transmission Rating (Cruise)	10,468	10,413	10,262	10,962	11,041	13,130	13,130	17,433
	Losses	3.51%	3.42%	3.06%	3.67%	3.26%	3.92%	3.47%	3.69%
PERFORMANCE									
ROTOR HOVER TAKEOFF FM		0.775	0.775	0.775	0.772	0.772	0.767	0.767	0.764
AIRCRAFT CRUISE ALTITUDE		25,000	25,000	25,000	25,000	25,000	25,000	25,000	25,000
AIRCRAFT DESIGN & CRUISE AIRSPEED		**310.0**	**310.0**	**310.0**	**310.0**	**310.0**	**310.0**	**310.0**	**310.0**
ROTOR CRUISE EFFICIENCY		0.848	0.847	0.846	0.848	0.846	0.842	0.841	0.760
AIRFRAME CRUISE L/D (max)		10.66	10.67	10.69	10.61	10.63	10.62	10.62	10.67
AIRFRAME CRUISE L/D (1st cruise)		10.51	10.52	10.54	10.45	10.47	10.47	10.47	10.52

A graph of vehicle GW and empty weight is shown in Figure 71, and installed SHP is shown in Figure 72.

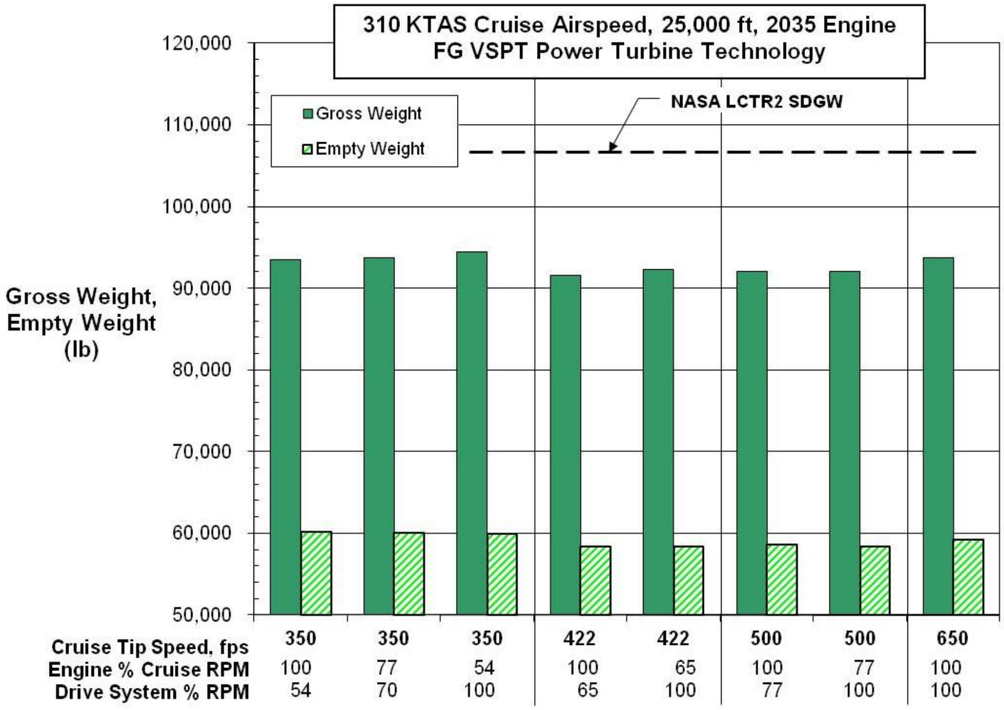


Figure 71. 2035 FG VSPT Engine: Rotor Tip Speed and Engine/Drive System RPM Effect on GW

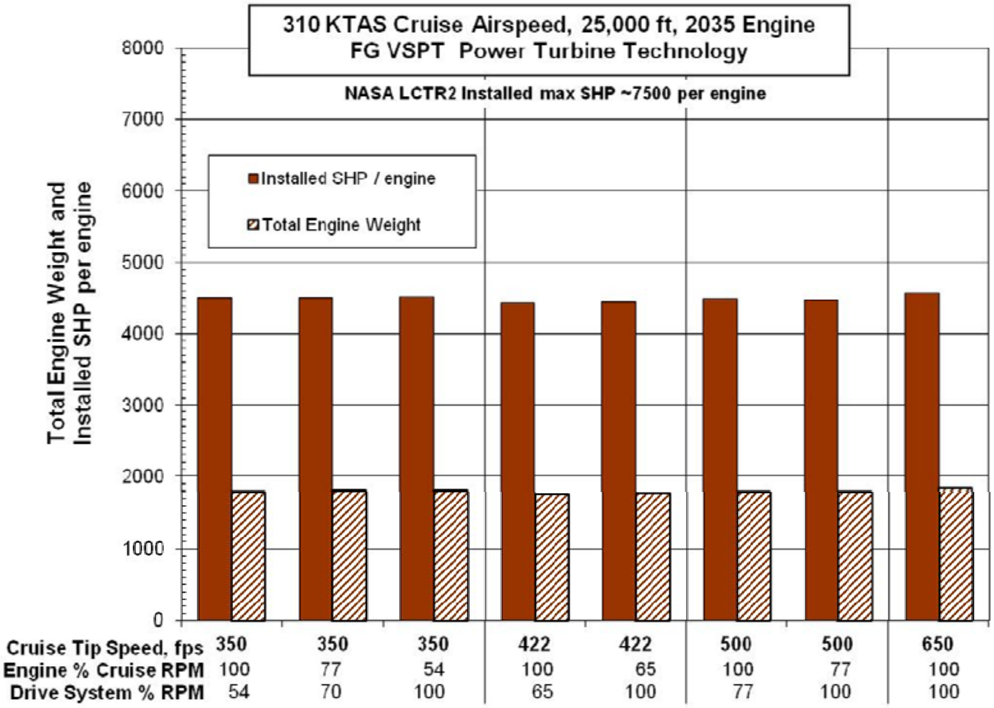


Figure 72. 2035 FG-VSPT Engine Installed SHP and Weight

Figure 73 graphs the propulsion system component weights, i.e rotor weight, drive system weight, and total engine weight. The combination of rotor and drive system weight clearly overshadows the engine weight. The 2035 drive system is estimated to weigh about 12.5% less than the 2015 drive system, for a given gear reduction and power rating. Actual sizing results showed the average 2015 drive system weight to be about 0.41 lb/rated HP, whereas the average 2035 drive system weighed 0.344 lb/rated HP, a significant weight reduction.

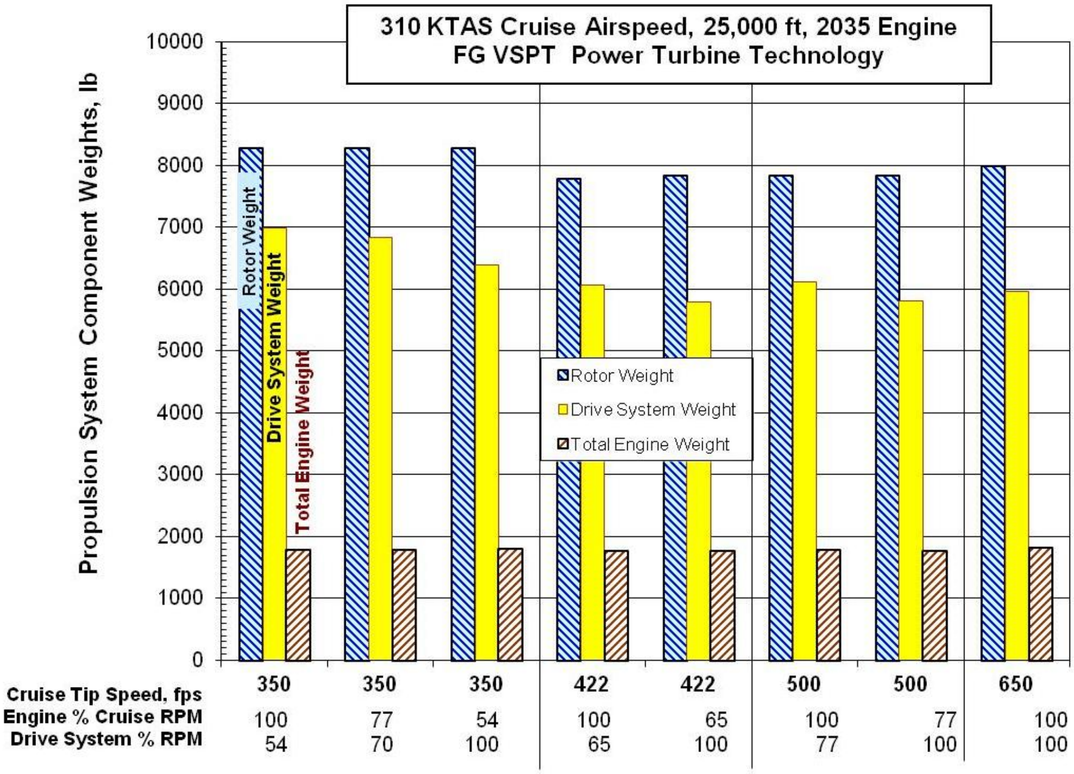


Figure 73. Propulsion System Component Weights for 2035 FG-VSPT Engine

Figure 74 shows the variation of the fuel weight as a fraction of GW for this group. The 2035 FG-VSPT engine is considerably lighter than either of the other engines, bringing the empty weight down, and it has lower fuel flow. These fuel weight fractions are much lower than the 2015 fuel weight fractions spotted on the graph.

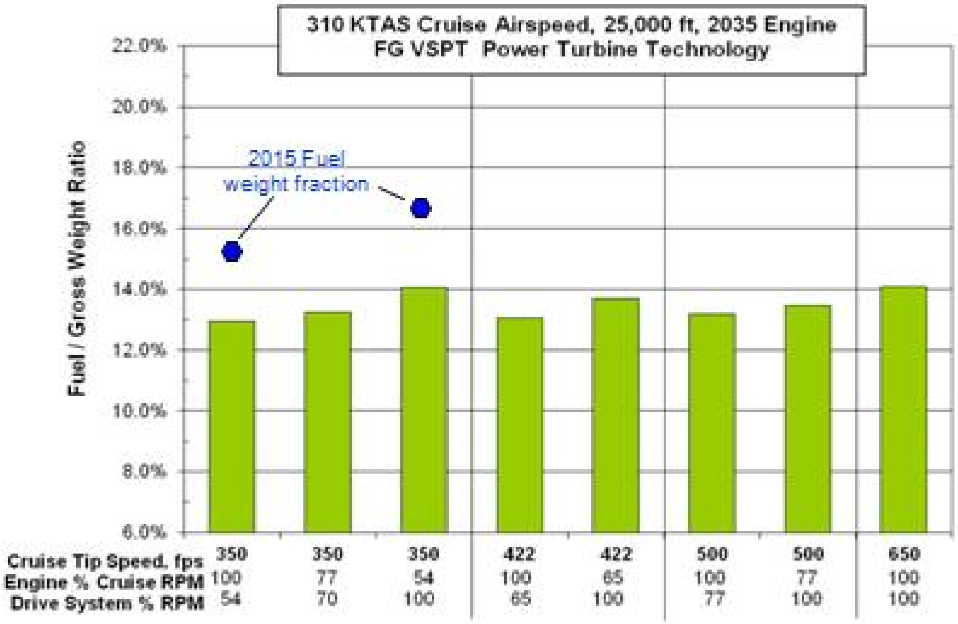


Figure 74. Mission Fuel Weight Fraction for 2035 FG-VSPT Engine

7.7 Sensitivity to Increased Airspeed and Range

Tasks were added to explore the sensitivity of LCTR2 to design cruise airspeed and mission range, in concert with estimated operational costs. This section shows aircraft sensitivity to airspeed and range, with estimated operating cost, using the best engine match for LCTR2, the 2035 FG-VSPT engine.

Three design airspeeds are evaluated;

- 310 ktas with the 422 fps tip speed rotor designed for 310 ktas cruise airspeed.
- 350 ktas with the new 350 fps tip speed rotor designed for 350 ktas cruise airspeed.
- 375 ktas with the new 350 fps tip speed rotor designed for 375 ktas cruise airspeed.

7.7.1 Aircraft Weight Growth with Design Airspeed and Range

The LCTR2 was resized at each design airspeed for mission ranges of 400 nmi up to 1200 nmi, including estimated operating costs. The carpet plot in Figure 75 quantifies the growth of vehicle Gross Weight for higher design cruise airspeeds (more required SHP) and for longer range (increased mission fuel). Both trends are as expected.

The growth of GW with design airspeed is dramatic. Considering the 1000 nmi mission range, GW grows from 91,600 lb at a 310 ktas design airspeed to 110,000 lb at a 350 ktas design airspeed, on up to over 125,000 lb at a 375 ktas design airspeed. Increasing mission range from 1000 nmi by 20% to 1200 nmi increased the takeoff GW by 5% to 7%, obviously driven by the added fuel requirement, and compounded by increased installed SHP to satisfy higher cruise airspeeds.

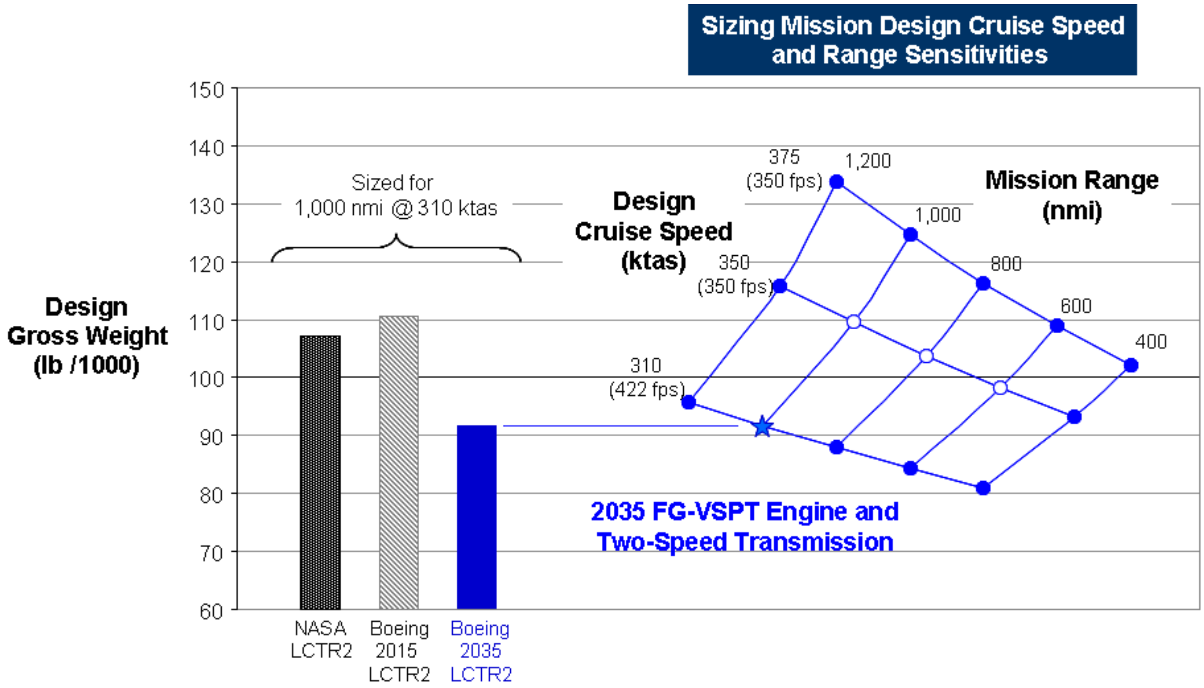


Figure 75. Design Gross Weight Sensitivity to Design Airspeed and Range

The accompanying bar chart on the left hand side provides reference Gross Weights from three previous cases; the reference NASA LCTR2 design with 350 fps tip speed, the Boeing 2015 design with 500 fps tip speed, and the Boeing 2035 FG-VSPT design with 422 fps tip speed, where the selected Boeing tip speeds were the minimum GW for each engine technology.

Corresponding aircraft empty weight fractions (Empty Weight / Gross Weight) are shown in Figure 76. Higher design airspeeds require more installed SHP, heavier drive systems to deliver that power, and heavier rotors to provide increased thrust, all leading to a higher empty weight fraction. Contrarily, at a given design airspeed, increased range requires more fuel, necessarily reducing the empty weight fraction to account for the added useful load (fuel).

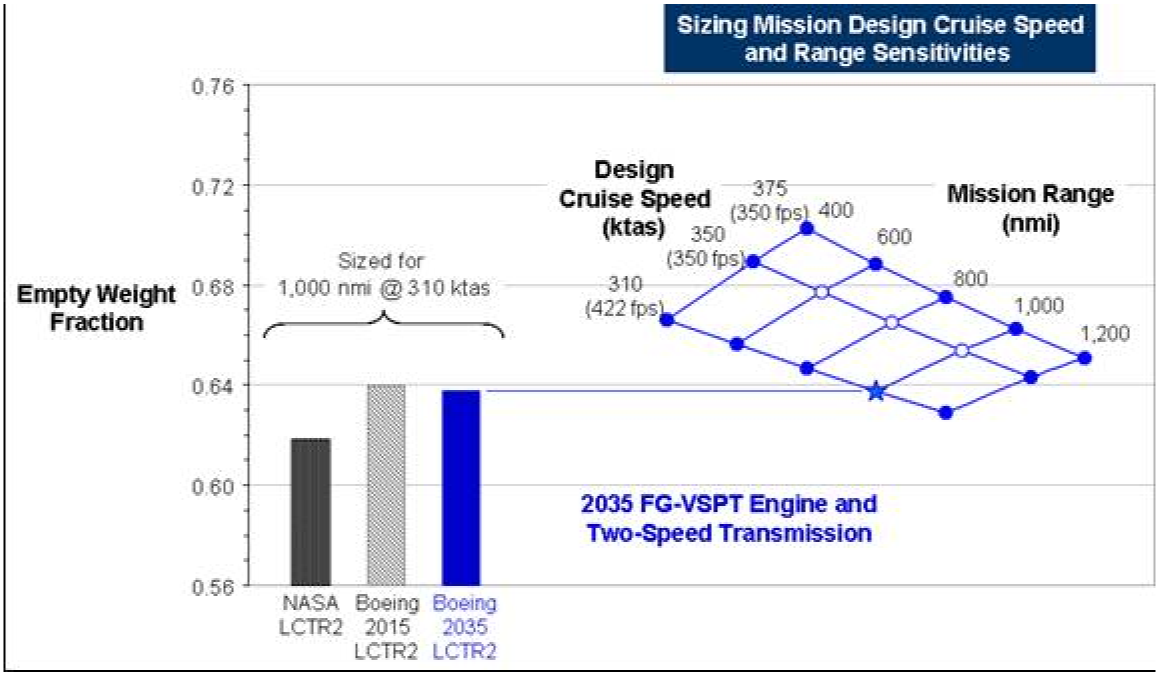


Figure 76. Aircraft Empty Weight Sensitivity to Design Airspeed and Range

7.7.2 Aircraft Operating Cost Variation with Design Airspeed and Range

Cost was estimated with the PRICE Estimating Suite, the identical PRICE model that was applied in reference 19 for previous civil tiltrotor analysis. Relevant output from the Excel sizing analysis was linked to the PRICE Estimating Suite and run in Phoenix Integration's ModelCenter environment. The cost model assumed a fleet of 300 aircraft operating 2500 flight hours per year. Indirect operating costs were based on a service life of 20 years and a 7.5% interest rate, but this study focused on direct costs.

The metric of Direct Operating Cost per Available Seat-NM (DOC/ASM) is used by commercial passenger airlines to track the financial health of daily operations. The revenue side of the balance sheet is revenue per available seat-nmi, which is essential to the airline's financial viability.

Cash Operating Cost comprises both direct and indirect operating cost. The term Cash DOC refers only to the direct operating cost components, including fuel, oil, maintenance, landing fees, crew expenses, supplies and catering, flight crew and cabin crew salaries, as shown in Table 11.

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[19] Wilkerson, Joseph, Smith, Roger, "Aircraft System Analysis of Technology Benefits to Civil Transport Rotorcraft", NASA/CR-2009-214594

Table 11. Definition of Cash DOC

	OPERATING COSTS		
Cash DOC	**Direct Operating Cost (DOC)**		
		Fuel & Oil	
		Maintenance *(Price)*	
			Airframe, Labor & Parts
			Engine Restoration
			Dynamic Systems/Life Ltd
			Burden
		Landing Fees	
		Crew Expenses	
		Supplies-Catering	
	Indirect (Fixed) Operating Cost		
		Flight Crew	Salaries + benefits
		Cabin Crew	Salaries + benefits
		Hanger Costs	
		Hull Insurance	
		Depreciation	
		Financing	
		Training	
		Computer Mgt pgm	
		Refurbishment	

DOC/ASM is defined as: $$\text{DOC}\Big/_{\text{ASM}} = \frac{\text{DOC/FH}}{\text{Number of seats} * \text{BlockSpeed}\ (nmi/hr)}$$

DOC/ASM accounts for more distance being covered per flight hour at higher cruise airspeeds.

Table 12 summarizes the components of Cash DOC used in the study and their source. PRICE estimates the Maintenance cost part of Cash DOC, but the other elements were estimated separately, crew salaries for instance. The ground rule utilization of 2500 flight hours per year actually required 2.5 flight crews and cabin crews per aircraft because air crews are limited to 1000 flight hours per year. Annual crew salaries came from Conklin & deDecker. They were multiplied by 2.5 crew sets and then divided by 2500 FH/aircraft/yr to express them as $/FH, per aircraft in the fleet.

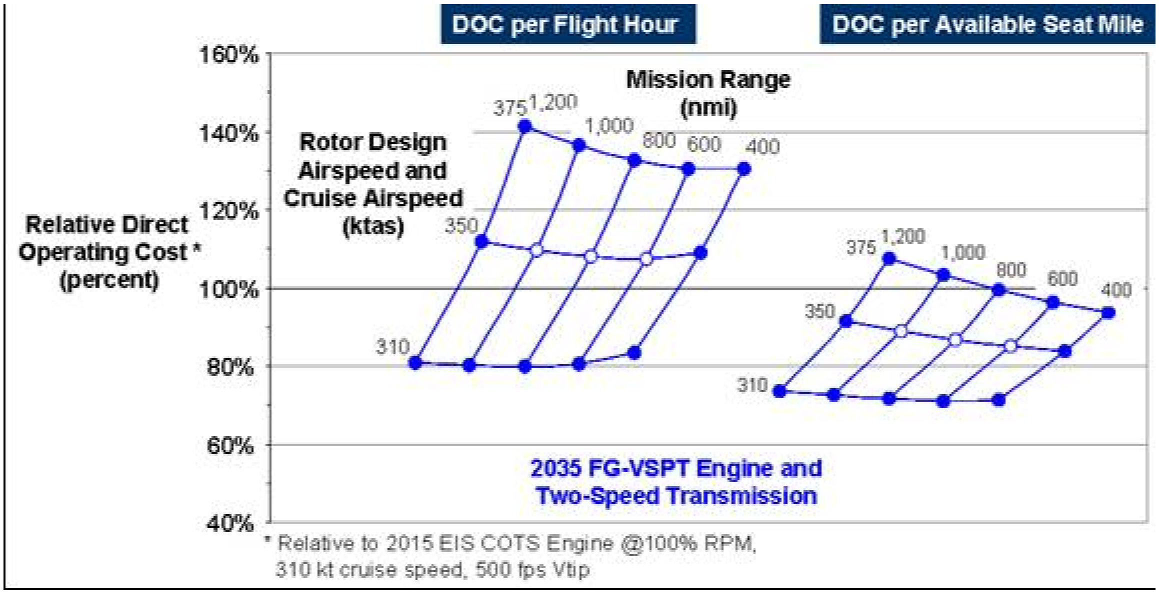
Mission fuel requirements came from the Excel sizing analysis, depending on the rotorcraft GW, cruise altitude and airspeed, and, as shown in this study, are greatly affected by advanced engine technologies. The cost of fuel and oil, flight crew salaries, cabin crew salaries, landing fees, crew expenses, and supplies and catering were added to the PRICE output with a Post-Price module in ModelCenter to arrive at Cash DOC/ASM.

Table 12. Cash DOC/ASM: Component Source and Values

O&S Element	Value or Basis	Source
Fuel Oil	$5.00 / gallon 3% of Fuel cost	Mission fuel from Sizing Analysis
Maintenance	Calibration with adjustment for civil production and technology	PRICE
Landing Fees & Crew Expenses	≈ $32 / FH	Conklin & deDecker Estimated
Supplies & Catering	$10 for each Passenger & Crew per Flight	Estimate
Flight Crew Salaries*	$511,875/yr for 2.5 sets / 2500 FH/yr = $204.75 /FH	Conklin & deDecker (2008)
Cabin Crew Salaries	$205,000/yr for 2.5 sets / 2500 FH/hr = $82 / FH	Conklin & deDecker (2008)

Estimated values of DOC per flight hour (DOC/FH) and DOC/ASM are shown in Figure 77 for the same combinations of design airspeed and mission range shown above. These metrics have been normalized by PRICE results for the 2015 COTS engine at 100% rpm, 310 ktas and the 500 fps rotor tip speed.

DOC/FH naturally increases with aircraft gross weight; larger aircraft generally requiring more fuel per FH. But Figure 77 shows DOC/FH to be fairly flat with mission range for the 310 ktas design, even as GW grew from about 80,000 lb at the 400 nmi range up to 96,000 lb for the 1200 nmi range. That reflects the content of DOC/FH: part fuel costs that do increase with GW and part fixed costs per flight hour, such as crew salaries and expenses (overnight stays).



* Relative to 2015 EIS COTS Engine @100% RPM, 310 kt cruise speed, 500 fps Vtip

Figure 77. Relative Cost Variation with Design Airspeed and Range

Notably, DOC/FH increases significantly for design airspeeds of 350 ktas and 375 ktas driven by increased maintenance cost and fuel per FH associated with heavier, more powerful aircraft. DOC/FH shows more sensitivity to mission range at the higher cruise airspeed designs, presumably due to lower nmi/lb of fuel at the higher GW.

The 2035 drive system and FG-VSPT engine technology results in a reduced GW for the 310 ktas aircraft and reduced relative fuel flow/SHP. The relative DOC in Figure 77 for the 2035 engine and drive system technology shows that advanced technology can result in nearly 30% lower DOC/ASM and 20% lower DOC/FH relative to the best combination with 2015 technology.

8.0 TASK 5 TECHNOLOGY PLANNING

8.1 Technology Challenges identified

During the execution of this propulsion system study project, several challenges and needs were discovered for the various concepts and corresponding technologies were identified for both engines and drive systems to address these areas and provide tangible downstream benefits. The areas for further study include:

8.1.1 Propulsion Performance/Aerodynamics

Tangible benefits would be derived from additional engine conceptual studies that optimize efficiency over a wide range of potential missions. The current project did not permit engine optimization due to time and budget constraints. Better understanding of variables such as cruise altitude on engine design, would be advantageous in establishing component design points.

Turbine variability to accommodate wide variations in incidence angle provides significant efficiency gains during low speed operation. Variable vane geometry was explored to develop incidence tolerant turbine maps, however, there are other aerodynamic features that could be employed by themselves to accommodate the incidence changes to further improve incidence tolerance. Limitations of this study prevented a thorough investigation of these concepts. Further exploration of these technologies, and characterization of the benefits will reveal the potential to reduce costs and improve performance.

8.1.2 Engine Controls

Two options exist that optimize cruise efficiency at part speed, a variable speed gearbox, and variable power turbine geometry. During a shift event as notionally described in section 4.2.1 of this report, engines must sequentially slow down to the preshift input speed. During this event, engines are unloaded (partially), gear ratios changed, and then power is increased to produce desired changes in rotor speed and loads. This usage scenario presents unique challenges to engine operability and control throughout the sequence. Construction of a transient controls system model would greatly facilitate the understanding of this system and the development of coupled controls strategies for the engines and transmission. Failure modes not present in aircraft today will need to be identified, understood, and addressed to fully assess the viability of this approach.

Drive system configurations that utilize a single reduction ratio will benefit from wide variability of engine speed and potentially variable turbine geometry to maximize efficiency. Control logic and algorithms that integrate turbine variability are required. As with the variable speed gearbox approach, variable turbine geometry, would also introduce new failure modes and developing control logic, such as “fail fixed,” or drive to open/closed for variable geometry features will need to be developed to address these concerns. Speed variability based on fixed geometry turbines would not have this issue.

To fully optimize efficiency over the operating envelope, performance seeking multivariate controls that actively vary speed and engine geometry during the various phases of flight may also be beneficial.

Proactive Engine Health Monitoring will improve safety, and will model each engine’s health in real time (on wing and in service) as it detects shifts from “normalcy” to predict impending failure conditions, For versions of the integrated propulsion system where speed reduction is accomplished through variable or 2 speed transmissions, there is a requirement for stable engine operation at part speed as the shifting or speed changes take place. Technologies and engine development for reliable operation at reduced speed will be important, even on engines that are optimized for efficiency and power output at full speed.

In addition there may be unique demands on engine pumps, controls and accessories during the transitions that need to be developed to operate over a broad speed range. In the case of multi-speed drive systems there is an opportunity to mitigate the impact of speed variation on accessories and accessory gearboxes by locating them on high speed portions of the drive train.

8.1.3 Hardware

Advanced methods of sealing a mechanism that provides turbine variability is required. There is a substantial body of knowledge for approaches to compressor variability, but these techniques cannot be directly applied in the turbine area due to material temperature. There is prior experience on turbine variability from JTDE (Joint Technology Demonstrator Engine) that can be built upon to provide a cost-effective, producible design.

Methods to substantially increase OEI power are needed. If OEI power can be significantly increased, cross shafting may not be necessary in a four-engine installation, or with cross shafting, a two-engine installation may be permitted. Approaches such as water/methanol injection (fine mist), which in combination with other power increase strategies, such as using high speed power turbine driven motor/alternators to transfer power, may be investigated, which would impact overall aircraft sizing. Lastly, turbine technology approaches that allow temporary large increases in temperature at the expense of engine life can be investigated.

System dynamic analysis is needed to better understand the relationship between the engines, the drive train, and the large rotor system. Given the size, analysis is needed to ensure proper system operation throughout the operating envelope.

8.1.4 Drive System technology needs, challenges

Drive system technology as presented in this report to meet the goal for reduced speed operation was grounded in present day experience from the V-22 and other current systems. This approach is necessary to provide a quantitative evaluation but also highlights the maturity of the concepts proposed. Two-speed planetary systems are functional and practical solutions for multispeed rotorcraft operations whereas practical versions of continuously variable transmission (CVT) systems are more elusive. Friction based CVTs are not practical for high power rotorcraft drive systems though some multiple input planetary drives or differential drive devices may be practical. The case for CVT mechanisms is further eroded by the fact that the cruise condition that dominates the LCTR2 mission profile can easily be conducted with a discreet ratio transmission and variable speed transmissions do not improve the aero efficiency and have a negative weight and mechanical efficiency impact. There may be a practical solution for variable speed systems but it was not considered within the scope of this project to seek new inventions in that area. Basic needs at the macro system level include:

- Continued configuration work in support of LCTR concept vehicles and configuration development at the subsystem level for speed changing transmission modules

- General improvements in power to weight ratio through use of light weight materials and improved properties for housing and gear materials
- Efficiency improvements through lubrication system technologies, configuration changes
- Evaluation of dynamics issues for reduced speed or broad operating speed range applications. Those issues would include both rotor and drive system dynamic effects from speed change events and a wide operating speed range. In addition there will be structural issues with respect to operating speeds that parallel the rotating system issues. Reduced speed operation may actually benefit the whirl flutter stability but could negatively impact dynamic interactions in the nacelle and wing structure.
- Break-through configurations for advanced applications

Planetary systems and concepts require further development and demonstration to be considered mature technology for an LCTR2 application. A speed changing planetary system similar to the A160 configuration may be considered at a TRL level of 3 for the LCTR2 application due to speed, scaling issues and interactions of multiple engines. Mechanisms that clutch/declutch to allow a constant input speed with a variable output speed must be reliable and lightweight. The multiple-speed transmission subsystem must be designed so that it integrates into the engine/drive/rotor system. Multiple-speed capability in the transmission and rotor can impact the dynamics of the engine/rotor/drive system. Changes in operational speed of the engine/drive/rotor system must be modeled and validated with testing to avoid resonance and torsional stability problems in the system. Configuration-related risks (such as multispeed transmission dynamics) will remain until the test phase is completed, however they will be mitigated through the use of analysis, modeling, and simulation. Technology needs associated with 2 speed compound planetary system should therefore include:

- Demonstration and development of 2 speed planetary systems at relevant scale and operating speeds for 7500 HP application
- Demonstration of transient conditions for 2 speed planetary systems at relevant scale and operating speeds
- Development of speed transition procedures, mechanisms, clutch materials, FMEA and analysis of ‘Fail Safe’ characteristics, and high reliability features. Of particular interest are advanced dry disk, and lubricated multi-plate clutches, as well as related actuation and control systems.
- Free wheel clutch devices that permit engine over-running and potentially engaging and disengaging an engine from the drive train (depending on configurations). Investigation of weight and reliability for these devices in multi-speed applications where extended periods of clutch operation in either fixed or over-running mode can be expected. Alternatives to traditional sprag and friction clutches should also be explored through focused technology development projects.
- Development HUMS (health and usage monitoring system) and CBM (condition based maintenance) technologies for 2 speed, multi-speed or variable speed modules.
- Full consideration of configuration options that allow accessory power systems to operate at a single speed (more compatible with the drive system based speed changers), and a careful consideration of accessory system duty cycles, operating speeds and mission requirements for the intended (LCTR2) application. There is expected to be a sizable weight impact for a

broad speed range accessory system that would require a deeper investigation than presented in this study to fully assess.

- There is room for innovation with break-through multi-speed or CVT configurations

CVTs may require significant additional R&D beyond the development tasks noted above for transition to practical applications. Mechanical or hydro-mechanical devices that allow for variations of speed can be large and complex with significant efficiency losses in transmitting power. It is recommended that dedicated configuration studies be performed in order to identify practical candidates prior to further investment in this area.

Self-diagnostic and prognostic capability will be increasingly important for future aircraft systems, particularly large-scale multi-speed systems. As aircraft structures and dynamic systems grow in size, the potential for manufacturing defects, complexity and material flaws also increases. The expectation is that future drive systems will operate at higher power densities in combination with new materials and processing technologies to provide low weight drive systems. In addition fatigue crack failure progression rates vary depending on the speed (cyclical rate) and stresses in a particular component thus creating the need for a real time airborne warning system for most of the transmission components in today's turbine powered helicopters, as opposed to a ground based "post-flight" analysis/warning system. The required capabilities for drive system diagnostics/prognostics are best discussed in terms of the capability goals and the required general technology elements and support needed for implementation. The near term requirement for drive train health monitoring is to provide indication at the on-set of fault. The long term requirements for the health monitoring of drive system is effective fault indication and progression at a minimal false alarm rate with increased lead time. Prognostic capability is currently possible for predictable failures such as bearing spalling but may also be improved for gear and shaft failures as crack growth analysis is included in HUMS.

Challenges associated with materials and process development are fundamental and critical to commercial viability of civil rotorcraft and tilt-rotor applications. Advanced materials and processes can improve the competitive posture of rotorcraft with respect to fixed wing aircraft. Desired material properties for increased power density and reduced operating cost must be developed and matured for production applications. The cost/benefit equation must always be applied to determine if new processes are feasible and affordable. Fortunately in some cases, new processes are found that can also reduce acquisition cost or life cycle costs.

Areas that have been identified for manufacturing technology development supporting propulsion and power transmission systems include lightweight metallic materials development, composite materials applications, process improvements, and heat treating of steels. Investments in these areas will not only provide benefits for propulsion and power train applications, but will also provide benefits across many systems, and platforms. An area of development that will support many of these efforts is material process modeling to optimize these improvements.

Current state of the art modeling is based on FE modeling, which is now commonplace. Advancements in tools and applications of FE modeling to simulate mechanical system behavior represents a unique modeling and simulation capability that is the result of advanced capability tools, skilled analysts, and in some cases the ability to validate complex models with test data. Progress in this area will promote:

- Evaluation of concepts through models prior to fabrication

- Reduction of costs for development of complex system through increased reliance on analysis and simulation rather than hardware development and modifications
- Reduction of duration and costs for qualification testing through increased reliance on analysis
- Simulation of degraded operating conditions and off-design conditions that cannot be duplicated in flight testing due to safety or test resource limitations.

8.2 Technology Recommendations

There are a broad range of technology needs that are highlighted in the previous section above that would support the development of reduced operating speeds for rotor system and civil tiltrotors in general. Near term technology needs include additional trade studies on optimum rotor speed/engine speed matching. While one of the methods to achieve optimum rotor speed is through a multi-speed gearbox, the trade between gearbox weight and low speed engine performance loss at an optimum rotor speed should be further understood through exploration and study. This project developed a methodology and tools to perform the study, and relevant parameters were analyzed, but only a limited number of operating conditions were included. The benefits of reduced rotor speed are subtle and interwoven with many aspects of vehicle design. Extension of this work with additional mission parameters could provide a more comprehensive understanding of the design space for civil tiltrotor concept vehicles. Investigation into multi-disciplinary design challenges for wide-speed range capability is also warranted. In particular, dynamic interactions between structural, aerodynamic, controls, and rotating dynamic systems in the tiltrotor air vehicle can be studied to a detailed concept level of detail. In this report the 2025 and 2035 engine technologies are presented with wide-speed range capability that provides impressive performance at reduced engine operating speeds, however the variable geometry capability comes at the expense of additional engine weight.

Two engine issues that must be further studied include - part speed turbine efficiency optimization through high incidence angle tolerant vs. variable-geometry design, and mechanical actuation system design approaches to a variable speed power turbine system. Of particular importance are sealing and wear resistant hardware strategies as well as actuation and sensing strategies for the high temperature variable-geometry turbine hardware.

Drive system speed shifting technologies featured in this report were focused on practical and known configurations to promote a quantitative evaluation per the project goals. Component technologies and scaling issues represent the greatest risk in this area. Further exploration of concepts is also recommended, but continued development of components, system controls, and demonstration hardware would provide a knowledge base for future development.

Integrated controls system approaches for speed transition event that involve engine and drive system controls are also recommended for near term study. This could be accomplished through simulation initially, and followed by demonstration projects. Simulation would include an evaluation of loads and stability for the integrated system, followed by an expanded evaluation and demonstration at a representative vehicle system level to assess loads, dynamics, control functions and handling qualities, noise and vibration, and other qualitative assessments.

9.0 PROJECT SUMMARY

9.1 Summary

This study investigated propulsion system concepts capable of achieving up to 54% reductions in rotor cruise tip speed for the NASA large civil tiltrotor (LCTR2) air vehicle, cruising at 310 ktas airspeed and 25,000 ft altitude over a 1000 nmi mission range with sensitivity studies at additional airspeeds and ranges. Variable (rotor) speed strategies and advanced technologies were evaluated for the integrated engine and drive system to reduce the rotor cruise tip speed. Overall gross weight of the aircraft was used as the measure of the benefit of engine technology and reduced rotor cruise tip speed, via engine speed reduction or 2-speed drive systems.

The NASA LCTR2 was sized to carry 90 passengers over a 1000 nmi range with 30 minutes of reserve fuel and a 30 nmi alternate destination. The NASA LCTR2 structural design gross weight (SDGW) was 107,124 lb and required 19,650 lb of fuel. The LCTR2 SDGW was taken as the reference Design Gross Weight (DGW) for comparisons in this study. A 5% conservative fuel flow factor was applied to all mission segments, consistent with previous NASA analyses of LCTR2.

Four rotor tip speeds were evaluated for their effect on LCTR2 size and cruise performance; 650 fps, 500 fps, 422 fps and 350 fps. The baseline NASA LCTR2 rotor hover tip speed was 650 fps with a 350 fps cruise tip speed. It has been extensively analyzed by NASA to achieve best performance for the civil application. This study did not attempt to validate that rotor design. Rather, three additional cruise tip speeds were evaluated for comparison. NASA airfoils, blade chord distribution and rotor solidity from the LCTR2 were preserved for 422 fps, 500 fps and 650 fps cruise tip speeds in this study, corresponding to 65%, 77% and 100% of hover RPM respectively. The twist distributions of these rotors were defined to be consistent with their respective cruise inflow angle distributions. Hover and cruise performance maps were generated with an in-house computer analysis applying the characteristics of the NASA LCTR2 rotor with the appropriate twist distribution. Cruise propulsive efficiency for the 350 fps cruise tip speed rotor was regenerated using the same computer analysis to be comparable, and results compared well to the NASA rotor performance.

Three levels of engine technology were evaluated; 2015 (commercial off-the-shelf technology), 2025 technology, and two versions of 2035 technology. Rolls-Royce developed the engine geometry and advanced concepts for the study. Tabulated engine data was provided for available horsepower, fuel flow and residual thrust over the operating range of Mach number and altitude. Engine weight was a function of installed SHP and the year of technology.

Drive system concepts were defined for single speed and two-speed transmissions to achieve the objective rotor tip speeds in cruise. Drive system weight and efficiency was assessed for the selected configurations at technology levels corresponding to that of the engines; 2015, 2025, and 2035. Transmission concepts for 2-speed operation utilized compound planetary configurations to vary from full to partial rotor speed conditions.

The LCTR2 configuration was resized to specific combinations of rotor cruise tip speed, engine RPM reduction and drive system RPM reduction, according to the table below. The eight combinations in the table were evaluated at propulsion system technology levels to quantify the net relative benefit of the combined multiple technologies, for a total of 32 design combinations as noted in Figure 3.

Table 13. Combinations of Engine and Drive System RPM Reductions

Rotor Design Cruise Tip Speed, (%)	**Engine Cruise RPM / Normal RPM, (%)**	**Drive System Cruise RPM Reduction, (%)**
650 fps (100%)	100%	100%
500 fps (77%)	100%	77%, 2-speed
	77%	100%
422 fps (65%)	100%	65%, 2-speed
	65%	100%
350 fps (54%)	100%	54%, 2-speed
	77%	70%, 2-speed
	54%	100%

Aircraft weight, engine performance, rotor performance, mission performance and overall vehicle sizing are provided by a customized spreadsheet sizing analysis, emulating the general VASCOMP sizing process. Data tables and curve fits are used to model the propulsion system and rotor performance. GW variations in this study were driven mostly by some combination of installed engine HP, engine power density (lb/SHP), engine or rotor performance as it varied with cruise tip speed, and consequences thereof. Resizing the LCTR2 included a buildup of empty weight, resizing the wing area and rotor diameter to preserve the LCTR2 wing loading and disc loading, and calculating the required mission fuel to arrive at a new size and gross weight (GW). Component weights were scaled from baseline values generated by the Boeing weights group for the LCTR2 configuration. The resized case for the reference LCTR2 design at 350 fps rotor tip speed with 54% engine RPM using 2015 level propulsion system technology resulted in a GW of 110,571 lb, about 3% more than the NASA DGW.

The results of sizing the LCTR2 with various combinations of propulsion system RPM reduction from engine and drive system, at anticipated technology levels (COTS, 2025, 2035), is fully described in section 7 of this report, and also discussed with highlights and conclusions in section 10. No additional discussion of the results is provided in this summary except to note that the most favorable sizing results for each technology level are given as follows:

- The lowest GW for the LCTR2 concept vehicle provided by COTS 2015 technology engines based speed reduction with single speed drive system occurs at 500 fps rotor tip speed, 310 ktas cruise condition resulting in a 105,687 lb GW.
- Technology 2025 VG-VSPT engines with a single speed drive system provides optimum sizing at 500 fps rotor tip speed, (310 ktas) resulting in a 106,656 lb GW.
- Advanced Technology 2035 FG-VSPT engines with VAATE technology (and incidence angle tolerant power turbine) with a two-speed drive system provides optimum sizing at 422 fps rotor tip speed, (310 ktas) resulting in a 91,612 lb GW.

10.0 CONCLUDING REMARKS

The 2035 FG-VSPT engine gave the lightest GW solution of the four engines evaluated, where the best rotor cruise tip speed was between 422 and 500 fps. This option had lower fuel flow and better available HP than the 350 fps tip speed (54% rpm). Analysis of the 2035 drive system technology and the 2035 FG-VSPT engine at the 422 fps rotor tip speed and a 2-speed drive system provided the lightest overall vehicle GW at 91,612 lbs. The 500 fps rotor tip speed produced a close second, 92,012 lb GW with either a single-speed or a 2-speed drive system. Reduced engine weight and fuel consumption associated with the 2035 FG-VSPT has a dramatic effect on vehicle sizing when compared to the 2015 COTS engine (best case) and represents a significant result in this study. That is approximately a 13% reduction in vehicle GW from technology improvements that develop between 2015 and 2035. If more detailed studies confirm the optimum rotor cruise tip speed to be in the range of 422 fps to 500 fps, as concluded in this study, then the NASA LCTR2 design with a 350 fps tip speed will have served a worthwhile purpose of pushing the boundary, as 422 to 500 fps tip speeds are far lower than the current V-22 cruise tip speed of 664 fps.

The LCTR2 GW weight differences between configurations that used engine based speed variation vs. drive system speed variation were subtle for the significant variations studied in this effort. As an example, for the 422 fps sizing cases at the 2035 technology level, which represents the most favorable sizing cases in the study, the difference between two-speed transmission and reduced engine speed cases (91,612 lbs and 92,260 lbs respectively) is a mere 0.7%. For the 2015 technology level, the difference between two-speed and reduced engine speed for 500 fps best sizing is 0.4%. In general the two-speed transmission approach becomes more favorable where the engine performance falls off dramatically, however cases where this difference is greater are not the optimum (lowest GW) configurations in this study.

The benefits that rotor tip speed reduction provides in this study are also relatively modest but nonetheless significant. Considering the 2015 COTS and 2035 (FG-VSPT) cases, the reduction in GW from sizing at 100% RPM to the best case reduced speed rotor was 2.7% (at 500 fps) and 2.2% (at 422 fps) respectively. The lowest 350 fps cruise tip speed (54%RPM) was competitive with the 500 fps cruise tip speed (77%RPM) when coupled with the 2025 or the 2035 engine technology, but not with the 2015 engine technology. Initially the lowest GW in all three engine technology groups (2015, 2025 EIS and 2035 EIS) resulted from the 500 fps rotor cruise tip speed, however the optimum rotor cruise tip speed appears to be between 422 fps and 500 fps. The small GW difference between the two cases with 422 fps is attributed to the balance between engine and drive system weights. The 100% engine rpm required 650 lb less fuel and the 65% drive system was about 250 lb heavier, so fuel savings of the 100% engine provided a small margin.

Aircraft gross weight for the 650 fps rotor cruise tip speed (always at 100% engine RPM) was consistently the highest gross weight or very near the highest gross weight for all six combinations of engine RPM, drive system RPM and rotor tip speed, and for all four engine technologies, with no redeeming features for operations at that cruise tip speed.

Engines in this study were sized to the greater of hover power required or cruise power required, which is less than the installed 7500 SHP per engine selected by NASA. In 24 of the 26 cases LCTR2 installed power was determined by the takeoff condition at 5000 ft / ISA+20° C for 310 ktas cruise airspeed, generally validating NASA's choice for the 310 cruise airspeed. The two exceptions were for the 350 fps tip speed with the 2015 engine operating at 54% RPM where it had less cruise HP than any other engine / RPM combination, and the 650 fps tip speed with the 2025 engine at 100% RPM where it had less cruise HP than any other. These two cases point out that engine cycles should [ideally] be selected to match the needs of airframe and rotor performance. The Rolls-Royce engines in this study have a higher fraction of available power at the takeoff ambient condition than the NASA engine model, relative to the respective engine's MRP at SLS.

Drive system weight tracks drive system power rating (torque) and RPM reduction. It is a considerable 12% of empty weight at the 2015 technology level. The weight penalty of a two-speed drive system providing 54% RPM output was roughly 800 lbs more than the single speed drive system weight.

The trade space examined in this study was heavily focused on vehicle sizing with the vehicle GW and system weights as the parameters of interest. A sensitivity study task was also conducted to evaluate weight trends and cost trends as mission range and speed were varied. Results are presented in Section 7 of this report that hold no surprises, the weight and cost of the LCTR2 vehicle rose proportionally to the variables of speed and range increases.

10.1 2015 Engine and Drive System Technology Group

The 2015 commercial off-the-shelf engine suffered significant decreases in available power and large increases in fuel flow at very low operating speeds, such as at 54% RPM for the 350 fps rotor cruise tip speed, and yielded the highest aircraft GW. The engine lost performance at 77% RPM for the 500 fps rotor cruise tip speed, whereas the projected VG-VSPT 2025 and 2035 engine technologies reversed that trend, making 350 fps tip speed with 54% engine RPM a competitive choice, but not the best choice.

The 500 fps rotor cruise tip speed (310 ktas cruise condition), provided the lowest GW solution of the three tip speeds evaluated in this group. A 77% engine RPM retained reasonable cruise performance and the single-speed drive system was lighter than a 2-speed drive system, producing the lightest aircraft GW (105,687 lb) in this technology group. A 100% engine RPM with a 77% RPM 2-speed drive system was a close second.

A 2-speed transmission module that allowed the engine to operate at 100% engine RPM gave lighter vehicle gross weights than a single-speed transmission for the 2015 engine technology group at 350 fps but a single speed drive system with 500 fps rotor cruise tip speeds yielded the lightest configuration for this technology group.

Conclusions for the 2015 Technology Group

- Trends from this study show an optimum rotor cruise tip speed is near 500 fps
- A 350 fps tip speed during cruise resulted in a higher GW than the 500 fps cruise tip speed, and offered no net benefit for the cruise dominated mission at 310 ktas cruise airspeed.

10.2 2025 Engine and Drive System Technology Group

The Rolls-Royce engine concepts for the 2025 era with variable-geometry power turbines did successfully tailor performance, gaining back cruise power and improving fuel flow at reduced

RPM. The engine cycle was tailored to provide greatest efficiency and power at very low cruise RPM, which resulted in about 5% less cruise power than the 2015 engine at 100% RPM.

The 2025 variable-geometry power turbine engine weighs 15% more than the 2015 engine, due to the additional weight, about 200 lb (per engine) of variable geometry actuators and mechanisms. This extra weight effectively counters the benefit of its reduced fuel flow and nullifies the net performance benefit to the aircraft. Interestingly the best GW sizing case for 2025 VG-VSPT engines was 106,656 lb with a single speed drive system at 500 fps (77% RPM) rotor tip speed and not at the lowest rotor speed, even though engines were optimized for the 54% RPM speed range. This best GW case, and in general, aircraft GW for the 2025 technology are higher than for the 2015. The single case showing reduced gross weight when compared to the same case in 2015 results was the 350 fps tip speed with 54% engine RPM, where the 2025 engine had been optimized.

Conclusions for the 2025 Technology Group

- A primary observation from this 2025 engine technology group was that tailoring engine performance at one RPM must be carefully matched to the drive system and rotor performance components to be successful.
- A favorable balance must be struck between engine weight and reduced fuel flow to realize a net benefit to the aircraft.

10.3 2035 Engine and Drive System Technology

Performance improvements from the 2035 engine with VAATE technology and variable-geometry variable-speed power turbine (VG-VSPT) were dramatic, producing about 27% more power available at 54% RPM, and dry engine weight was reduced by 25% relative to the 2015 engine, in contrast to the 15% weight increase for the 2025 engine cycle. This engine did include a significant weight penalty for variable geometry mechanisms and actuation, approximated at 150 lbs per engine, as did the 2025 VG-VSPT.

That combination of reduced engine weight, substantially lower fuel flow, and reduced drive system weight resulted in much lower vehicle gross weights for the 2035 technology. Aircraft GW was reduced in every case, with an average GW reduction of over 11%. A 12% reduction in 2035 drive system weight, relative to the 2015 group, was a substantial contributor.

A single-speed drive system with reduced engine RPM gave the lightest GW solutions for the VG-VSPT configurations, for both 500 fps and 350 fps tip speeds, even in light of the projected reduced weight of 2-speed drive systems in the 2035 time frame. Similar to results of the 2025 technology engines, 500 fps cruise rotor tip speed again produced the lowest GW for this variable geometry 2035 group at 93,557 lbs even though engines were optimized for the 54% RPM speed range.

Performance of the FG-VSPT 2035 engine with VAATE technology and incidence angle tolerant power turbine were equally impressive but unencumbered from the weight penalty of variable geometry features. Analysis of the 2035 FG-VSPT engine and 2035 drive system technology provided the lightest overall vehicle GW for this study at 91,612 lbs with the 422 fps rotor tip speed (65% rpm) and 2-speed drive system. The 500 fps rotor tip speed cases produced nearly the same result, just over 92,000 lb GW with either a single-speed or a 2-speed drive system. Impressive engine efficiencies offered by the advanced VAATE technology engines produced the largest effect on vehicle sizing for any of the technologies examined in this study.

Conclusions for the 2035 VG-VSPT Technology Group

- Advanced 2035 engines with VAATE technology and variable-speed power turbines provide significant reductions in fuel flow and weight (lb/shp), operating efficiently over a wide RPM range to support optimum rotor cruise tip speeds.
- The 500 fps rotor cruise tip speed with a single-speed drive system again produced the lowest gross weight, with a notable 1.2% margin to the closest 350 fps case. Rotor cruise propulsive efficiency for the 500 fps design was essentially the same as the 350 fps rotor tip speed.
- The combination of 100% engine RPM with a 77% drive system RPM for the 500 fps rotor tip speed was 2% heavier than a 77% engine RPM with a single-speed drive system configuration at that rotor tip speed.

Conclusions for the 2035 FG-VSPT Technology Group

- Engine dry weight for the 2035 FG-VSPT engine is 40% lighter than the 2015 technology engine, and 20% lighter than the 2035 VG-VSPT engine.
- An additional rotor tip speed of 422 fps was evaluated in this technology group, corresponding to 65% rpm, to better define the optimum rotor cruise tip speed. Gross weights at 422 fps rotor cruise tip speed were nearly the same as those for 500 fps tip speed, both of which were about 2000 lb less than the 350 fps cases. The minimum GW was roughly equivalent whether the speed reduction was due to engine speed variation or two-speed transmission, although the two-speed transmission resulted in slightly lower fuel burn (about 3-4%) with presumably better economics.
- The optimum rotor cruise tip speed for LCTR2 appears to be in the narrow region of 422 fps to 500 fps, evaluated with the 2035 engine.
- The engine had sufficient power at reduced rpm such that all cases were sized by the hover condition, not by cruise.

10.4 Sensitivity to Design Airspeed and Mission Range with 2035 Technology

Rotor designs for cruise airspeeds of 350 ktas and 375 ktas produced cruise propulsive efficiencies that were comparable to the cruise efficiency of the 310 ktas rotor design at 310 ktas airspeed. But these rotor designs retained reasonable cruise efficiency to the higher rotor advance ratios needed at the higher target cruise airspeeds, where the 310 ktas rotor design quickly lost efficiency at higher airspeed.

A 350 fps tip speed rotor design was a good match for the 350 ktas rotor cruise airspeed , as the 422-to-500 fps tip speed was a good match for a 310 ktas cruise airspeed. Boeing’s design for the 375 ktas design also used a 350 fps tip speed, but found it necessary to reduce blade airfoil thickness ratio over the entire blade length to stay within acceptable bounds of matching airfoil drag divergence with the local operating Mach number.

Even with reasonable cruise efficiency, the 350 ktas and 375 rotor designs resulted in significantly higher GW than the 310 ktas design. While that is expected, as power grows with the cube of airspeed, it is recognized that NASA chose a good airspeed for the LCTR2.

The relative operating cost analysis showed that designs for higher cruise airspeeds are not only heavier aircraft, increasing production cost, but they also increased the DOC/ASM metric as well. There was no unexpected result discovered in this area. This analysis also quantified that the 2035 technologies reduced DOC/ASM by nearly 30% and DOC/FH by 20%, relative to the 2015 COTS operating costs, a highly worthwhile goal for any commercial aircraft.

Conclusions for the Airspeed and Range Excursions with the 2035 FG-VSPT

- The 2035 drive system and FG-VSPT engine technology have the potential to reduce DOC/ASM by nearly 30% and DOC/FH by 20%, relative to the 2015 COTS operating costs, a worthwhile goal for any commercial aircraft
- Designing the LCTR2 concept to airspeeds above 310 ktas, such as 350 ktas or 375ktas, resulted in larger, more powerful designs that demanded more fuel and had correspondingly higher operating costs.

11.0 APPENDIX A - STATEMENT OF WORK

Additional detail is provided below for the WBS elements of this study project as refined during execution.

Final reports for Task orders 2, 4, and 6 will be integrated or attached as Addendum reports to the final report for Task Order 10 which will be a "CR" report with no data restrictions. If proprietary data is exchanged with interim or periodic reports, it will be clearly marked as proprietary data, and available with limited rights, for government use only. Proprietary data that is intended to be part of the final report will be clearly marked as proprietary data, designated as an addendum to the final report, and available to government with limited rights

Weight trending information and procedures are based on legacy data and are not deliverable in this project. Data from weights analysis for drive systems conducted in this project is considered a deliverable with unlimited data rights.

11.1 Task Order 10

WBS 1 – High Level Initial Study

LCTR2 vehicle sizing is conducted for 54% rotor-tip speed variation and power requirements. Weights and mission performance analysis considers full (100%) rotor speed at cruise and 2 partial rotor speeds (up to approximately 50% variation at cruise condition from maximum speed rating of 100% at hover). A review of the current state of art for drive systems speed variation concepts is also conducted with a literature research of related R&D reports and technical papers. Rolls-Royce assesses the engine speed variation and concepts for a COTS engine. Evaluation of speed variation splits are conducted for approximately 0/50, 25/25, and 50/0 splits between engine and transmission.

1.1 Assemble tools, methods and comparison data for execution of Task 1. Generate Prop-Rotor performance maps from NASA provided Prop-Rotor configuration data. Perform functional check-out of spreadsheet vehicle sizing tool assembled from existing software.

1.2 Perform initial analysis/ validation on NASA LCTR Configuration, weights, aero performance, and propulsion/ drive system baseline. Engine data is based on a (Rolls-Royce) engine from task 1.4. Analysis of weights and aero performance considers prior Boeing experience and available industry data.

1.3 Assess current state of art for drive system speed variation concepts, and rank technology needs, and risks. This review will consist of literature review and review of current R&D efforts.

1.4 Rolls-Royce provides engine performance data in tabular for the COTS engine. The COTS engine is a conventional turbo-shaft engine that is a derivative of the Rolls-Royce RB282 core. Rolls engineers assess high level engine speed variation concepts and technologies for (Rolls-Royce) COTS, EIS 2025, EIS 2035 engines.

1.5 Perform initial evaluation of speed variation split with COTS engine (with existing/ available engine deck) and 0/50, 25/25, and 50/0 (speed reduction share) splits between engine and transmission. Also assess the benefits attaining speed reduction with discrete ratio transmissions and continuously variable transmissions. Analysis will be performed at 54%, 77% and 100% rotor speed.

WBS 2 – Establish Engine Performance Models and Baseline

In Task 2, Rolls-Royce defines the engine architecture and identifies technology challenges for advanced engine configurations. Rolls-Royce defines the engine cycles for EIS 2025, and EIS 2035 at the desired operating conditions for rotor speed, altitude and vehicle airspeed. EIS 2025 uses an updated version of the COTS engine to reflect improvements in engine performance technology. The EIS 2035 utilizes the Rolls-Royce Future Affordable Turbine Engine (FATE).

2.1 Define Engine baseline and technology challenges, needs, risks

2.2 Define Engine cycles for EIS 2025, and EIS 2035 engines. Engine decks should be functional for operating conditions to 54%, 77% and 100% of rated rotor speed

2.3 Define specific speed variation strategies and performance parameters, and provide descriptions for use in this study and reporting.

WBS 3 – Establish Drive System Concepts and Baseline

For Task 3, Boeing Rotorcraft defines drive system baseline concepts, parameters and models. Technology needs, and barriers are also investigated in this task. As a Tiltrotor, LCTR2 has a very similar configuration to that of the Bell-Boeing V-22 Osprey. Therefore, the V-22 drive system is used as a reference for the LCTR2 vehicle. Speed reduction configurations are studied through literature researches. Schematic diagrams will be the method of characterizing drive system configurations in this study, since they posses enough information to apply parametric weight trends that will be needed for vehicle sizing. Schematics will describe power levels, number and type of gearing, directions of rotation and speed, and other relevant information. Development of drive system details beyond this level is not within the scope of this project, except to the extent necessary to support analysis and feasibility evaluations.

3.1 Define drive system baseline concepts, parameters and models for study efforts

3.2 Define technology needs, barriers, and risk reduction challenges

3.3 Provide Descriptions and data for detailed speed reduction strategies to be used within this study effort

WBS 4 – Analyze Effects of Speed Split Variation

In Task 4, air vehicle performance is analyzed base on mission requirements, baseline propulsion, and drive system models. This analysis examines baseline systems at TBD% speed reduction and 50% speed reduction with a speed variation split varying from 50/0 “all engine”, to 0/50 “all drive system” in even increments. These analyses will determine which system provides the best overall performance considering weight, range, fuel consumption, SFC for tip speed reduction for the LCTR2 aircraft.

4.1 Perform Air Vehicle performance analysis based on mission requirements and baseline propulsion and drive system models to determine baseline results. Analysis will examine baseline systems with (1) TBD% speed reduction and 50% speed reduction with a speed variation split varying from 50/0 “all engine”, to 0/50 “all drive system” in even increments.

4.2 Review analysis and determine the system for best overall performance considering parameters of weight, range, fuel consumption, SFC for tip speed reduction

4.3 Re-Analyze the system for best overall performance with given parameters of weight, range, fuel consumption, and SFC (from 4.2) with additional considerations for technology insertions for Engines and Drives

WBS 5 – Technology Assessment

During this study, technology challenges and barriers for engine and drive systems are documented as part of Task 5. Since there are many analysis tools and methods, Boeing's data might be different from those provided by NASA. Therefore, Boeing will use the results to assess the associated risk as well as the benefits. Related R&D programs will also be use as recommendations to develop the required technologies for LCTR2.

5.1 Document and re-assess technology challenges, barriers, and needs, for engine and drive systems and sub-systems in light of study results

5.2 Perform risk/benefit assessment for technologies identified

5.3 Perform gap analysis for technologies identified

5.4 Develop recommendations for related R&D programs to develop required technologies

WBS 6 – Reporting

Results from this study will be recorded in Task 6. This task keeps track of all analysis and documentations.

6.1 Document analysis and study results in written report and presentation materials for oral briefs

6.2 Present oral reports to NASA

11.2 Task Order 2

WBS 1.0 Detailed Speed Changing Configuration Studies for Engine and Drive Systems/ Sub-systems

1.1 Building upon results from the previous task 10 project, Boeing will develop a preferred configuration for LCTR drive system speed variation mechanisms in concept sketches and CATIA models.

Rolls-Royce/LibertyWorks will support this effort by developing tabular engine cycle information for an engine configuration optimized for a single speed operation at 100% nominal speed but capable of stable transition through a broad speed range as needed during shifting events in the rotor/drive system. These engines will be consistent with 2025 and 2035 EIS technology levels.

1.2 Perform supporting analysis to characterize vehicle performance and sizing to justify selections and technology recommendations. Analysis will be performed with existing spreadsheet sizing tool from previous projects.

1.3 Analysis of speed changing mechanisms (performance, stress and weight) will be performed to guide concept development.

1.4 Provide design and analysis documents and recommendations for development and related R&D programs

WBS 2.0 Perform Analysis to determine transient dynamic behavior for optimal system to reduce risk

2.1 Develop characteristics (inertias, masses, spring rates, and damping) of LCTR propulsion system based on concept schematics and sizing, LCTR system characteristics, similar experience from CH47, HLH, A160, relevant engines etc.

Rolls-Royce/LibertyWorks will support this effort by developing engine mass and inertia data for Boeing models, and will provide information and simple models for engine control systems compatible with vehicle concepts in this study. Control system is for engines described above, optimized for a single speed operation at 100% nominal speed but capable of transition through a broad speed range.

2.2 Perform ADAMS or SIMULINK multi body dynamic transient analysis of speed variation transients based on selected configurations, etc. to determine risk severity of speed changing transient dynamics for LCTR sized vehicle.

2.3 Examine effects of technology insertions that reduce system inertia, reduce stability, etc.

2.4 Document results for this activity and provide addendum report

11.3 Task Order 4

Task Order 4 further examines engines with EIS 2035 technologies. The Variable-geometry VSPT engine from Task 10 was compared to a new Fixed Geometry VSPT at the same technology level. Mission and sizing analyses are performed to support this study.

11.4 Task Order 5

11.4.1 General Description

During the course of the Task Order 10 contracted study "SRW Augmentation Engine / gearbox assessment for 50% variable rotor tip speed", subtle distinctions of benefits at 500 and 350 feet-per-second (fps) rotor cruise tips speeds were noted when including the effects of drive system weight and efficiency, and engine performance at reduced operating RPM. The intent of this proposed task is to maintain the same vehicle and focus on entry-in-service (EIS) 2035 technology levels for the drive system (engine and gearbox / transmission), including a wider range of operating conditions' (greater range of rotor cruise tips speeds, airspeeds, and mission ranges,) and additional engine performance data to refine and complement the efforts that have already been performed.

It is expected that this further effort, combined with the results of the earlier results, would define engine and gearbox combinations that minimize vehicle takeoff weight and mission fuel usage. To present an example: some combination of vehicle and mission requirement would favor employing a single-speed gearbox with engine technologies (such as variable or fixed geometry, VSPT) to minimize gross weight and mission fuel; other vehicle and mission combinations would realize minimum gross weight and mission fuel employing a multispeed gearbox and gas turbine with a "standard" power turbine.

To help understand results from another perspective, Operating and Support (O&S) costs will be estimated for some of the vehicle results. Reporting these new results will include integrating with previous efforts (such as the comprehensive Task Order 10 draft report, as applicable) and reporting in new, more concise reports that focus more on summary of results and conclusions more useful for guiding technology investment strategies.

11.4.2 Task Descriptions

WBS 1.0 – Develop engine performance and weight assuming EIS 2035 VSPT technologies.

WBS 2.0 – Additional rotor tip speed of 422 fps

– Select airfoil distribution and twist distribution for rotor cruise tip speed of 422 fps at 310 ktas and 400 ktas design airspeeds, and generate rotor performance maps for hover and cruise

WBS 3.0 – Mission and Sizing analysis for the EIS 2035 fixed geometry VSPT.

– Produce a new matrix with airspeed at 400 ktas with rotor tip speeds of 350 fps, 422 fps, and 500 fps.

- Generate analysis for mission range cases of 500, 1000, and up to 1500 nautical miles.

– Select the most relevant combination (by mutual agreement of NASA and Boeing) to achieve the desired result.

– Perform O&S cost analysis using a similar methodology as reported in NASA CR-2009-214594

WBS 4.0 – Documentation

– Results shall be integrated and reported along with Task 10 final paper.

– Update Task 10 paper to create a cohesive final report.

12.0 APPENDIX B – NASA LCTR2 VEHICLE DESCRIPTION

The NASA Large Civil Tiltrotor (LCTR2) shown in Figure 78 has been defined by NASA studies and reported in multiple technical papers. It has focused on the performance benefits of low-speed rotors in cruise with associated weight benefits to the rotor and wing. The LCTR2 was sized to carry 90 passengers in a single-aisle pressurized fuselage with 4-abreast seating over 1,000 nmi range. Rotors were sized for vertical takeoff at 5,000 ft/ISA+20°C and a cruise airspeed of 310 ktas at 25,000 ft altitude. Four (4) notional 7,500 SHP class engines were selected for the propulsion system, which exceeds the hover takeoff requirement but provides continued cruise capability at altitude under OEI conditions.

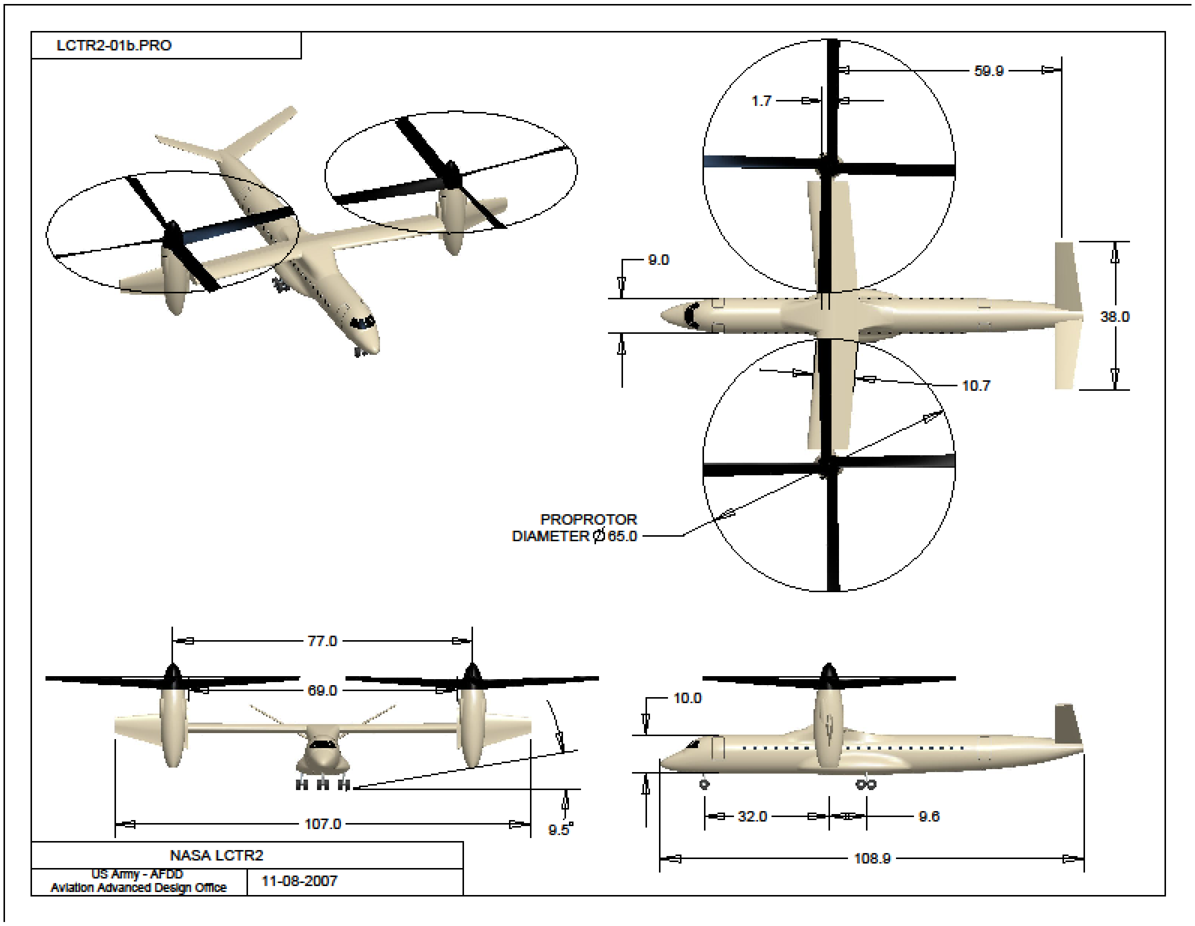


Figure 78. LCTR2 General Arrangement

12.1 Dimensions And Weight

General characteristics of LCTR2 provide by NASA are shown in Table 14 and dimensions are in Table 15.

Table 14. General Characteristics of the NASA LCTR2 Configuration

Structural Design Gross Wt.	107,124 lb	Overall Length	108.9 ft
Max Take-off Gross Weight	123,192 lb	Overall Width	142.0 ft
Operating Weight Empty	67,652 lb	Wing Span	107 ft
Installed Power	4x7,500 shp	Inner Wing Span	77 ft
Design Payload	19,800 lb	Disk Loading (SDGW)	16.14 psf
Main Cabin	Single Class	Wing Loading (SDGW)	107.4 psf
	2x2 Seating	4-abreast	

Table 15. LCTR2 Tabulated Dimensions

Item	Dimension/Area Units	Size
Proprotor	Diameter ft	65.00
	Sweep (c/4) deg	none
	Dihedral deg	none
	Blade Aspect Ratio	8.9
	Nacelle Conversion axis to Hub Distance ft	12.08
	Solidity, geometric	0.1429
	Rotor Spacing ft	77.03
	C_T/σ (5,000ft ISA +20°C)	0.1621
Nacelle (x2)	Length ft	20.00
	Diameter (approx) ft	7.33
	Wetted Area (each) ft^2	385
Conversion(x2)	Wetted Area (each) ft^2	21
Fuselage	Major Diameter ft	9.00
	Overall Length ft	108.92
	Frontal Area ft^2	64
	Wetted Area ft^2	1927
Sponson	Length ft	26.67
	Frontal Area ft^2	29
	Wetted Area ft^2	712
Wing Mount	Frontal Area ft^2	32
	Wetted Area ft^2	270
Inner Wing	Span (to mid nacelle) ft	77.0
	Root Chord ft	10.75
	Root Incidence deg	3.3
	Root Airfoil Thickness/chord	0.23
	Tip Chord in	10.75
	Tip Incidence deg	3.3
	Tip Airfoil Thickness/chord	0.23
	Sweep (c/4) deg	-5
	Dihedral deg	0
	Plan Area ft^2	828
	Aspect Ratio	7
	Wetted Area ft^2	1441

Table 15 LCTR2 Tabulated Dimensions - Concluded

Item	Dimension/Area Units	Size
Outer Wing	Span (mid nacelle to tip) ft	15.00
	Root Chord ft	9.67
	Root & Tip Incidence deg	3.3
	Root Airfoil Thickness/chord	0.18
	Tip Chord in	3.97
	Tip Airfoil Thickness/chord	0.18
	Sweep (c/4) deg	0
	Dihedral deg	0
	Plan Area ft^2	204.5
	Wetted Area (each) ft^2	158
Total Wing	Span ft	107
	Plan Area ft^2	1000.9
	Aspect Ratio	11.44
Tail (x2)	Span ft	38.02
	Root Chord ft	5.85
	Root Incidence deg	-3
	Root Airfoil Thickness/chord	0.12
	Tip Chord ft	3.51
	Tip Incidence deg	-3
	Tip Airfoil Thickness/chord	0.12
	Sweep (c/4) deg	0
	Dihedral deg	35
	Plan Area ft^2	222.4
	Aspect Ratio	6.5
	Overall Height ft	13.3
	Wetted Area (each) ft^2	235

13.0 APPENDIX C – ROLLS-ROYCE ENGINE DESIGNS

13.1 General Engine Description

Rolls-Royce/LibertyWorks defined four engines representing COTS (2015), 2025, and 2035 EIS technology levels, to be used in two aircraft versions: one with a rotor gearbox featuring a gear change mechanism and another without gear change capability. The resulting variation in rotor speed was from 100% to 54% speed. Scalable installation and performance data were provided by Rolls-Royce for three engines with technology consistent with the 2015, 2025, and 2035 time frames. Each configuration and performance model was assigned individual Preliminary Design (PD) model numbers:

- PD627 designates the 2015 engine
- PD646 designates the 2025 engine
- PD647 designates the 2035 engine with variable-geometry, variable-speed power turbine (VG-VSPT).
- PD628 designates the 2035 engine with fixed-geometry, variable-speed power turbine (FG-VSPT)

This appendix provides supplemental information about the engine design strategy for this study and the Turbine Engine Reverse Modeling Aid Program (TERMAP) software

13.2 Engine Modeling

Engine performance data for both the 2025 and 2035 engines were generated using Rolls-Royce's mature and validated in-house engine performance analysis program Turbine Engine Reverse Modeling Aid Program (TERMAP) software. As such, component maps were generated that included Reynolds number effect tables to better model the altitude lapse rates. Additionally, the PT matching was selected to offer a compromise between performance at takeoff and at part speed for cruise conditions.

Windage and bearing losses are included in the models for all turbine components. Compressor map scaling was accomplished to maintain a surge margin of 15% with polytropic efficiency matched to the sizing effects curve. The turbine sizing effect curves are based on historical data trends of efficiency vs. turbine inlet corrected flow. Within the TERMAP model, the design point efficiency is calculated by applying a delta to a nominal, or maximum, efficiency for each turbine. All turbines use the same table of deltas vs. turbine inlet corrected flow, but with separate nominal (maximum) efficiencies defined by Turbine-Aero for the various turbine configurations. Secondary flow models were constructed and flow rates input into the cycle with exit and re-entry at the appropriate station locations. Cooling flows were established based on the level of technology available for the three reference time frames. Both the PT cycle and map speeds were set to 100% for the 4000 ft/95°F day design point, but as noted in the header information, the PT design was optimized for a notional cruise condition at 80% power to address requests from the customers for better cruise performance. As the engine is scaled with the design shaft power (PWSD), the PT mechanical speed was scaled by holding PT turbine airfoil aerodynamic loading constant.

The model utilized user-defined calculations (USRCALs) for the following:

- Turboprop thrust, equivalent power and SFC calculations based on user-input rotor efficiency and power-to-thrust factor
- Conversion of the Turbine-Aero Reynolds number corrections from a delta adiabatic efficiency to an adiabatic efficiency scalar
- Parasitic losses on the HP, IP, and PT shafts. In the case of the HP spool, the total power extraction from the HP shaft includes engine related and some customer Power Extraction (PWX) from the HP shaft.
- Scaled PT mechanical speed and overall engine dimensions and weight

Full engine computer-aided design (CAD) models were generated for the baseline designs at 12,500 shp.

13.3 Engine Components

13.3.1 Compressor

The compressor designs insured adequate surge margin with polytropic design point efficiencies in line with the three EIS technology levels. Compressor performance predictions are derived from rig data as well as fully validated design and analysis tools. Extensive rig, core and engine testing has been conducted by Rolls-Royce/LibertyWorks; several relevant test articles used for substantiation of axial, centrifugal and axial-centrifugal compressor design and performance are listed in Table 16 below.

Table 16. Compressor Experience

Axial Compressors	Axi-Centrifugal Compressors	Centrifugal Compressors
• F136 Fan, 3 stages • XF-26 (APSI), 2 stages • HFC, 5 stages • Rig 639, 9 stages • AE 1107 HPC, 14 stages • YJ102R (HiSTED), 7 stages • ASTC, 2 stages • CX-65 (ACCS), 4 stages • XTC 76/2 (ATEGG), 5 stages • XTL 17 (JETEC), 4 stages	• Model 250-C20B (6+1) • Model 250-C20R (4+1) • GMA 580 (MTDE) (6+1)	• TS1230A (M1), single stage • XC20, single stage • CX31, single stage • Model 250-C30, single stage • Model 250-C40, single stage • RR300, single stage • RR500, single stage • GMA 500, two stage • CX-55, two stage

13.3.2 Combustor

Combustor designs utilize well-established technology based on fuel-rich burning in the primary zone. These combustor concepts have been successfully used in numerous Rolls-Royce plc engines, including the Trent family of engines and the Rolls-Royce AE 3007 family. Predictions of emissions are based on certified AE 3007 engine data.

13.3.3 Turbines

The turbine performance predictions are based on extensive rig, core and engine testing conducted by Rolls-Royce/LibertyWorks. The performance predictions are derived from rig data as well as fully validated design and analysis tools which have been proven over the past 30+ years. Design tools have been developed for flow-path sizing, throughflow calculations, airfoil shape generation and optimization and advanced 3-D CFD. The fully validated design and analysis tools include the following:

- Flow-path sizer, performance prediction and map generation tool
- Throughflow solver
- Airfoil shape generator and optimizer
  - AIRFOILOPT – Multi-variable/multi-objective airfoil shape optimization code developed under U.S. Air Force funding with ongoing improvements for 25 years
- 3-D CFD tools
  - ADPAC – Advanced Propulsion Analysis Code. Advanced 3-D viscous multi-block flow solver developed under NASA funding
  - VBI – Vane-Blade Interaction. Unsteady flow solver developed under U.S. Air Force funding

The turbine performance predictions are based on extensive rig, core, and engine tests over the past 30+ years. The above design and analysis tools have been developed and validated on the following representative turbine tests:

- Small High Work Turbine (SHWT) Rig (`76)
  - Detailed aero performance used to validate CFD tools
- Model 250-C34 engine (`82 – `83)
  - Strain gage data for a SHWT
- Controlled Overall Pressure Ratio (COPE) Dual Spool Rig Tests ('96 – `98)
  - HPT/LPT performance, off-design maps and limiting output
  - Tip clearance performance derivative
  - Aeromechanics data/calibration of 2-D and 3-D VBI code
- F120 Coupled Turbine Blowdown Rig (`97)
  - HPT and LPT Kulite pressure transducers and thin film strain gages
  - Tests provided aeromechanics tool calibration
- F120 Core Test (`00)
  - HPT performance verification for F136 HPT predecessor
- JSF Dual Spool Rig Test (`00 – `02)
  - Test data matching on a scaled F120 HP/LP turbine rig
- XTC-76 Core Test (Three builds from `99 – `05)
  - World record Rotor Inlet Temperature (RIT)

In addition to the above experience, Rolls-Royce has an ongoing effort to study and test high-work, high-pressure turbines. Rolls-Royce High-Work Single-Stage (HWSS) turbine rig testing, in progress since 2007, has provided results that have aligned well with pretest predictions and has demonstrated good margin to limiting load.

In addition to the HWSS turbine tests listed, the following power turbine programs have been used in the development and validation of Rolls-Royce turbine design and analysis tools:

- T800 Power Turbine Rig Test (`86)
    - Extensive two-stage turbine rig test demonstrating high PT efficiency
- High Load Coefficient LPT (`92 – `95)
    - Single-stage design for DoD Joint Technology Demonstrator Engine (JTDE)
- AE3007H Global Hawk Altitude Tests (`95 – `01)
    - Extensive altitude testing at Arnold Engineering Development Center (AEDC)
    - Reynolds number lapse rate confirmed
- 1½ Stage Vaneless Counter-rotating LPT (`98 – `03)
    - Design and rig test of LPT behind a HWSS high reaction HPT for JTDE
- HPT/LPT Interaction (`00 – `02)
    - Rig test and code validation (2-D and 3-D VBI) of HPT/LPT interaction for JSF F120 risk reduction test
- Low Reynolds Number LPT Research (`02 – `05)
    - Collaborative research activity with the US Air Force Research Lab (AFRL)
- F136 Engine Tests ('04 – present)
    - LPT test data confirms performance predictions over a broad operating range

13.4 Substantiation of 2015 Engine Component Technologies

13.4.1 High Pressure Compressor

The technology in the COTS high pressure compressor (HPC) is based on Rolls-Royce design experience with current and past products as well as advanced development work as previously cited. Aerodynamic advancements have improved efficiency at higher loading per stage allowing the same work to be done in fewer stages with lower blade and vane counts. The basis for the COTS HPC is directly linked to recent experience gained on Rolls-Royce experimental compressor Rig 639, which has now undergone two full builds. From these rig runs advanced compressor maps have been developed, with surge line predictions covering the full speed range. Rig 639 work included variable stator vane (VSV) studies and optimization. Also, baseline Reynolds number studies were completed for the high pressure compressor design. Based on development testing, no speed restrictions were required due to blade or vane vibration concerns. The development testing also demonstrated high speed flow, stall margin, and component efficiencies that met or exceeded the analytical predictions. Additionally, the efficiency lapse rate is better than for many past compressor designs. The high-pressure compressor technology validation testing completed in Rig 639 to date includes baseline map development, surge testing, baseline Reynolds number studies, and bleed effects. The following results have been demonstrated by test:

- Component efficiencies and pressure rise, overall and stage to stage.
- High speed flow, stall line, and component efficiencies meet or exceed predictions.
- Low speed stall line meets predictions.
- Efficiency lapse rate exceeds the levels shown on past compressors.
- No speed restrictions due to blade or vane vibrations.

13.4.2 Combustor

Combustor design utilizes well established technology based on fuel-rich burning in the primary zone as demonstrated in numerous Rolls-Royce engines, including the Trent and the AE 3007 families. The combustor is sized for good altitude relight characteristics with geometry to facilitate low pattern factors. Predictions of combustion efficiency and emissions produced are based on the AE 3007 combustor, which has a similar heat rise. The benefits of the annular combustion system are:

- Excellent pattern factor and stability
- Low NOx levels
- High carbon monoxide (CO) and unburned hydrocarbons (UHC) margins relative to International Civil Aircraft Organization (ICAO) Standards
- Low smoke levels

13.4.3 Turbines

The baseline COTS engine studied both high-work single-stage (HWSS) and two stage HPT options, with the HWSS turbine selected for the final cycle. The HWSS high-pressure turbine performance predictions were based on recent experimental test results from the Rolls-Royce corporate HWSS turbine rig. These results lined up well with pretest predictions and formed the basis for the model included in the PD627 cycle deck. Results from the HWSS rig fully support:

- Expansion and work levels fully characterized
- Component efficiencies demonstrated
- Good margin to limiting load (where the performance falls off sharply) in a flat portion of the efficiency characteristic at the design point

The low pressure turbine in the baseline engine is similar to turbines in production today and has little risk.

13.5 Approach to 2035 Engine Design

To provide good operability and part power efficiency, the 2035 engine is a three-shaft design with IP and HP spools. The IP compressor is an all-axial configuration, while the HP compressor is an axial-centrifugal unit. The axial-centrifugal HPC has appreciable efficiency benefits over an all-axial design given the low exit corrected flow rates produced by the high OPR cycle. The performance modeling conducted shows that the axial-centrifugal design maintains these efficiency benefits even as the engine is scaled up to high flow sizes, providing improved performance for cores going up to 20,000 shp. Both the HP and IP turbines make full use of the advanced materials and cooling technologies based on expected technology maturation within this time period. The IP turbine is a vaneless, counter-rotating design that eliminates the cost and cooling penalties associated with the IP vane stage. Cooling requirements are further reduced by incorporating an efficient heat exchanger that cools the cooling air prior to entry into the turbine blades. As with the 2025 engine, power turbine variability was included to improve engine performance at the low speed (54%) cruise point. The engine also embodies advanced controls and diagnostic technologies.

The 2035 engine equipped with these technologies provides huge benefits in SFC across the operating range. The ability to run the IP and HP spools independently results in improved operability and part power efficiency. This also allows the HP rotor to be run to much higher speeds, which significantly reduces the diameter of the core. This correspondingly reduces component weights and also reduces blade counts resulting in a lighter, lower cost engine. Rolls-Royce has an extensive background in three-shaft engine design. The portfolio of three-shaft engines includes:

- RB211 turbofan family
- Trent turbofan family
- GEM turboshaft
- TP400 turboprop

As with the 2015 baseline and 2025 derivative, the 2035 engine has been through numerous design iterations to optimize the cycle pressures, work splits, and temperatures. This includes the mechanical design necessary to size the rotors and shafting.

13.6 Component Technologies for 2035 Engines

13.6.1 Compressor

A two-spool core was selected to provide acceptable operability at the elevated pressure ratios. One of the factors that heavily influenced the IP and HP spool design was the selection of a vaneless, counter-rotating HP/IP turbine arrangement. To maintain high IP turbine efficiency over a broad operating range, the work level for the IP rotor had to be constrained, which then dictated the IP to HP work split in the compressor.

The intermediate compressor is an all-axial design based on the wide flow range compressor technology as demonstrated in prior Rig 639 experience. It is anticipated that advancements in aerodynamics and flow control features currently being developed in the Air Force HEETE program (Highly Embedded Efficient Turbine Engine) will also positively impact the design of the PD647 compressor.

The HP compressor is an axial plus centrifugal unit similar in design to the compressor currently found in the Model 250-C20R engine. The aerodynamics will take full advantage of the improvements in CFD modeling provided by the updated JACC codes. These codes were recently used to develop the RR300 and RR500 centrifugal compressors, which have demonstrated, by rig test, to have exceeded the initial design goals. An innovative feature of the centrifugal compressor is the active clearance control employed on the impeller shroud. This concept has also been successfully run in the Model 250-C30 compressor rig, which has demonstrated the feasibility of such systems during both steady-state and transient operation.

13.6.2 Combustor

PD647 incorporates an advanced, compact annular combustor based on prior IR&D studies, which achieve high intensity mixing and recirculation in a limited envelope. The combination of low surface area and Rolls-Royce proprietary Lamilloy cooling technology minimizes cooling flows to facilitate high temperature rise combustion with good pattern control.

13.6.3 Turbines

With the three-shaft architecture, the aerodynamics of the HP turbine is not overly aggressive and reflects a lower level of work than that required for the baseline engine. The design of the HP turbine incorporates Rolls-Royce proprietary Lamilloy cooling technology, which minimizes chargeable cooling flow. The cooling air is also cooled prior to entry to the turbine to increase the delta T available and further reduce cooling levels.

The IP turbine is a vaneless, counter-rotating design that eliminates the IP vane stage. High efficiency is maintained over a broad operating range, due to the fact that the HP/IP work split selected reduces the work required in the IPT. The blades are also shrouded to reduce losses and improve efficiency. The predictions for the IP turbine stage are based on the rig test results of a counter-rotating LPT behind an HWSS high reaction HPT design for JTDE. The IP turbine is a conventional, film-cooled design that uses interstage air from the HP compressor.

The power turbine is uncooled and incorporates the variable-geometry system envisioned for the PD646 power turbine. As with PD646, the power turbine design is a compromise to optimize efficiency at the desired, reduced output shaft speed cruise condition while minimizing impact to power available at takeoff and 100% shaft speed.

14.0 APPENDIX D– BOEING WEIGHT ESTIMATES FOR LCTR

14.1 Initial Comparison

Boeing initially estimated the LCTR2 component weights using the NASA LCTR2 geometry and NASA weights for engines, engine systems, contingency weight, fixed useful load, fixed equipment and payload. Boeing's weight model estimated the drive system weight to be 7% higher than the NASA drive system weight. The rotor, wing, and landing gear weights were 4.7%, 15.4% and 17.1% higher, respectively. However, these were compensated by a much lighter fuel system weight, resulting in only a 3.6% net increase in weight empty. These differences were chalked up to Boeing's parametric weight trends being based on different historical data from NASA's historical data, taking confidence in the relatively small difference in empty weight.

LCTR2 engines were resized to the greater of hover power required at 5K'/ISA+20°C or cruise power at the objective cruise airspeed, both based on the basic mission GW, i.e. the NASA SDGW. The required installed power was estimated to be 20,744 SHP, in contrast to NASA's 30,000 SHP, but that is not reflected in the constrained value of engine weight, or the engine systems, or the engine section weights.

The effect of reduced installed power was amplified in the study results that followed, by the effect explained above.

14.2 Component Weight Estimation

New component weights for resizing cases were estimated by scaling weight equations derived from parametric weight equations in the VASCOMP sizing program. The scaling relationships were applied against a set of baseline component weights Boeing developed for the LCTR2 design. For example, the NASA weight for the LCTR2 main rotor group was 8891 lbs, whereas the Boeing estimate for the main rotor group was 9362 lbs, 471 lb heavier. Component weights for Boeing sizing cases were scaled from the Boeing baseline weight according to the factors that were changed during the study. For example, the VASCOMP rotor group weight equation is:

$$W_R = K * k^{0.67}$$

Where K is a constant selected for the type of rotor and k is:

$$k = r^{0.25} * \left[\frac{\mathrm{HP}r}{100}\right]^{0.5} * \left[\frac{\mathrm{V}tip}{100}\right]^{0.5} * \left[\frac{R\,b\,\bar{c}}{10}\right] * F$$

Where:

r = blade attachment radius, ft

HPr = main rotor transmission limit power (per rotor), HP

Vtip is the design tip speed, fps

R = rotor radius, ft

b = number of blades per rotor

c = mean blade chord, ft

F is a droop factor

Table 17. Component Weights for NASA and Boeing LCTR2

2015 Technology, 350 fps Cruise Tip Speed, 54% Engine RPM, 100% D.S. RPM

	LCTR2 Reference		Boeing Baseline for NASA LCTR2		% Weight Difference
MANEUVER LOAD FACTOR		3.00		3.00	
ULTIMATE LOAD FACTOR		4.50		4.50	
TOTAL INSTALLED HORSEPOWER		30,000		24,895	
TOTAL MAIN ROTOR GRP	8891		9307		4.7%
DRIVE SYSTEM	7776		8322	Config 1	7.0%
PRIMARY ENGINES	3147		3147	Assumed =	0.0%
PRIMARY ENGINE SYSTEMS	950		950	Assumed =	0.0%
FUEL SYSTEM	2283		2283		0.0%
PROPUSION GROUP WT INCREMENT					
TOTAL PROPULSION GROUP WEIGHT		23,047		24,009	4.2%
WING	5970		6890		15.4%
TAIL GROUP	919		752		-18.2%
FUSELAGE	10632		10699		0.6%
LANDING GEAR	2575		3017		17.2%
TOTAL ENGINE SECTION	3338		3342		0.1%
PRIMARY ENGINE SECTION	2964		2968		
AIR INDUCTION	374		374		
CONTINGENCY WT	3971		3971	Assumed =	0.0%
TOTAL STRUCTURE GROUP WEIGHT		27,405		28,672	4.6%
PRIMARY FLIGHT CONTROLS	3471		3624		4.4%
COCKPIT CONTROLS	75		178		
MAIN ROTOR CONTROLS			1396		
MAIN ROTOR SYSTEMS CONTROLS	3261				
FIXED WING CONTROLS			1380		
TILT MECHANISM			535		
SAS	135		135		
CONTROL WT INCREMENT	0		0		
TOTAL CONTROL GROUP WEIGHT		3,471		3,624	4.4%
WEIGHT OF FIXED EQUIPMENT		12,279		12,279	Assumed =
WEIGHT EMPTY		66,202		68,584	3.6%
FIXED USEFUL LOAD		1,450		1,450	Assumed =
OPERATING WEIGHT EMPTY		67,652		70,034	3.5%
PAYLOAD		19,800		19,800	Assumed =
FUEL		19,650		19,650	Assumed =
GROSS WEIGHT		107,102		109,484	2.2%

The scaling equation for the rotor group weight assumed all blades had the blade attachment radius (r), and a substitution of σ*π*r2 was made for R*b*c. The rotor hover Vtip was always 650 fps for both the NASA LCTR2 and for the Boeing analyses. After canceling like terms, such as the constant K, the main rotor group scaling equation became the following, where 9362 lb was the Boeing weights engineer estimate for the LCTR2 rotor group weight. Ultimately the rotor solidity terms had no effect, as the sizing rules always gave the NASA LCTR2 solidity, leaving the rotor group weight dependent on variations of HPr and rotor radius (R)

$$W_R = 9362 * \left(\sqrt{\frac{\mathrm{HP}r}{20490}} * \frac{(\mathrm{Re}\, sized)\sigma * R^2}{(NASA\ LCTR2)\,\sigma * R^2} \right)^{0.67}$$

Basic drive system weight changed in accordance with both the RPM reduction and the year of technology to stay consistent with the engine technology. Drive system losses were estimated as a percent power loss, which changed with both RPM reduction and technology. Values of the drive system weight and efficiency are shown in Table 18. The drive system weights are the reference weights used in the Excel/VB sizing analysis, which is then scaled according to the actual rotor HP required.

Table 18. Drive System Weight and Efficiency, and Wing Weight Factors

Technology	**Rotor Cruise Tip Speed, fps**	**Engine % RPM**	**Drive System % RPM**	**Drive System Reference Weight** (@ 6000 SHP)	**Drive System Losses** (% SHP)	**Wing Weight Factor**
2015	650	100	100	8989	4.10	1.00
	500	100	77 *	9406	4.35	0.981
		77	100	8989	3.85	
	350	100	54 *	9669	3.90	0.972
		77	70 *	9497	3.80	
		54	100	8989	3.40	
2025	650	100	100	8427	3.90	1.00
	500	100	77 *	8819	4.13	0.981
		77	100	8427	3.66	
	350	100	54 *	9065	3.71	0.972
		77	70 *	8904	3.61	
		54	100	8427	3.23	
2035	650	100	100	7866	3.69	1.00
	500	100	77 *	8231	3.92	0.981
		77	100	7866	3.47	
	422	100	65 *	8270	3.67	0.976
		65	100	7866	3.26	
	350	100	54 *	8460	3.51	0.972
		77	70 *	8310	3.42	
		54	100	7866	3.06	
2035 350 ktas	350	Same as 350 fps above				0.9777
2035 375 ktas	350	Same as 350 fps above				0.9814

* Two-speed Main Rotor Transmissions

The drive system weight equation in VASCOMP is driven by the torque, as described below.

$$W_{DS} = k_{DS}\ K_3\ (k)^{0.80}$$

Where K3 is a weight adjustment factor selected to account for the drive system type and number of gearboxes and k is:

$$k = \left[\frac{1.1\ HP_{Total}}{k_{VT}\ \ RPM_{rotor}}\right]$$

Where:

kDS = constant for drive system weight (nominally 300)

HPTotal = total aircraft transmission rating, HP

KVT is another weight adjustment factor

RPMrotor = rotor design rpm

A reference drive system weight was established for each drive system technology and RPM reduction, for a 6000 SHP reference transmission rating. Applying this method, some terms fall out of the scaling equation, and it simplifies to this,

Wds = Ref DS wt * (Xmsn rating*Dia/Vtip) / (6000*Ref Dia/Ref Vtip))^0.8

where the reference diameter and reference Vtip are those of the NASA LCTR2.

All structural weights were estimated at a 2025 technology level, to avoid any confusion about structural impact versus the primary objective of evaluating rotor cruise operating tip speed and the engine rpm versus drive system rpm reduction.