Range and Endurance Tradeoffs on Personal Rotorcraft Design

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ABSTRACT

Rotorcraft design has always been a challenging tradeoff among overall size, capabilities, complexity, and other factors based on available technology and customer requirements. Advancements in propulsion, energy systems and other technologies have enabled new vehicles and missions; complementary advances in analysis methods and tools enable exploration of these enhanced vehicles and the evolving mission design space. A system study was performed to better understand the interdependency between vehicle design and propulsion system capabilities versus hover / loiter requirements and range capability. Three representative vertical lift vehicles were developed to explore the tradeoff in capability between hover efficiency versus range and endurance capability. The vehicles were a single-main rotor helicopter, a tilt rotor, and a vertical take-off and landing (VTOL) aircraft. Vehicle capability was limited to two or three people (including pilot or crew) and maximum range within one hour of flight (100-200 miles, depending on vehicle). Two types of propulsion and energy storage systems were used in this study. First was traditional hydrocarbon-fueled cycles (such as Otto, diesel or gas turbine cycles). Second was an all-electric system using electric motors, power management and distribution, assuming batteries for energy storage, with the possibility of hydrocarbon-fueled range extenders. The high power requirements for hover significantly reduced mission radius capability. Loiter was less power intensive, resulting in about ½ the equivalent mission radius penalty. With so many design variables, the VTOL aircraft has the potential to perform well for a variety of missions. This vehicle is a good candidate for additional study; component model development is also required to adequately assess performance over the design space of interest.

NOTATION

DGW = design gross weight
ISA = international standard atmosphere
MCP = maximum continuous power
MRP = maximum rated power
OGE = out of ground effect
SMR = single-main rotor (helicopter)
SOA = state of the art
V_{be} = best endurance velocity
V_{br} = best range velocity
VTOL = vertical take-off and landing
η = efficiency

INTRODUCTION

There are increasing social pressures to reduce aviation's environmental impacts. The aviation air quality goal is to significantly reduce or eliminate point-of-use carbon dioxide and oxides of nitrogen emissions. Propulsion and vehicle noise is another consideration, which is even more pertinent to helicopters and other vertical lift vehicles since they tend to operate closer to the general population than their fixed-wing counterparts. Recent and projected improvements cited in Reference 1 for electric motor, generator and battery weights, coupled with their high system efficiency, expected reliability, scalability and operational flexibility, can enable new vehicle designs and missions, while mitigating noise and emissions impacts. To assess the potential for these new technologies, vehicles and missions; complementary efforts will be required to enhance the various methods and tools to accurately assess their potential, as well as define relevant requirements to guide research and development efforts.

Under NASA's Aeronautics Research Mission Directorate (ARMD), research and development over a broad range of technology efforts proceed "to meet future needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation" (Ref. 2). ARMD's Advanced Air Vehicle Program (AAVP) / Revolutionary Vertical Lift Technology (RVLT) Project supports the development and validation of tools and models to help define and refine research themes for vertical lift vehicles and missions. RVLT efforts focus on the technologies for larger (up to ninety passenger) vertical lift vehicles, down to vehicles designed for only 2-4 people. An ancillary effort under ARMD's Transformative Aeronautics Concepts Program (TACP) / Convergent Aeronautics Solutions (CAS) Project is the Design Environment for Novel Vertical Lift Vehicles (DELIVER) sub-project. DELIVER is a three year, fast-paced activity to explore the potential for developing, extending, and validating tools and models for smaller, vertical lift vehicles; focusing on vehicles ranging

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from three occupants to small, unmanned aerial vehicles (UAVs). The convergence of societal pressures, advanced electric technologies, and research priorities has re-invigorated vertical lift vehicle analyses. For vertical lift vehicles, the tradeoffs among vehicle size, complexity, capabilities, and other requirements have always been challenging. With recent and anticipated future gains in advanced electric propulsion and energy storage technologies that can be distributed throughout the vehicle with minimal capability loss at reduced size, new vehicle designs varying in their efficacy for hover, endurance, range and speed can be conceptualized and compared. Three representative vertical-lift concepts with a variety of today's propulsion systems plus future envisioned systems were developed to explore the effects on their design, range and endurance. Vehicles explored include a single-main rotor (SMR) helicopter, a tilt rotor, and an advanced vertical take-off and landing (VTOL) aircraft enabled by distributed propulsion. For such disparate vehicles, it is difficult to directly compare their specific performance capabilities and select a clear optimum without well-defined requirements. Thus, general design parameters and mission requirements were chosen and analyses performed to quantify performance characteristics. Traditional hydrocarbon-fueled propulsion systems as well as electric motors powered by battery systems that could be flight-ready in 15 and 30 years are included. Hydrocarbon-fueled range extenders will also be examined to mitigate deficiencies in battery, energy storage technology.

Vehicle concepts will be covered first, highlighting similarities and differences among the chosen vehicles and their respective design philosophy. Next, present and future propulsion and energy systems will be examined, including performance levels expected in the near and farther term. Then the analysis methodology will discuss the various study assumptions, the specific tools and vehicle models. Finally, results will be presented and analyzed and conclusions discussed.

VEHICLE CONCEPTS

A single-main rotor (SMR) helicopter, a tilt rotor, and an advanced VTOL aircraft enabled by distributed propulsion were explored and compared. Notional pictures are shown in Figure 1 and base concept vehicle specifications are given in Table 1. For each concept, design choices and resulting characteristics are described next. The vehicle payload mission capability was selected as 1-2 passengers (450 lb., 205 kg maximum total payload) with a 200 pound (91 kg) pilot. The default mission range for each vehicle was determined assuming five minutes each for idle and hover, with approximately an hour mission duration including climb to and cruise at a representative altitude assuming best range speed (V_{br}). A few, pertinent design considerations are mentioned with each concept; a more thorough discussion for each concept can be found in many textbooks and would be superfluous here.

Single Main Rotor (SMR) Helicopter

The SMR helicopter is based on current design philosophy. A large, main rotor for fairly low disk loading is used. This results in reduced hover and overall propulsion power requirements, including a low engine power to vehicle design gross weight (DGW). Low engine power is especially important at this modest vehicle size and mission, as engine choices are generally limited to low thermal efficiency (<30%) and power-to-weight (<1 hp/lb., barely above 1 kW/kg) reciprocating, gasoline (Otto cycle) engines. Although the vehicle is relatively efficient at hover and low-speed loiter and endurance, such low, main rotor disk loading and modest overall power limits cruise speeds to around 100 knots (185 km/h). A single engine is used to minimize losses in engine power-to-weight and efficiency that results from reduced engine size when using multiple engines. A single engine and main rotor also reduce the vehicle's overall mechanical complexity, although it also limits redundancy. To maintain safety limits in these smaller vehicle designs, engines are often de-rated in maximum power capability and flight hours. Other components are designed with additional robustness and safety margins with increased inspection and maintenance requirements. With these strengths and weaknesses, the SMR helicopter design is well-aligned with search and rescue, air taxi, and other missions; and is therefore expected to remain as a viable vertical lift design option for many years.

Tilt Rotor

Johnson, et al. (Ref. 3) found that the tilt rotor is one of the more efficient cruise vehicles among traditional, hybrid helicopter / airplane designs. Although a tilt rotor generally has less rotor swept area (higher disk loading) and lower hover efficiency than other, traditional hybrid helicopter / airplane designs, it can effectively use the rotated rotors like large propellers for propulsive thrust while in airplane mode. Although more mechanically complicated than the SMR helicopter, it also has VTOL capabilities, with higher speed and range potential. Tilt rotor design is a complex balance between hover and airplane mode performance (rotor and wing, design and sizing), based on overall mission requirements. Vehicle requirements and design are generally biased toward airplane mode performance rather than hover efficiency. In more traditional tilt rotor designs, vehicle lift and propulsion is limited to two rotors, each on a pylon that can rotate from vertical to horizontal, located near the end of the wing. Again, the number of engines is limited to minimize losses in engine power-to-weight and efficiency that results from reduced engine size when using multiple engines. Tilt rotor mechanical design generally includes a cross-shaft to transfer motive power between the two rotors for some redundancy and increased operational flexibility and safety.

Figure 1. Notional vehicle representations: a) Single Main Rotor (SMR) Helicopter, b) Tilt Rotor, and c) Advanced, All-Electric VTOL Aircraft.

Table 1. Base Concept Vehicle Specifications.

Vehicle → Parameter ↓	Single Main Rotor (SMR) Helicopter	Tilt Rotor	All-Electric VTOL Aircraft, 15 year technology	All-Electric VTOL Aircraft, 30 year technology
Design gross weight (DGW), lb. (kg)	2,050 (930)	2,545 (1,154)	2,785 (1,263)	2,199 (1,000)
Empty weight, lb. (kg)	1,100 (500)	1,690 (767)	2,135 (970)	1,549 (703)
Disk loading / wing loading, lb/ft^2	3.6 / N.A.	14 / 50	16 / 50	16 / 50
Nominal fuel weight, lb. (kg), % DGW *	160 (73), 8%	200 (91), 8%	628 (285), 23% (589 MJ battery)	270 (123), 12% (456 MJ battery)
Sea level maximum rated power (MRP), hp (kW)	190 (142)	470 (350)	456 (340)	350 (262)
Engine type	Reciprocating (Otto cycle)	Advanced turboshaft	All-electric, 15 year technology	All-electric, 30 year technology
Engine weight, lb. (kg), % DGW	270 (123), 13%	310 (141), 12%	105 (48), 4%	60 (27), 3%
Engine power / weight, hp/lb. (kW/kg)	0.71 (1.2)	1.50 (2.46)	4.34 (7.1)	5.6 (9.2)
Sea level power specific fuel consumption, lb./hp-h (kg/kw-h)	0.500 (0.305)	0.574 (0.350)	N.A.	N.A.
Power / DGW, hp/lb. (kW/kg)	0.09 (0.15)	0.18 (0.30)	0.16 (0.27)	0.16 (0.27)
Cruise velocity (V_{br}), knots (km/h) *	95 (176)	185 (343)	200 (370)	200 (370)
Range, nmi (km) *	195 (360)	200 (370)	150 (280)	150 (280)

* from mission analysis

Advanced, All-Electric VTOL Aircraft

The advanced, all-electric, VTOL aircraft is another hybrid helicopter / airplane design, enabled by advances in electric propulsion technologies. Advanced electric motors and generators, with their high efficiency and power-to-weight, also have the potential to scale with reduced or no performance penalties. Instead of one, or only a few, vertical lift rotors; many, distributed, smaller electric motor / rotor combinations can be used to enhance performance, propulsion redundancy and safety. Using distributed propulsion adds the potential for additional design freedom to optimize design for one or a host of missions, although many of the vehicle and propulsion design interactions are not presently well understood. A recent work by Young (Ref. 4) noted both positive and negative interactions from multi-rotor designs, but that level of detail was not included in this preliminary study. This particular vehicle's design and performance is also highly sensitive to electrical energy storage density, especially for 15 year battery technology, where it comprises almost ¼ of vehicle design gross weight. The matrix of propulsion and energy storage concepts used for this effort is discussed in the next section.

PROPULSION AND ENERGY STORAGE CONCEPTS

The two more traditional, base concept vehicle designs include internal combustion propulsion concepts using hydrocarbon fuels. Advanced, all-electric systems propulsion and energy storage concepts are discussed and compared on a component and overall system perspective. Because traditional propulsion concepts and fuels are fairly well understood, they will not be discussed in detail here, but their performance assumptions are included for comparison with the all-electric systems. Both traditional and all-electric concepts are modeled to estimate their effect on vehicle design and performance. For some operational scenarios, hydrocarbon-fueled "range extenders" are considered an interim step to more or all-electric systems and are discussed.

Electric Motors

There is substantial interest in all-electric systems for a new generation of aviation propulsion systems. Impressive levels of electric motor and generator power-to-weight ratio, efficiency and reliability are being demonstrated in hybrid cars. There are concurrent efforts developing and testing various architectures for aircraft. Additional advantages are that high efficiency and power-to-weight are maintained at various scales, with high efficiency also maintained at part power operation. These attributes enable innovative designs and operations to further improve redundancy, safety, and overall vehicle capability and flexibility. Reference 1 discusses recent efforts trying to quantify various technology approaches to realize significant weight and efficiency improvements for non-cryogenic hybrid electric propulsion components. As shown in Table 2, material and design improvements reduce losses by a factor of five from state of the art (SOA) electric motors, while reducing weight by over a factor of 2.5.

Table 2. Electric motor parameters (from Reference 1).

Technology year	Power/weight hp/lb. (kW/kg)	η, %	Controller η,%	Net η, %	Total loss, %
SOA	1.9 (3.1)	90	94	85	15
15 year	3.4 (5.6)	95	98	93	7
30 year	4.9 (8.0)	98	99	97	3

Power-to-weight includes electric motor + controller

Engine / Energy Storage

Even with high efficiency, all-electric propulsion systems are presently limited by the low energy density of present battery, capacitors, or other electrical energy storage systems. This can be illustrated by comparison with present systems in Table 3. Hydrocarbon-fueled systems are substantially less efficient than electrical systems, but the high energy density of hydrocarbon fuels enables these fueled systems to have significantly better net energy density than 30 year projections for batteries. Diesel cycles have the potential to reduce carbon dioxide emissions because of their higher efficiency versus the Otto cycle or gas turbine; if improved power-to-weight diesel engines can be developed and certified for aviation (Ref. 5). Current, certified aviation diesel engines have lower power-to-weight than existing helicopter engines, adversely impacting engine and overall vehicle weight, and diminishing fuel burn benefits. For these reasons, diesel cycles are only included here for comparison and advanced diesel as a possible range extender option.

Table 3. Example engine / energy storage characteristics.

Engine type	Power / weight, hp/lb. (kW/kg)	η, %	Fuel, energy density, MJ/kg	Net energy density, MJ/kg
Reciprocating gasoline (Otto) Cycle	0.71 (1.2)	27	Gasoline, 43.5	11.7
Advanced gas turbine[a]	5.0 (8.2)	24	Jet-A, 42.8	10.3
all-electric, SOA[b]	1.9 (3.1)	85	0.70	0.60
15 year	3.4 (5.6)	93	1.75	1.63
30 year	4.9 (8.0)	97	3.15	3.06
Diesel cycle, SOA Advanced	0.53 (0.9) 1.06 (1.8)	37	Diesel, 43.0	15.9

[a] Representative values at 500hp (373 kW) engine size
[b] “Fuel” is lithium battery, cell only average of lithium ion and sulfur technologies

Range Extenders

A possible design option with an all-electric propulsion system is using a range extender; a fueled device to produce electrical power for electrical systems, which can mitigate deficiencies in other energy storage technologies. It is generally optimized for maximum efficiency at a fixed operating point to extend vehicle range and endurance, while the battery system handles variations in power requirements, such as takeoff or descent. Adding a range extender to an all-electric vehicle (without removing other energy storage devices) removes some payload capability and produces emissions during its operation, but can extend mission range and duration. Thus using a range extender enables some capability to perform a niche mission, without compromising vehicle / mission capability for the majority of its operating missions. Range extenders are generally most effective for long range / duration missions requiring significantly less than 50% available power. Low power levels are important because the range extender should not have to be sized at power levels similar to the main propulsion system, as one is effectively doubling propulsion weight and size. The low efficiency for reciprocating Otto and gas turbine cycles is compounded by further efficiency losses at 50% and lower power levels. For estimating range extender performance and weight, the performance buildup methodology used is similar to that described in Reference 5, combining engine, motor, and controller characteristics into an overall power-to-weight ratio and efficiency for each particular range extender system. Table 4 illustrates diesel and gas turbine powered system and fuel weights for a system generating 100 hp (74.6 kW) electrical power output for 1 hour, with equivalent lithium ion batteries values assuming active weight only. As can be seen, significant weight reductions can be realized using a range extender versus 15 year lithium battery technology. Thirty year lithium battery values are similar to the hydrocarbon options for one hour duration. For longer missions, the range extender would only require additional fuel and therefore would be significantly lighter than the additional battery weight for similar, additional duration. At such relatively low power levels as being studied here, gas turbine engine efficiency and power to weight drop significantly, resulting is similar hardware weight to advanced diesel systems. The advanced diesel is significantly more fuel efficient, and therefore has the lightest total system weight.

Table 4. Example Range Extender performance.

Engine Type	Hardware weight, lb. (kg)	Fuel Weight, lb. (kg)	Total weight, lb. (kg)
Advanced diesel 15 year	127 (58)	41 (18)	167 (76)
30 year	114 (52)	39 (18)	153 (70)
Gas turbine 15 year	101 (46)	81 (37)	181 (82)
30 year	89 (41)	77 (35)	167 (76)
Lithium Battery 15 year	-	337 (153)	337 (153)
30 year		188 (85)	188 (85)

100 hp (74.6 kW) output electrical power for 1 hour
Diesel 1.1 hp/lb. (1.8 kW/kg), 0.377 lb./hp-h (0.23 kg/kw-h)
Gas Turbine 1.5 hp/lb. (2.46 kW/kg), 0.75 lb./hp-h (0.457 kg/kw-h)

ANALYSIS METHODOLOGY

This section discusses the analysis tools, baseline vehicle models, mission profiles and propulsion system modeling. Different sizing methodologies are used for the various vehicles and are discussed below. Similar mission profiles are used for all vehicles; however, slightly different speeds and altitudes over certain mission phases were chosen depending on the vehicle. Additional details are also given below to clarify electric propulsion and energy storage modeling.

Analysis Tools and Baseline Models

The design code, NASA Design and Analysis of Rotorcraft (NDARC, Ref. 6-9) was used to study the sizing and performance effects for the various vehicles and future electric propulsion technology levels. As described in Reference 9, NDARC's propulsion models were expanded to include additional propulsion and power system concepts, including those necessary for electric propulsion components. The vehicle and mission models were developed from the single-main rotor helicopter and tilt rotor examples distributed with NDARC v1.9. The actual sizing model for the SMR helicopter was already available from previous efforts (Ref. 10) and used to guide tilt rotor and VTOL aircraft requirements. Since the latter vehicle designs are more biased toward distance versus hover, the mission range was set to roughly an hour of climb and cruise, as opposed to distance. For the helicopter and tilt rotor, traditional propulsion systems were used to size the vehicles. Modeling these vehicles with all-electric propulsion and energy storage systems might be considered a retrofit, replacing the engine, fuel and their related systems with the electrical system equivalents. No redesign for the remainder of vehicle components, including rotor, gearbox or drivetrain was performed. Vehicle battery energy capacity was sized by weight, such that the all-electric vehicle's empty weight (which included battery and ancillary battery weight, such as the battery management system) was equal to the sum of the baseline's empty weight plus its nominal fuel load. Therefore, vehicle size and weight are roughly fixed and performance determined; as opposed to resizing the vehicle to match or exceed its original performance.

The VTOL aircraft has additional design choices, although many are coupled. For instance, the number of rotors on the wing is dependent on several parameters, including individual rotor diameter, inter-rotor spacing, clearance between rotor and fuselage, etc., which directly impact rotor disk loading and hover performance and efficiency. For this preliminary study, geometry parameters were chosen similar to the tilt rotor, while adjusting weight and drag parameters to yield performance expected at its actual wing and disk loading. Since there was no VTOL aircraft baseline using traditional propulsion and energy storage, it was resized assuming 15 and 30 year electric systems technology to meet design and mission requirements.

Mission Profile

The simple mission profile shown in Figure 2 was used to determine nominal fuel load and range for each baseline vehicle. Cruise altitude was set to 2,000 ft., ISA for the SMR helicopter, but 5,000 ft., ISA for the faster tilt rotor and VTOL aircraft. The higher cruise altitude slightly improved range for the tilt rotor and VTOL aircraft, as they were designed for higher cruise speed. The mission profile for hover / loiter performance is illustrated in Figure 3; hover or loiter is assumed at cruise altitude. The tilt rotor and VTOL aircraft propulsion was sized to enable hover at 5,000 ft., ISA (at maximum rated engine power). The SMR helicopter is capable of 2,000 ft., ISA hover, with full payload (650 lb.) and nominal fuel load at maximum continuous power.

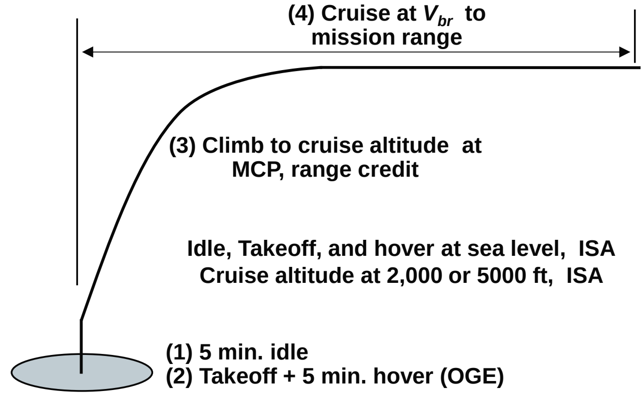

Figure 2. Vehicle sizing mission profile.

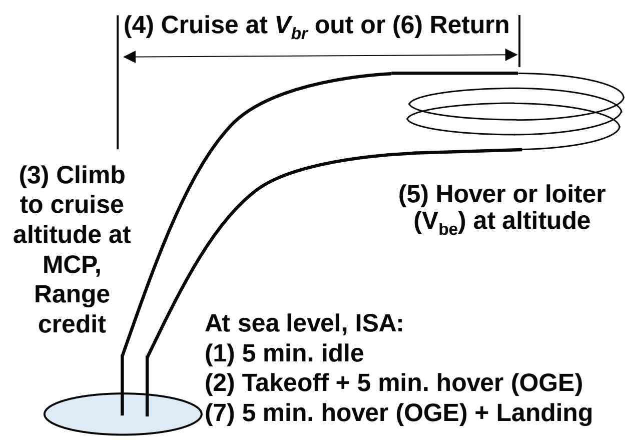

Figure 3. Vehicle hover / loiter mission profile.

Propulsion Modeling

For this preliminary effort, fairly simple (constant power or energy to weight and efficiency) models were developed for the electric system components to understand gross sizing effects and develop understanding for the most critical performance parameters and component operating range over defined missions. Performance values for electric motors, motor controllers and batteries came from Reference 1 and are listed in Tables 2 and 3. Since electric motor power does not lapse with hot day or increased altitude, the all-electric vehicle electric motor may be sized to a different maximum power level than the baseline vehicle to meet mission requirements. The battery management system weight is assumed to be 20% of battery active weight to account for cell containment and thermal management. Another 20% of battery active weight is added to account for power management and distribution (PMAD), with its losses assumed to be included within the electric motor and controller losses. To assess viability of range extenders, values from Table 4 are used. Range extender hardware weight scales directly with its design power level; fuel weight scales directly with power and duration the range extender is used. Gas turbine range extenders are significantly less fuel efficient than the advanced diesel at the relatively low vehicle power levels considered here (as shown in Table 4), and therefore are not considered further.

RESULTS AND DISCUSSION

Mission radius versus hover duration is shown in Figure 4; while a similar plot versus loiter duration is shown in Figure 5. Maintaining hover is very power intensive and quickly drains energy reserves, limiting mission radius. Loiter results are more encouraging; loiter times are roughly double hover time for the same mission radius. The rate of reduction in mission radius with hover or loiter duration does correlate with rotor disk loading. The all-electric VTOL aircraft, notionally designed for effective cruise and has the highest disk loading (lowest hover efficiency), also has the greatest range penalty for increasing hover or loiter time; conversely, the SMR helicopter has the least range penalty. Replacing the traditional propulsion and fuel systems with all-electric while maintaining total weight of those systems resulted in significant reductions in mission radius, largely driven by the substantially lower battery energy density versus hydrocarbon fuels. Additional results and discussion are included next for each vehicle.

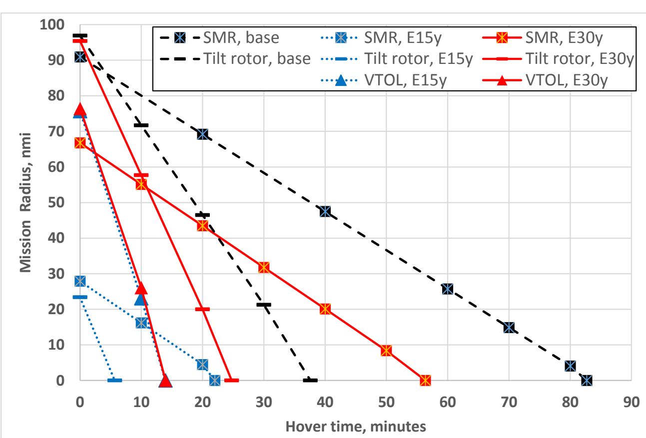

Figure 4. Mission Radius versus Hover time.

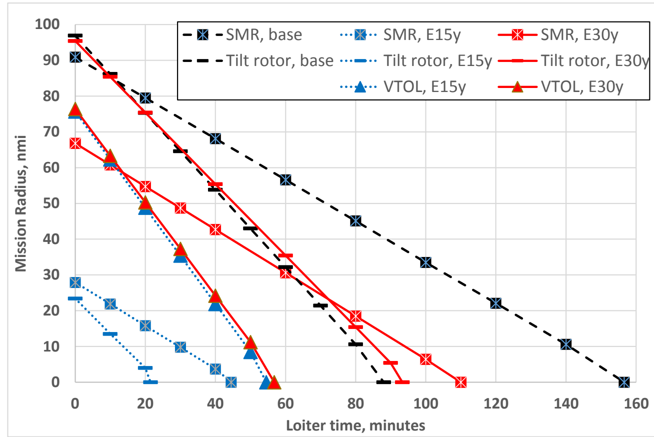

Figure 5. Mission Radius versus Loiter time.

SMR Helicopter

Table 5 shows selected SMR helicopter sizing results for replacing traditional propulsion and fuels with all-electric technologies. Propulsion plus fuel weight was assumed to stay constant; the significantly higher power-to-weight of the electric motor enables additional battery energy storage. For this vehicle, it roughly triples energy storage mass, although the resulting total energy carried is still 6 to 10 times less for the all-electric versions. Even though electric motor performance does not drop with altitude, electric motor size was increased to enable 2,000 ft., ISA hover at DGW. This increased weight capacity at hover enables it to carry some auxiliary weight, such as additional energy storage to increase range, without impacting normal payload capability.

Table 5. Selected SMR Helicopter sizing results.

Parameter	Base	15 year electric	30 year electric
Sea level, ISA max. rated power, hp (kW)	190 (142)	210 (157)	210 (157)
Engine weight, lb. (kg)	267 (121)	61 (28)	43 (20)
Fuel weight, lb. (kg)	160 (73)	469 (213)	490 (223)
Fuel Energy, MJ	3,121	266	500
Mission range*, nmi (km)	195 (360)	64 (119)	145 (269)

* 450 lb. (205 kg) payload, no auxiliary energy

Although hover power (175 hp, 130.5 kW) is too high to justify using a range extender, loiter power requirements are just under ½ of design maximum rated power (MRP). Table 6 includes the weight for an advanced diesel range extender versus batteries. The advanced diesel weighs only 1/2 of the additional batteries for one hour loiter duration, assuming 15 year technology. At 30 year technology projections, the advanced diesel is only 19% lighter. The SMR helicopter is a reasonable blend of range, speed, hover and loiter capability. Its relative simplicity and efficiency enables it to have some capability with 15 year battery technology or readily gain capability with a range extender.

Table 6. SMR Helicopter Range Extender results.

Engine Type	Hardware weight, lb. (kg)	Fuel Weight, lb. (kg)	Total weight, lb. (kg)
15 year diesel	132 (60)	42 (19)	174 (79)
Battery	-	351 (159)	351 (159)
30 year diesel	119 (54)	40 (18)	159 (72)
Battery	-	196 (89)	196 (89)

1 hour duration (61 nmi, 113 km)

Tilt Rotor

Table 7 shows selected tilt rotor sizing results for replacing traditional propulsion and fuels with all-electric technologies. Propulsion plus fuel weight was assumed to stay constant; there is still a 200 lb. reduction in engine weight, but only resulting in roughly doubling the energy storage mass. For this vehicle, the resulting total energy carried is still 5 to 11 times less for the all-electric versions. Because electric motor performance does not drop with altitude, electric motor power was reduced from the baseline air breathing system, but still enables 5,000 ft., ISA hover at DGW. The higher efficiency of the all-electric system at part power results in 30 year technology achieving better loiter mission duration than the baseline, hydrocarbon-fueled system.

Table 7. Selected Tilt Rotor sizing results.

Parameter	Base	15 year electric	30 year electric
Sea level, ISA max. rated power, hp (kW)	469 (350)	396 (295)	396 (295)
Engine weight, lb. (kg)	312 (142)	116 (52.5)	81 (37)
Fuel weight, lb. (kg)	200 (91)	376 (171)	424 (193)
Fuel Energy, MJ	3,883	353	717
Mission range*, nmi (km)	204 (377)	100 (185)	205 (380)

* 450 lb. (205 kg) payload, no auxiliary energy

Hover power levels (MRP, 396 hp, 295 kW) are again too high to justify using a range extender there. Loiter power requirements are roughly the same as the SMR helicopter, as the tilt rotor efficiently loiters on its wings, although roughly 60% faster. Table 8 includes the weight for an advanced diesel range extender versus batteries; results are very similar to those from the SMR helicopter. The advanced diesel weighs only 1/2 of the additional batteries for one hour loiter duration, assuming 15 year technology. At 30 year technology projections, the advanced diesel is again only 19% lighter.

Table 8. Tilt Rotor Range Extender results.

Engine Type	Hardware weight, lb. (kg)	Fuel Weight, lb. (kg)	Total weight, lb. (kg)
15 year diesel	134 (61)	43 (19.5)	177 (81)
Battery	-	357 (162)	357 (162)
30 year diesel	121 (55)	41 (19)	162 (74)
Battery	-	199 (91)	199 (91)

1 hour duration (100 nmi, 185 km)

All-Electric, VTOL Aircraft

The all-electric VTOL aircraft was sized for 200 nautical mile range and hover at DGW at 5,000 ft., ISA, assuming 15 or 30 year all-electric propulsion and energy storage technology. Because there was no replacement of traditional propulsion and energy storage systems, there was no substituting engine for battery weight. Consequently, there are similar range versus hover or loiter results with respect to electric component technology levels shown in Figures 4 and 5. Hover power levels (MRP values, 456 hp, 340 kW or 351 hp, 262 kW) are again too high to justify using a range extender there. Loiter power requirements are similar to the other vehicles, scaling similarly to the tilt rotor when corrected by the difference in DGW. Similar to the tilt rotor, this vehicle also efficiently loiters on its wings at over twice the speed of the SMR helicopter. Table 9 includes the weight for an advanced diesel range extender versus batteries; results are very similar to those from the other cases, except the variation is greater between the 15 year and 30 year results due to the VTOL aircraft's higher DGW assuming 15 year technology. This vehicle design was cruise-biased and therefore lost significant performance with increased hover or loiter requirements. This vehicle is a good candidate for additional study. The additional design flexibility enabled by all-electric propulsion offer vehicle optimization potential over a variety of missions and should be better understood.

Table 9. All-Electric VTOL Aircraft Range Extender results.

Engine Type	Hardware weight, lb. (kg)	Fuel Weight, lb. (kg)	Total weight, lb. (kg)
15 year diesel	150 (68)	48 (22)	197 (90)
Battery	-	398 (181)	398 (181)
30 year diesel	105 (48)	36 (16)	141 (64)
Battery	-	173 (79)	173 (79)

1 hour duration (135 nmi, 250 km)

CONCLUSIONS

A preliminary assessment was performed to compare and contrast the performance for three vehicle designs, a single main rotor (SMR) helicopter, a tilt rotor, and an advanced, all-electric, vertical take-off and landing (VTOL) aircraft. Vehicle design and performance models were developed within the NASA Design and Analysis of Rotorcraft (NDARC) design code. The effect on vehicle design and performance from incorporating advanced, all-electric versus traditional hydrocarbon-fueled propulsion concepts was explored. Hydrocarbon-fueled range extenders were also considered to add capability if electric energy storage density performance was deemed inadequate. Missions considered included a baseline cruise mission and mission radius for incorporating varying amounts of hover or loiter.

Hover is a power-intensive mission segment; increasing hover duration significantly reduced mission radius. The SMR helicopter had highest hover efficiency; it suffered the least mission radius reduction with increased hover duration. The tilt rotor and VTOL aircraft designs are cruise-biased and have significantly lower hover efficiency. This results in greater mission radius loss versus hover duration. Loiter was less energy intensive and roughly doubled duration for a given mission radius.

Fifteen year all-electric technology always significantly reduced vehicle capability or increased weight, resulting from the low, battery energy storage density. Thirty year all-electric technology results were better, but generally still fell short of baseline results for the same reason. The exception was loiter mission range for the tilt rotor. The higher efficiency of the all-electric system at part power resulted in the tilt rotor with 30 year all-electric technology achieving better loiter mission duration than the baseline, hydrocarbon-fueled system.

A hydrocarbon-fueled range extender would not be practical to meet the high power levels required for sustained hover, which are close to vehicle maximum rated power. Loiter power levels are significantly less than hover. Range extenders would be substantially lighter than 15 year technology batteries and result in only small decrements to vehicle payload for significant mission duration improvements. Thirty year battery technology results were more favorable, but the hydrocarbon-fueled range extender was still 19% lighter.

The tilt rotor and VTOL aircraft are cruise-biased designs and therefore lost significant performance with increased hover or loiter requirements. With so many design variables, the VTOL aircraft has the potential to perform well for a variety of missions. This vehicle is a good candidate for additional study. To be effective, component model development is also required to adequately assess performance over the design space of interest.

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