Exploring propulsion system requirements for more and all-electric helicopters

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Motivation

There is increasing interest in vertical-lift vehicles and assessing their potential for increasing mobility.

Portions of or entire vertical-lift missions tend to be closer to the populace, so environmental considerations (noise, emissions, etc.) are especially important.

Electric systems offer the potential for reduced noise and point of use emissions, enhanced vehicle and mission capability, etc.

Develop propulsion models incorporating more and all-electric systems to better understand their strengths and identify areas to focus future analysis and research / development.

Outline

- Introduce baseline vehicles and their characteristics
- Review propulsion and energy systems
  - Electric motors / system parameters (Dever)
  - Compare and contrast traditional versus battery / electric motor systems
  - Fuelled, range extenders
- Discuss analysis methodology and assumptions
- Present Results
  - Payload versus Range, and Range Extender
  - Thermal load and airflow requirements
- Summary
- Future work

Baseline vehicles

Vehicle class (approximate example) → Parameter ↓	Light Utility (Sikorsky S-300C)	Multi-Mission (Bell 206L4)	Medium Utility (Airbus Helicopters EC175)
Design gross weight (DGW), lb. (kg)	2,050 (932)	4,550 (2,068)	16,000 (7,273)
Empty weight, lb. (kg)	1,100 (500)	2,447 (1,112)	10,100 (4,591)
Nominal fuel weight, lb. (kg), % DGW *	160 (73), **8%**	737 (335), **16%**	2,143 (974), **13%**
Engine weight (each), lb. (kg), % DGW	267 (121), **13%**	255 (116), **5.6%**	430 (195), **5.4%**
Power / DGW, hp/lb. (kW/kg)	**0.09 (0.15)**	**0.165 (0.27)**	**0.20 (0.33)**
Cruise velocity, knots (km/h) *	95 (176)	120 (222)	130 (241)
Range, nmi (km) *	200 (370)	220 (407)	340 (630)
# crew (C) + passengers (P)	1 C + 1 or 2 P	1 C + 5 P	3C + 10P + 1000 lb. (450 kg)

* Calculated from mission analyses

Electric Motor Parameters

(non-cryogenic) *

Technology year	Power/weight, hp/lb. (kW/kg)	Electric motor efficiency	Controller efficiency	Net efficiency
State of the art	1.9 (3.1)	90%	94%	85%
15 year	3.4 (5.6)	95%	98%	93%
30 year	4.9 (9.7)	98%	99%	97%
***Power-to-weight includes electric motor** (3,8,16) **+ controller** (5,6,7)* *Maximum temperature allowable:* *SOA / 15 year = 220°F (105°C)* *30 year = 465°F (240°C)*				

Impressive gains in weight and efficiency are possible.
Higher operating temperatures could improve thermal management design (depending on temperature effects on efficiency)

* Dever, T.P.; Duffy, K.P.; Provenza, A.J.; Loyselle, P.L.; Choi, B.B.; Morrison, C.R.; and Lowe, A.M. "Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion", NASA TP-2015-216588, January 2015.

Engine / Energy Storage Characteristics

Engine type	Power / weight, hp/lb. (kW/kg)	Efficiency	Fuel, energy density, MJ/kg	**Net energy density, MJ/kg**
Battery all-electric, SOA 15 year 30 year	1.9 (3.1) 3.4 (5.6) 4.9 (9.7)	85 93 97	0.70 1.75 3.15	**0.60** **1.63** **3.06**
Diesel cycle, SOA Advanced	0.53 (0.9) 1.06 (1.8)	37	Diesel, 43.0	**15.9**
Reciprocating Otto Cycle *(Light Utility)*	0.71 (1.2)	27	Gasoline, 43.5	**11.7**
Gas turbine (750hp) *(Multi-Mission)*	2.94 (4.8)	20	Jet-A, 42.8	**8.6**
Gas turbine (1,600hp) *(Medium Utility)*	3.72 (6.1)	30	Jet-A, 42.8	**12.8**
Lithium battery are average of lithium ion and sulfur, cell only (also from Dever) SOA – state of the art				

Electric motor's power-to-weight is competitive or improvement versus base, their efficiency is substantially higher.

Hydrocarbon fuels are difficult to match for energy density (≈ range / endurance)

Range Extender Performance

(alternate to battery energy storage)

Engine type	Hardware weight, lb. (kg)	Fuel weight, lb. (kg)	Total weight, lb. (kg)
Advanced diesel - 15 year - 30 year	127 (58) 114 (52)	41 (18) 39 (18)	167 (76) 153 (70)
Gas turbine - 15 year - 30 year	51 (23) 41 (19)	49 (22) 47 (21)	99 (45) 88 (40)
Lithium Battery - 15 year - 30 year	-	337 (153) 188 (85)	337 (153) 188 (85)

100 hp (74.6 kW) output electrical power for 1 hour (for scaling purposes)

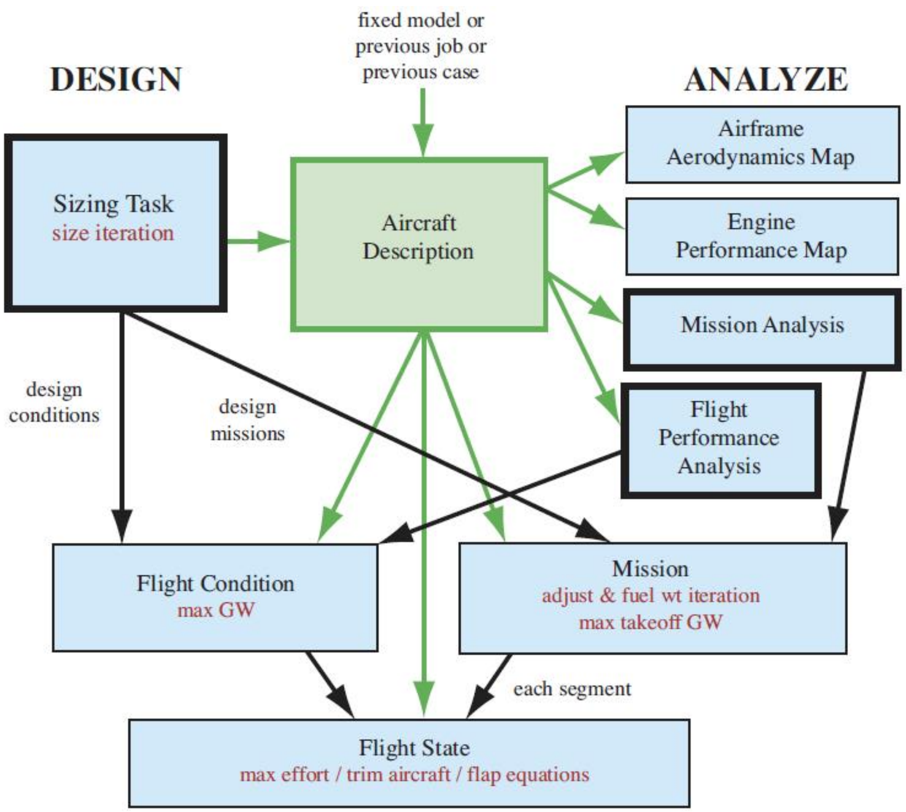
Assume advanced hydrocarbon-fueled engine:

Diesel 1.1 hp/lb. (1.8 kW/kg), 0.377 lb./hp-h (0.23 kg/kw-h)

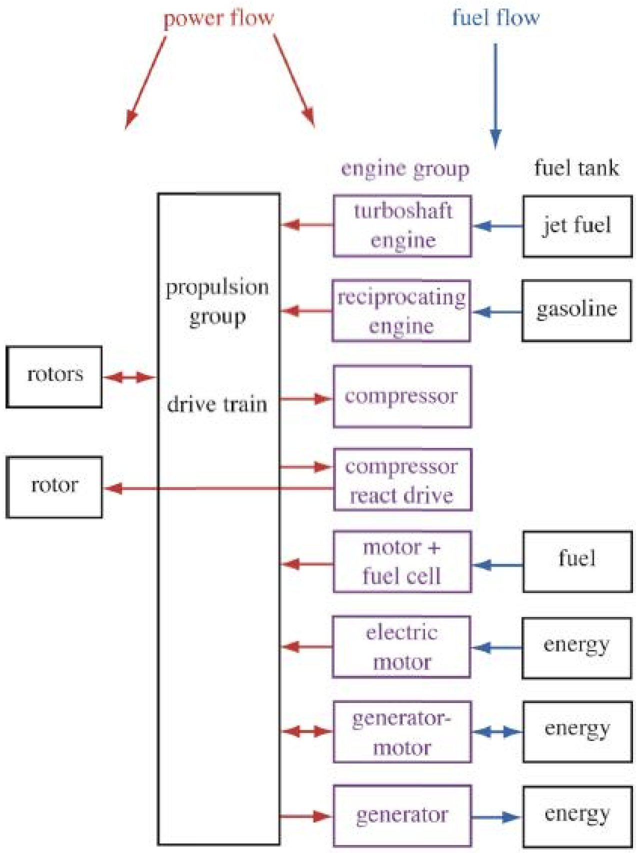
Gas Turbine 5.0 hp/lb. (8.2 kW/kg), 0.454 lb./hp-h (0.277 kg/kw-h)

(Gas turbine range extender not used for light utility, not applicable at that size)

Analysis Tool: NASA Design and Analysis of Rotorcraft (NDARC)

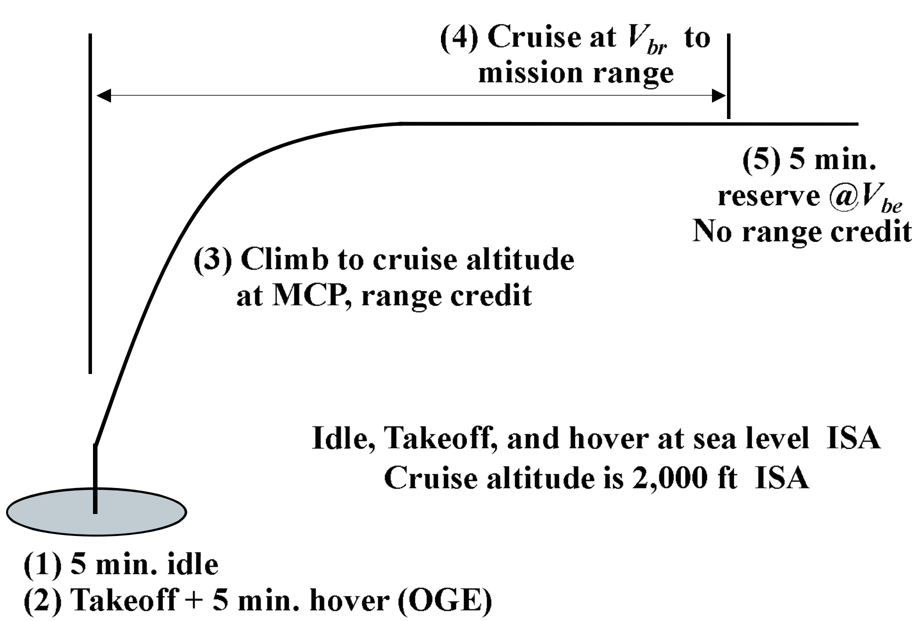


Overall Program Layout

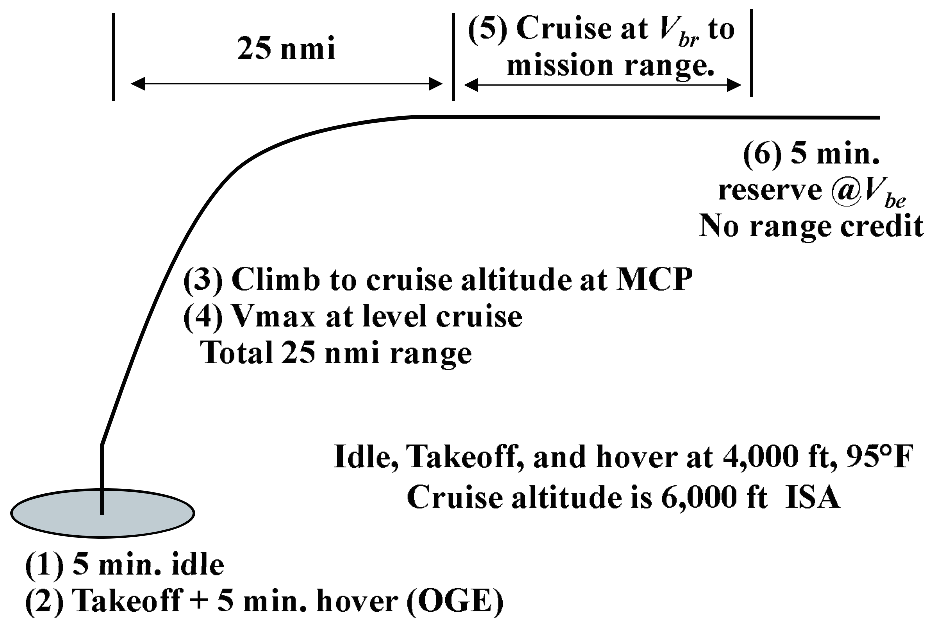


Propulsion / energy models

Mission Profiles



"Simple" Profile
(baselines and Light Utility)



High / Hot Profile
(for range / payload of Multi-Mission and Medium Utility)

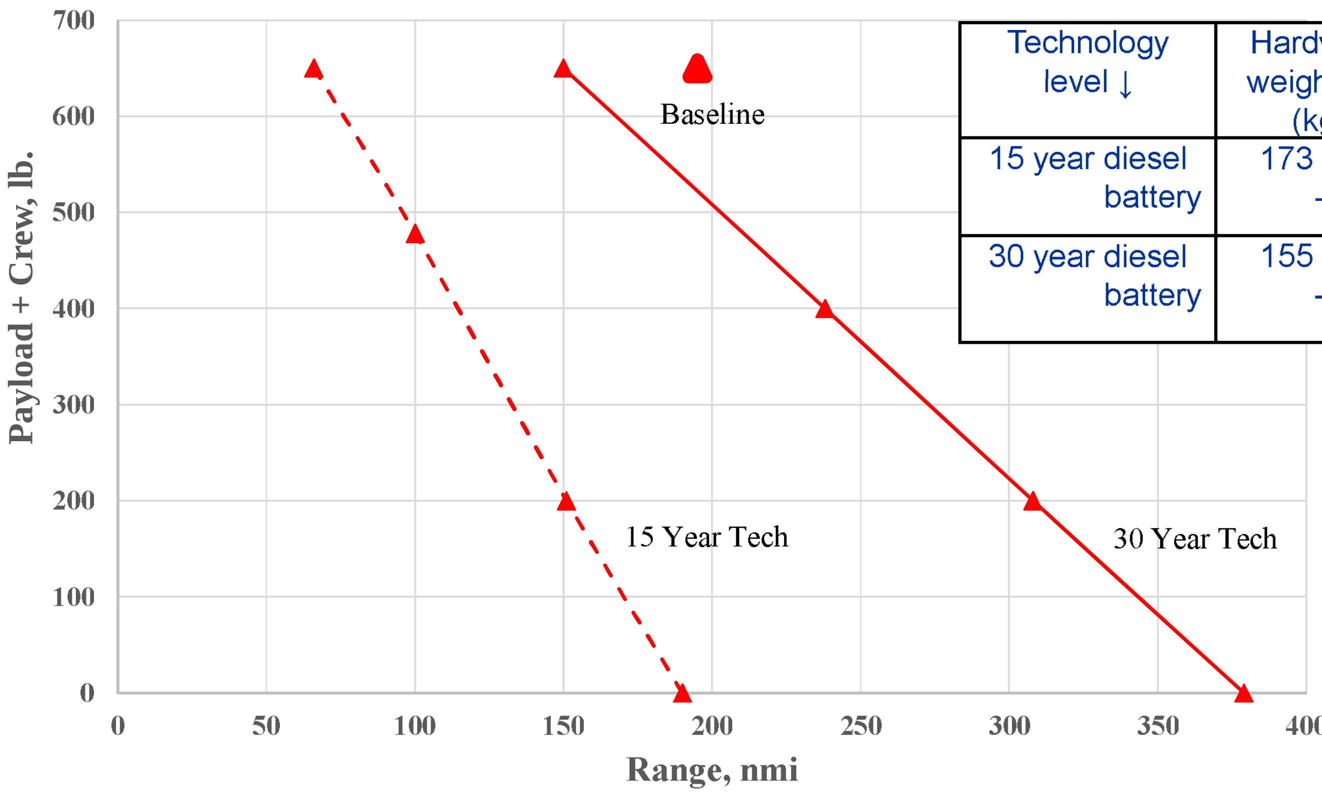
High/hot profile used for Multi-Mission and Medium Utility vehicles because considered more applicable to actual mission / use

Additional study assumptions

- Takeoff at Design Gross Weight*, difference from empty weight split between payload and energy storage to determine range.
- Electric motors sized for mission requirements (no power lapse with high / hot).
- "Viable" design achieved 100 nmi. range.
- Estimated cooling airflow from vehicle power for each flight segment, respective efficiency, cooling air heated to 80% of temperature difference between ambient and maximum electrical system temperature.
- Cruise speed and power used to estimate weight for 100 nmi. range extender.

Results

Light Utility Range / Payload

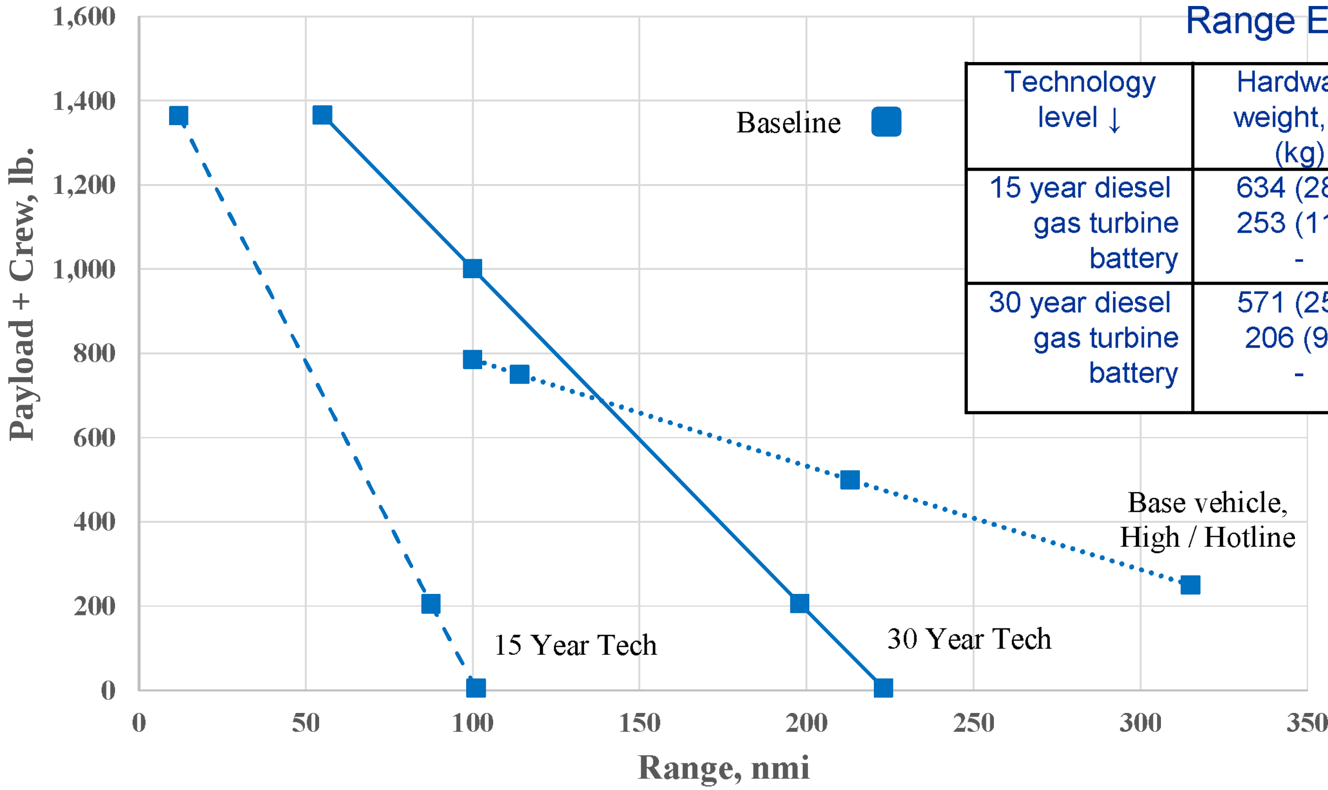


Range Extender (100 nmi.)

Technology level ↓	Hardware weight, lb. (kg)	Fuel, lb. (kg)	Total, weight, lb. (kg)
15 year diesel battery	173 (79) -	58 (26) 483 (220)	231 (105) 483 (220)
30 year diesel battery	155 (71) -	56 (25) 269 (122)	**211 (96)** 269 (122)

- Electric motors much lighter than IC engine, allowing additional battery mass
- 15 year technology enables viable design
- 30 year technology roughly matches current design

Multi-Mission Range / Payload

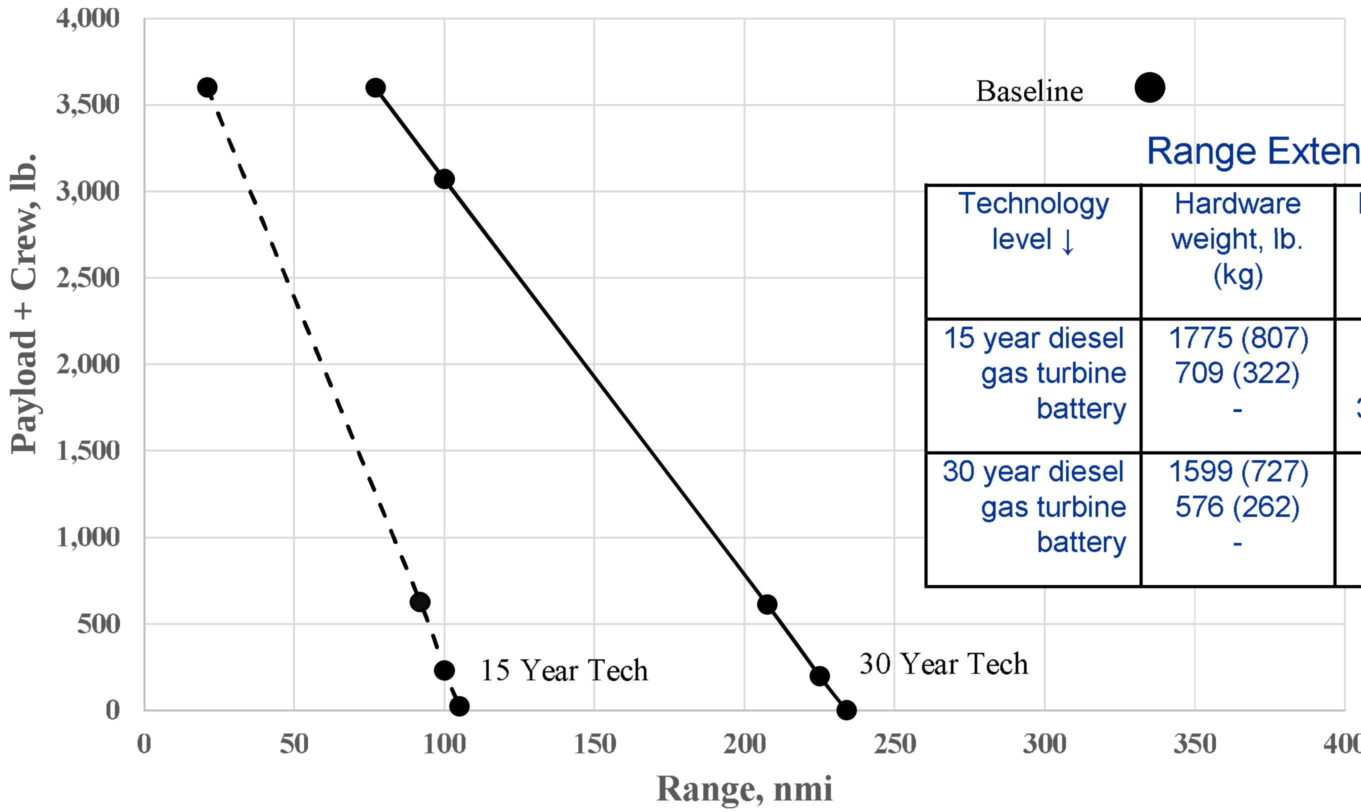


Range Extender (100 nmi.)

Technology level ↓	Hardware weight, lb. (kg)	Fuel, lb. (kg)	Total, weight, lb. (kg)
15 year diesel gas turbine battery	634 (288) 253 (116) -	167 (76) 201 (91) 1,393 (633)	801 (364) 454 (207) 1,393 (633)
30 year diesel gas turbine battery	571 (259) 206 (93) -	160 (73) 193 (88) 775 (352)	731 (332) **399 (181)** 775 (352)

- *Baseline has insufficient power for high / hot at design gross weight, but still capable of substantial range*
- *Electric motor gives substantial high / hot vehicle weight advantage, but requires 30 year technology for viable design (payload / range)*

Medium Utility Range / Payload



Range Extender (100 nmi.)

Technology level ↓	Hardware weight, lb. (kg)	Fuel, lb. (kg)	Total, weight, lb. (kg)
15 year diesel gas turbine battery	1775 (807) 709 (322) -	469 (213) 564 (256) 3,905 (1775)	2,244 (1,020) 1,273 (579) 3,905 (1775)
30 year diesel gas turbine battery	1599 (727) 576 (262) -	450 (205) 541 (246) 2,169 (986)	2,049 (931) **1,118 (508)** 2,169 (986)

- *Baseline's balanced design gives impressive performance*
- *30 year technology gives viable design, but energy storage lacking for electric systems to match range / endurance.*

Light Utility Thermal Load

Mission segment → Vehicle, parameter ↓	1 idle	2 hover OGE	3 climb	4 cruise	5 endurance
Electric: 15 year technology					
Power, hp (kW)	61.1 (45.6)	196.5 (146.5)	172 (128.3)	136.2 (101.6)	101.3 (75.5)
Thermal load, hp (kW)	4.3 (3.2)	13.8 (10.3)	12.0 (9.0)	9.5 (7.1)	7.1 (5.3)
Cooling airflow, ft^3/min. (l/s)	76.1 (35.9)	245 (116)	210 (99)	172 (81)	126 (60)
lb./s (kg/s)	0.10 (0.06)	0.31 (0.14)	0.27 (0.12)	0.21 (0.09)	0.16 (0.07)
Electric: 30 year technology					
Power, hp (kW)	61.1 (45.6)	196.5 (146.5)	172 (128.3)	136.4 (101.7)	101.3 (75.5)
Thermal load, hp (kW)	1.8 (1.4)	5.9 (4.4)	5.2 (3.8)	4.1 (3.1)	3.0 (2.3)
Cooling airflow (lo T), ft^3/min. (l/s)	32.6 (15.4)	105 (50)	89.9 (42.4)	74.0 (34.9)	54.1 (25.5)
lb./s (kg/s)	0.04 (2.02)	0.13 (0.06)	0.11 (0.05)	0.09 (0.04)	0.07 (0.03)
Cooling airflow (hi T), ft^3/min. (l/s)	13.0 (6.1)	41.7 (19.7)	36.2 (17.1)	30.2 (14.2)	21.5 (10.1)
lb./s (kg/s)	0.02 (.01)	0.05 (0.24)	0.05 (0.02)	0.04 (0.02)	0.03 (0.01)

- *Highest power and thermal load at hover OGE*
- *30 year technologies halve cooling load and airflow, roughly 1/10 of baseline IC engine airflow*
- *Higher temperature electric systems could reduced airflow requirements by another 60%*

Multi-Mission Thermal Load

Mission segment → Vehicle, parameter ↓	1 idle	2 hover OGE	3 climb	4 Vmax cruise	5 Best range cruise	6 endurance
Electric: 15 year technology						
Power, hp (kW)	132.5 (98.8)	730 (544)	714 (532)	**713 (532)**	499 (372)	366 (273)
Thermal load, hp (kW)	9.3 (6.9)	51.1 (38.1)	50.0 (37.3)	**49.9 (37.2)**	34.9 (26.0)	25.6 (19.1)
Cooling airflow, ft^3/min. (l/s)	262 (124)	1,445 (682)	1,414 (667)	**940 (444)**	657 (310)	456 (215)
lb./s (kg/s)	0.27 (0.12)	1.50 (0.68)	1.46 (0.66)	**1.00 (0.46)**	0.70 (0.32)	0.58 (0.26)
Electric: 30 year technology						
Power, hp (kW)	132.5 (98.8)	730 (544)	714 (532)	**713 (532)**	499 (372)	366 (273)
Thermal load, hp (kW)	4.0 (3.0)	21.9 (16.3)	21.4 (16.0)	**21.4 (16.0)**	14.9 (11.1)	11.0 (8.2)
Cooling airflow (lo T), ft^3/min. (l/s)	112.5 (53.1)	619 (292)	606 (286)	**403 (190)**	281 (133)	195 (92)
lb./s (kg/s)	0.12 (0.05)	0.64 (0.29)	0.62 (0.28)	**0.43 (0.20)**	0.30 (0.14)	0.25 (0.11)
Cooling airflow (hi T), ft^3/min. (l/s)	38.2 (18.0)	210 (99)	206 (97)	**172 (81)**	120 (57)	77.5 (36.6)
lb./s (kg/s)	0.04 (0.02)	0.22 (0.10)	0.21 (0.10)	**0.18 (0.08)**	0.13 (0.06)	0.10 (0.045)

- *Highest power and thermal load at hover OGE, although climb and maximum velocity cases are within ≈2%*
- *30 year technologies thermal trends similar to Light Utility, except cooling airflow is roughly 1/5 of baseline gas turbine engine*

Medium Utility Thermal Load

Mission segment → Vehicle, parameter ↓	1 idle	2 hover OGE	3 climb	4 Vmax cruise	5 Best range cruise	6 endurance
Electric: 15 year technology						
Power, hp (kW)	356 (265)	2,098 (1,565)	2,284 (1,703)	2,280 (1,700)	1,393 (1,039)	1,058 (789)
Thermal load, hp (kW)	24.9 (18.6)	147 (110)	160 (119)	160 (119)	97.5 (72.7)	74.0 (55.2)
Cooling airflow, ft^3/min. (l/s)	704 (332)	4,155 (1,961)	4,523 (2,135)	3,005 (1,418)	1,582 (747)	1,317 (622)
lb./s (kg/s)	0.72 (0.33)	4.28 (1.94)	4.66 (2.12)	3.20 (1.46)	1.96 (0.89)	1.68 (0.76)
Electric: 30 year technology						
Power, hp (kW)	356 (265)	2,098 (1,565)	2,284 (1,703)	2,280 (1,700)	1,394 (1,040)	1,058 (789)
Thermal load, hp (kW)	10.7 (8.0)	62.9 (46.9)	68.5 (51.1)	68.4 (51.0)	41.8 (31.2)	31.7 (23.6)
Cooling airflow (lo T), ft^3/min. (l/s)	302 (142)	1,781 (840)	1,939 (915)	1,288 (608)	787 (372)	564 (266)
lb./s (kg/s)	0.31 (0.14)	1.83 (0.83)	2.00 (0.91)	1.37 (0.62)	0.84 (0.38)	0.72 (0.33)
Cooling airflow (hi T), ft^3/min. (l/s)	102 (48.3)	604 (285)	658 (310)	550 (260)	336 (159)	224 (106)
lb./s (kg/s)	0.11 (0.05)	0.62 (0.28)	0.68 (0.31)	0.59 (0.27)	0.36 (0.16)	0.29 (0.13)

- *Highest power and thermal load for start of climb and maximum velocity cases, cooler temperatures at cruise reduces airflow required*
- *30 year technologies thermal trends similar to Light Utility and Multi-Mission (cooling airflow is roughly 1/5 is equal baseline gas turbine engine)*

Summary

- Non-cryogenic systems generally need 30 year technology levels for viable design
- Energy storage (battery) technology is limiting factor
- Electric systems may enhance high / hot performance (thermal management?)
- Range extenders would seem to be good option to increase range / endurance (especially if can remove some battery storage to maintain payload). Pointing toward a hybrid solution.
- Preliminary thermal management estimates suggest that it isn't a showstopper, especially for 30 year technology levels

Future Work

- Just scratched the surface, new vehicles and missions are being developed and analyzed to better understand and exploit the potential for these systems.
- Tools / various performance models are being upgraded. Capture inter-dependencies among systems and components
- Push / pull of research and technology:
  - What is the potential for various, future technologies?
  - Which future technology (or suite of technologies) have the best promise?

Acknowledgments

Wayne Johnson and Carl Russell (NASA Ames)

and

Jeff Sinsay (U.S. Army at NASA Ames)

Questions?

NASA

Backup Slides

Baseline vehicles

Sikorsky S-300C, Bell Model 206L4, Airbus Helicopters EC175

Baseline vehicles

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Sea level maximum power, hp (kW)	190 (142)	750 (560)	2 x 1,600 (2 x 1,193)
Engine type	Reciprocating (Otto cycle)	Gas turbine	Gas turbine
Engine weight (each), lb. (kg), % DGW	267 (121), 13%	255 (116), 5.6%	430 (195), 5.4%
Engine power / weight, hp/lb. (kW/kg)	0.71 (1.2)	2.94 (4.8)	3.72 (6.1)
Engine volume (each), ft^3, (l)	14.1 (401)	13.0 (369)	14.2 (402)
Sea level PSFC, lb./hp-h (kg/kw-h)	0.500 (0.305)	0.689 (0.420)	0.454 (0.277)
Power / DGW, hp/lb. (kW/kg)	0.09 (0.15)	0.165 (0.27)	0.20 (0.33)
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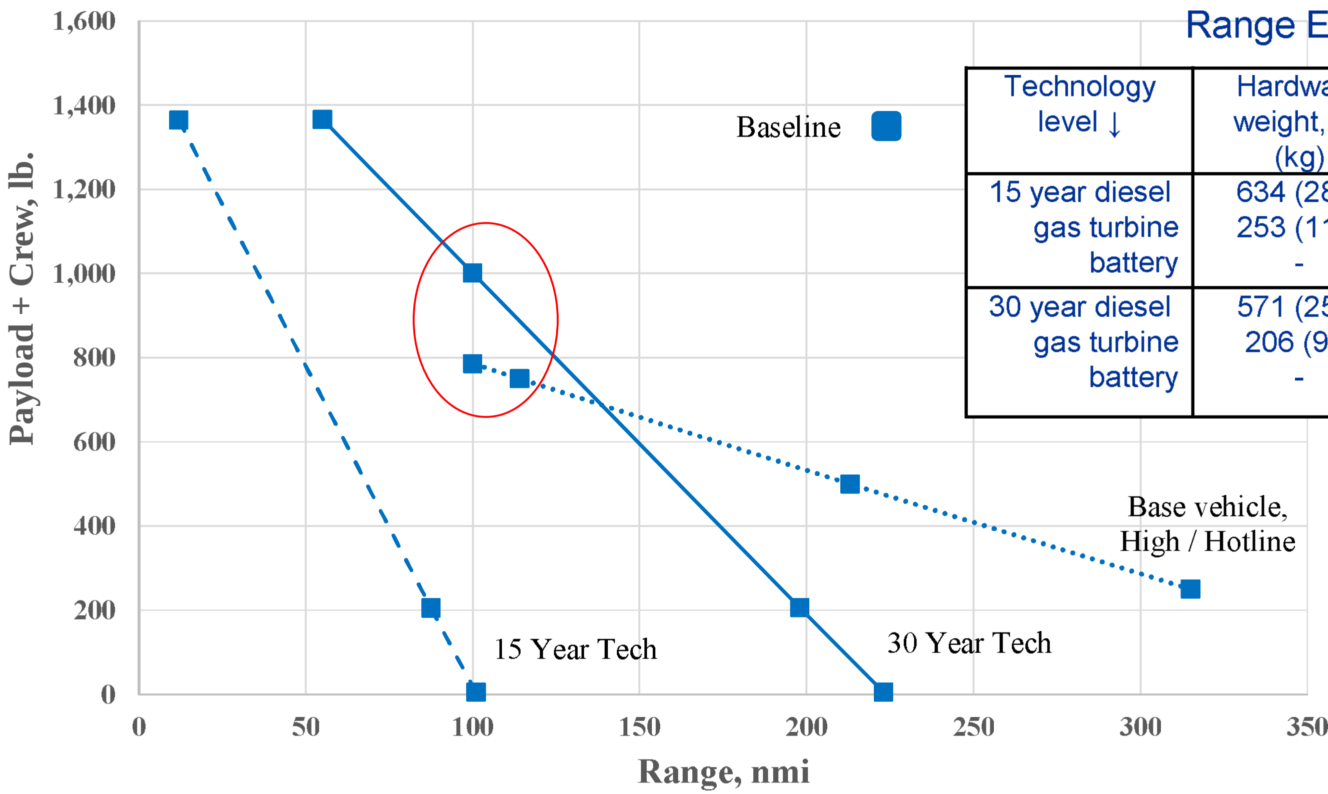
# crew (C) + passengers (P)	1 C + 1 or 2 P	1 C + 5 P	3C + 10P + 1000 lb. (450 kg)

* *from mission analyses*

Multi-Mission Range / Payload



Range Extender (100 nmi.)

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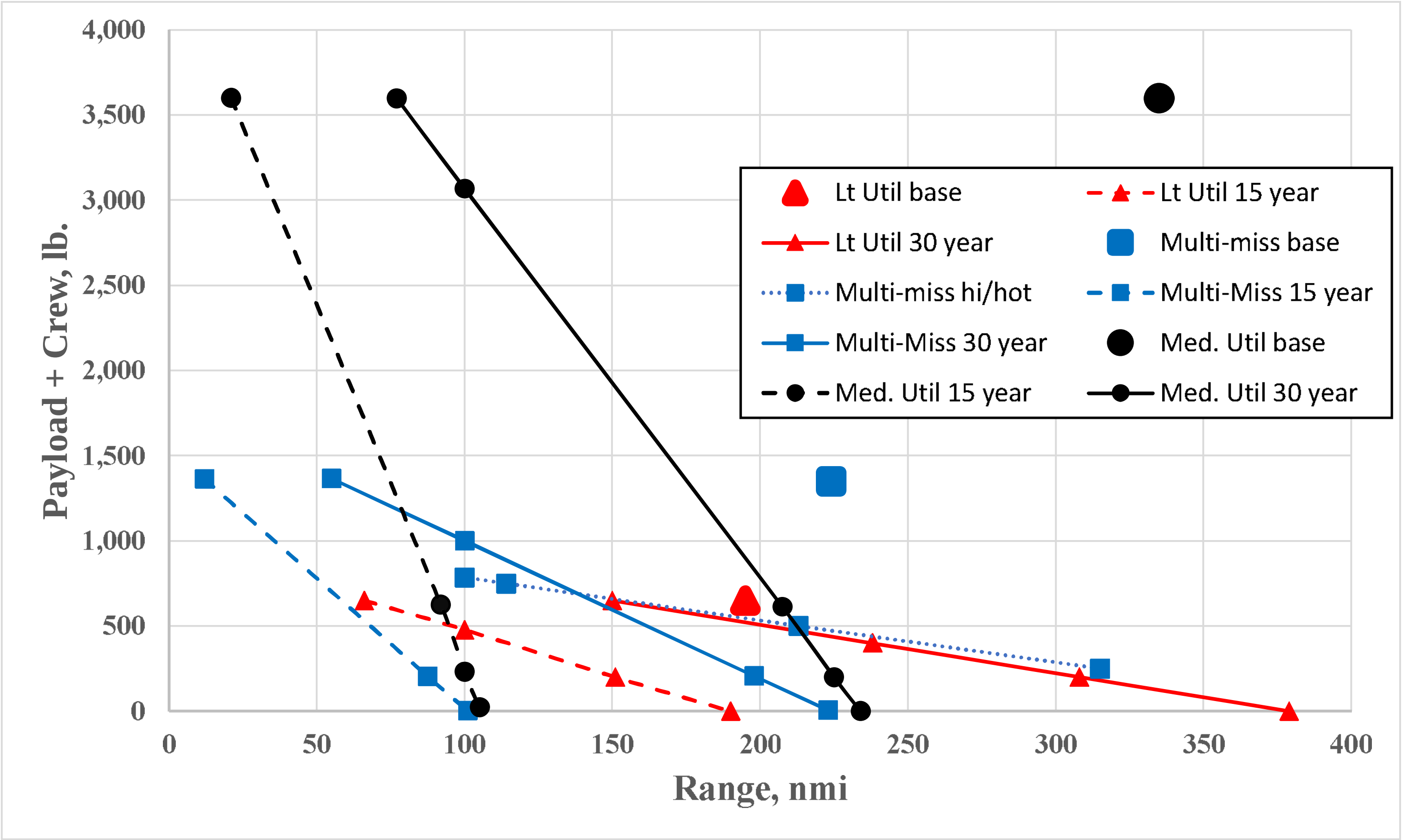
- *Electric motor gives substantial high / hot vehicle weight advantage, but requires 30 year technology for viable design (payload / range)*

Overall Range / Payload



- Battery energy storage systems have substantially less ideal and actual energy density than present, hydrocarbon systems.
- Electric motor gives substantial high / hot vehicle weight advantage, but requires 30 year (or better) technology for viable design (payload / range)

END