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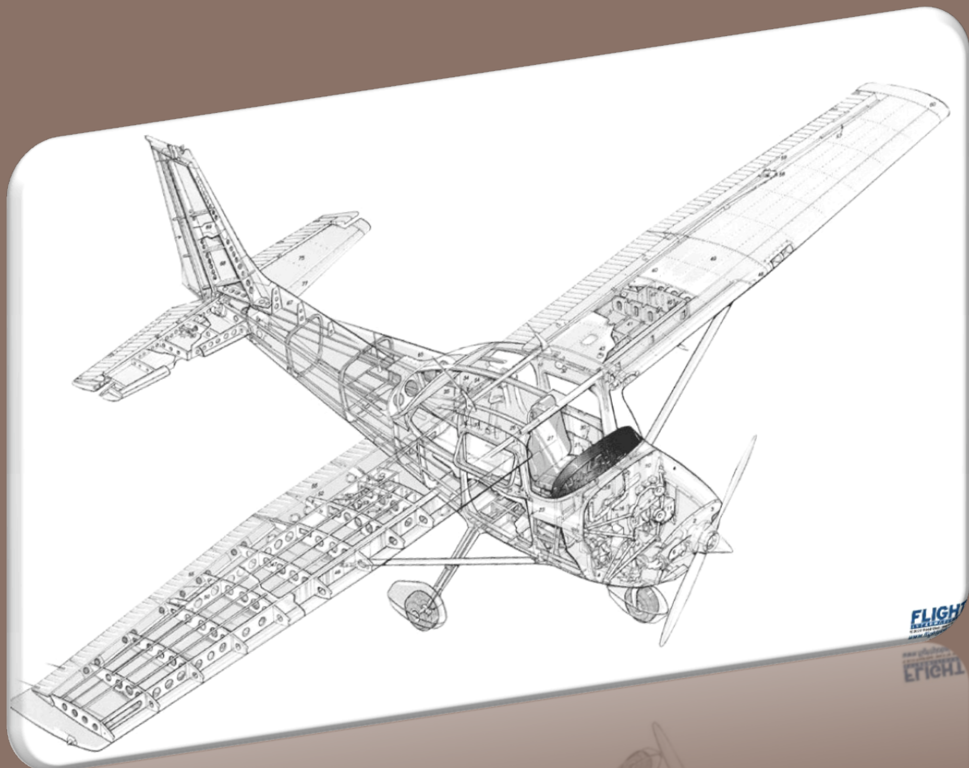
Electric Motor & Power Source Selection for Small Aircraft Propulsion

Jeremy Fehrenbacher

ELECTRIC MOTOR & POWER SOURCE SELECTION FOR SMALL AIRCRAFT PROPULSION



Committee Council

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April 11, 2011

A Directed Project by Jeremy Fehrenbacher

Outline

- Introduction
- Literature Review
- Methodology
- Results
- Conclusion/Considerations
- Future Research

Introduction

- Research Question
- Scope
- Significance
- Assumptions
- Limitations
- Delimitations

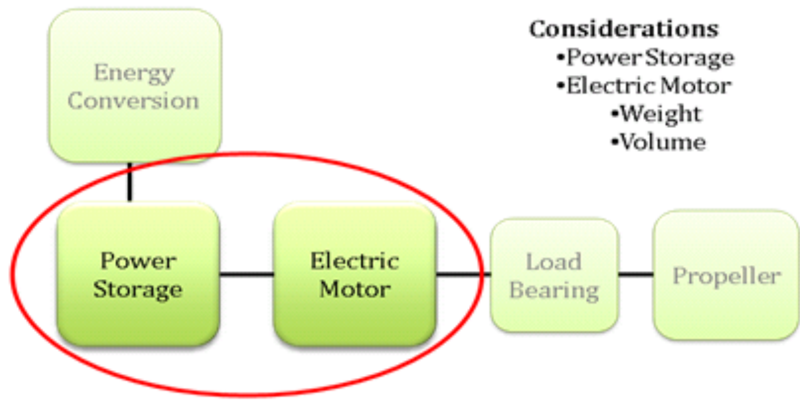
Research Question & Scope

- Research Question

  Can current electric motor and power storage technologies conceptually support flight operations for a Cessna 172K in terms of aircraft performance criteria?

  - Performance Criteria
    - Takeoff
    - Cruise

- Scope
  - Electric Motor Integration
  - Power Storage Integration
    - Pugh Matrix analysis

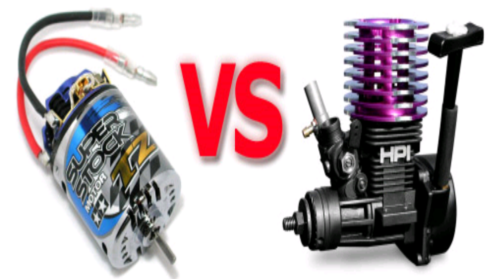


Significance

- Industry push for alternative fuels and propulsion modules

- Electric motor efficiencies are greater than internal combustion engine efficiencies

- Electric motor unaffected by environmental changes



Statement of Purpose

- Recent aviation research provides incremental improvements

  (i.e. increased piston size, increased piston count, turbochargers, etc.)

- Improvements bandage the dilemma of relying on unsustainable fuels; they do not solve the problem

- Environmental Protection Agency (EPA) has threatened the use of lead in aviation fuels
  - Tetraethyl lead (TEL) is a required additive on some aviation engines to increase octane rating, serve as an antiknock agent, and prevent premature detonation

Assumptions

- Motor and power storage manufacturers will release technical product data
- Environmental variables will operate at standard day
  - Humidity: 0%
  - Altitude: Sea Level
  - Air Density: 0.00237 slug/ft^3
  - Temperature: 59°F
  - Barometric Pressure: 14.7 lb/in^2
  - Air Velocity: 3.62 x 10^{-7} lb-s/ft^2
  - Wind Velocity: 0 knots

Limitations & Delimitations

Limitations

- Product market availability
- Electromagnetic Force grounding
- Propeller
  - Oil supply
  - RPM vs. Tip speed
- Power Storage
  - Physical Size
  - Weight

Delimitations

- Aircraft: Cessna 172K
- Engine: Lycoming O-320-E2D
- Lycoming vs. Electric motor Comparison
  - Horsepower
  - Torque
  - Qualitative analysis
- Power storage technology
  - Heat dissipation consideration
- Thrust production module
  - i.e. ducted fan

Literature Review

- Applicable Research
- Electric Flight Committees
- Preferred Motor Characteristics
- Applicable Motor Technology
- Applicable Battery Technology
- Aircraft Integration
- Benefits of Electric Propulsion
- Pugh Matrices

Applicable Research

- NASA/Glenn Research Center Funded Research
  - High Temperature Superconducting Motors
    - Cessna 172 Application (Masson & Luongo):
      - Replaced 200 HP engine with 220 HP electric motor
      - Reduced weight from 160 kg to 28 kg
    - Disadvantage: deep, cryogenic cooling
  - Magnetically levitated ducted fan (Emerson)
- Notre Dame/Nanjing University Research
  - Electrically-powered unmanned aerial vehicle
    - Disadvantage: additional required power

Electric Flight Committees

- Regulators
  - ASTM International Committee
    - F37: Light Sport Aircraft all-electric aircraft standards
  - Federal Aviation Administration (FAA)
    - "Companies and industries (to) prove technology first"
  - European Aviation Safety Agency (EASA)
    - "We are open minded to new technology as long as they are safe enough"
  - CAFÉ Foundation
    - Non-for-profit organization (originally an EAA chapter) focused on advancing personal aircraft technology
    - Green Flight Challenge:
      - NASA Funded: $1.65M
      - July 11-17, 2011 in Santa Rosa, California

Preferred Motor Characteristics

1. Direct Current (DC)

	AC Motor	DC Motor
Pros	**Higher Torque/ Horsepower Capabilities**	Less Rotor Heat
	No Permanent Magnet	**Wide Spectrum of Optimal Power Setting**
	Magnetic Field Strength Adjustable	**No Efficiency Losses due to DC to AC Conversion**
	Cost Advantage	
Cons	Optimal Power Factor: 85 percent	Permanent Magnet Expensive
	Cumbersome to Control	

2. Brushless

	Brushed Motor	Brushless Motor
Pros	Simplicity of Control	**Less Maintenance**
	Simplicity of Maintenance	**More Controllable Speed/ Torque Settings**
	Lower Cost of Construction	No Voltage Drop Across Brushes
	Simpler Control Unit	**High Output Power**
	Extreme Environmental Operation	**Small Frame Size**
		High Speed Range
		Low Electromagnetic Forces
Cons	Higher Electromagnetic Force	High Cost of Construction
	Poor Heat Dissipation	Complexity/Expense of Control Unit
	Continuing Maintenance	
	Lower Operating Speed	
	Speed/Torque Less Optimized	

3. Pancake Configuration

Applicable Motor Technology

- Motor Selection
  - Raser Technologies G-100 Generator
    - 160 HP; 406 ft-lb torque; 172 lbs
  - Lange Aviation: EA42 Electric Motor
    - 52 HP; 64 lbs
  - Tesla Motors: Roadster Motor
    - 288 HP; 115 lbs
  - U. S. Hybrid: HPM 450 Motor
    - 161 HP; 143 lbs

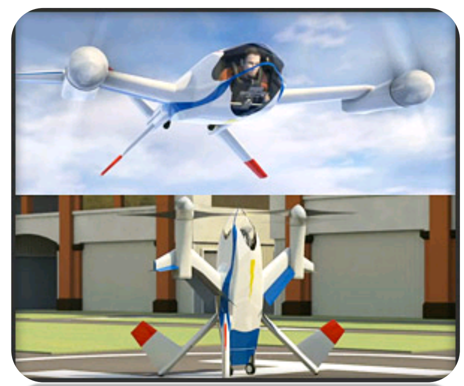
- Inapplicable Motors
  - High Temperature Superconducting: Cryogenic cooling
  - Baldor Motors: D50150P-BV(without controller):150 HP, 1519 lbs

Applicable Battery Technology

- Li-Ion Batteries
  - Large electric capacity to weight ratio
  - Disadvantage: Pressure change issues
    - February 7, 2006: UPS Flight 1307: Li-Ion batteries overheated due to pressure changes & ignited surrounding materials
- Li-Polymer Batteries
  - Similar chemical makeup as Li-Ion batteries, but are less affected by altitude variations
  - Potential power to weight ratio: 0.25 kW/lb
    - Avgas power to weight ratio: 6.0 kW/lb

Aircraft Integration

- Sailplane Sector
  - Pipistrel
  - Lange Aviation
    - Max Weight: 1455 lbs
    - Motor: 42 kW/57 HP DC brushless motor
- Proof of Concept Aircraft
  - The Boeing Company
    - Diamond Dimona motorglider: 55 knot; 20 minute flight
  - NASA
    - VTOL Puffin: 60 HP; 259 knot V_{ne}; 80 km range



Aircraft Integration

- Commercial Production Aircraft
  - Bye Energy
    - November 2010, Bye Energy announces the all-electric Cessna 172:
      - Phase 1: 40 to 45 lbs motor; 1 hour flight time
      - Phase 2: 6-bladed propeller; solar panels; regenerative circuitry
  - Yuneec e430

Bye Energy electric powered Cessna 172 project

General		Batteries	
Seat Quantity	2	Type	Li-Po
Empty Wt w/ Batteries	561 lbs	Weight	184 lbs
Useful Load	385 lbs	Voltage	133.2V
Flight Time (hours)	1.5 to 3.0	Amperage	100 Ah
Motor		**Flight Characteristics**	
Output	40Kw	Maximum Speed	95 mph
	54 hp	Cruise Speed	60 mph
Size (diameter)	9.45 in	Glide Ratio	24:1
Weight	42 lbs		
Controller Weight	15.4 lbs		

Benefits of Electric Propulsion

- Efficiency
  - Electric Motor: 95%
  - Internal Combustion Engines: 18% to 23%
- Audibility
  - From 150 meters electric motors peak 50 decibels
    - Roughly comparable to volume level of a conversation
- Heat Factor
  - Electric motors have a reduced thermal heat signature in comparison to the internal combustion engine
    - Beneficial in hostile territories

Benefits of Electric Propulsion

- Maintenance
  - Electric motors have less moving parts and controls
    - Fewer controls, wear points, and reduction in potential for system failure
  - Less internal heat
    - Reduction in heat related engine failures
    - Reduction in use of costly materials (i.e. inconel)
  - Improved safety & reliability

Benefits of Electric Propulsion

- Environmental Factors
  - Atmospheric Variables
    - Internal combustion engine performance is affected by:
      - Fuel input
      - Altitude
      - Humidity
      - Air temperature/pressure
      - Relative aircraft speed
    - Electric motors are not affected by these variables
  - Emissions
    - Some aviation piston engines require tetra ethyl lead (TEL) additives to prevent premature detonation and increase octane level
      - EPA has pushed to aviation industry to eliminate the use of the lead found in TEL
    - Electric motors do not produce CO or hydrocarbons directly

Pugh Matrices

- Six Sigma based tool
  - Commonly used with a Quality Function Deployment
- Evaluates options against one another
- Details the importance of each variable, then compares variables to product selection
  - Provides prioritization between options
  - Demonstrates overall significance between options

Example of a Decision Matrix

	Safety Risk	Inflation Risk	Rate of Return	Management Difficulty	Stability	Compatibility With Current Business	Totals
Real Estate Rentals	9	7	5	9	9	9	112.5
Blimpie Franchise	5	6	4	3	6	9	74.0
Carpet Cleaning Business	3	6	4	3	5	9	64.5
Note Buying Business	6	8	6	6	7	9	97.5
Retail Convenience Store	4	4	3	3	6	9	61.0
Business Consultant	9	5	4	6	8	9	96.0
Investment Advisor	7	7	9	6	7	7	105.5
Web Designer	7	5	5	6	7	6	86.5
Lifestyle Consultant	6	4	7	6	6	9	87.0
Travel Specialist	6	7	7	6	5	9	94.5
Internet Business	8	7	9	8	7	8	114.5
Weight	4	3	3	2	1.5	1	

Methodology

- Study Design
- Measurement and Instrumentation
- Mission Profile
- Sampling Approach
- Deliverables

Study Design

- Study Framework
  - Quantitative Analysis: analysis of crucial operations
    - Baseline Cessna 172K engine: Lycoming O-320-E2D piston engine
    - Alternative propulsion: electric motor and supporting technologies
    - Analysis of crucial aircraft operations
      - Takeoff, cruise, climb rate, maximum payload, and aircraft range
  - Qualitative Analysis
    - Benefits of electrical propulsion

Study Design

- Pugh matrix: Technology Selection
  1. Analyze commercially available potential motors and power storage devices
  2. Define the feasible range/aircraft parameters
     - Filter out options that do not fall within the feasible range
  3. Design a Pugh matrix to evaluate the following criteria for each technology

a) Motors
- Maximum continuous horsepower
- Maximum torque vs. RPM
- Physical weight
- Physical dimensions
- Cooling techniques
- Required controller
- Gear reduction

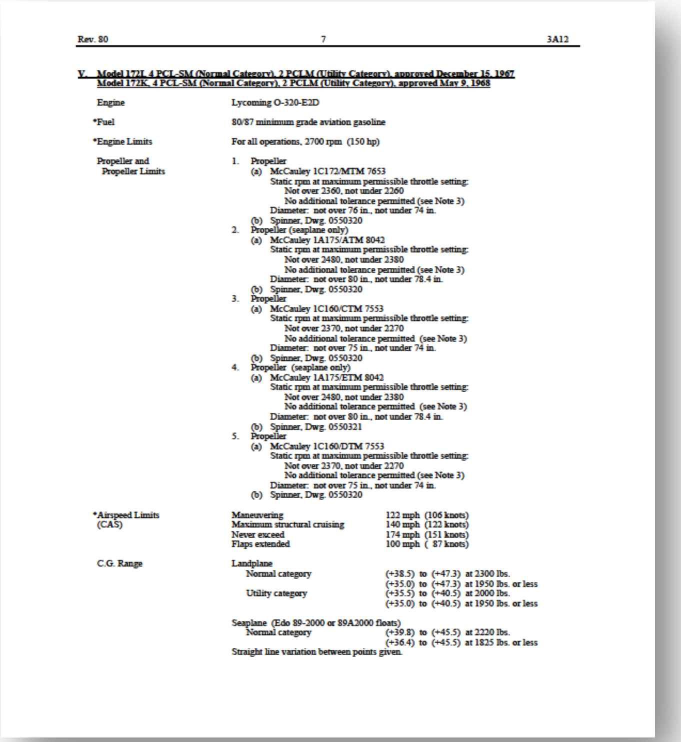
b) Power Storage
- Physical weight
- Physical dimensions
- Continuous voltage capability
- Maximum voltage capability
- Continuous ampere-hour capability
- Maximum ampere-hour capability
- Capable of high altitudes

Study Design

4. After technology has been evaluated, a motor solution is decided
   - Motor is the primary driver of electrical propulsion
5. After motor has been selected, power storage solution is decided
   - Power storage selection limited by physical space and weight available

Measurement and Instrumentation

- Manufacturer's Data
  - Airframe and powerplant information in Type Certificate Data Sheet (TCDS)
    - Aircraft flight characteristics
    - Center of Gravity range
    - Specific weights
- Electric Motor/Power Storage Data
  - Manufacturer's data publicly distributed



Rev. 80 7 3A12

V. Model 172L, 4 PCL-SM (Normal Category), 2 PCLM (Utility Category), approved December 15, 1967
Model 172K, 4 PCL-SM (Normal Category), 2 PCLM (Utility Category), approved May 9, 1968

Engine	Lycoming O-320-E2D
*Fuel	80/87 minimum grade aviation gasoline
*Engine Limits	For all operations, 2700 rpm (150 hp)
Propeller and Propeller Limits	1. Propeller (a) McCauley 1C172/MTM 7653 Static rpm at maximum permissible throttle setting: Not over 2360, not under 2260 No additional tolerance permitted (see Note 3) Diameter: not over 76 in., not under 74 in. (b) Spinner, Dwg. 0550320 2. Propeller (seaplane only) (a) McCauley 1A175/ATM 8042 Static rpm at maximum permissible throttle setting: Not over 2480, not under 2380 No additional tolerance permitted (see Note 3) Diameter: not over 80 in., not under 78.4 in. (b) Spinner, Dwg. 0550320 3. Propeller (a) McCauley 1C160/CTM 7553 Static rpm at maximum permissible throttle setting: Not over 2370, not under 2270 No additional tolerance permitted (see Note 3) Diameter: not over 75 in., not under 74 in. (b) Spinner, Dwg. 0550320 4. Propeller (seaplane only) (a) McCauley 1A175/ETM 8042 Static rpm at maximum permissible throttle setting: Not over 2480, not under 2380 No additional tolerance permitted (see Note 3) Diameter: not over 80 in., not under 78.4 in. (b) Spinner, Dwg. 0550321 5. Propeller (a) McCauley 1C160/DTM 7553 Static rpm at maximum permissible throttle setting: Not over 2370, not under 2270 No additional tolerance permitted (see Note 3) Diameter: not over 75 in., not under 74 in. (b) Spinner, Dwg. 0550320
*Airspeed Limits (CAS)	Maneuvering 122 mph (106 knots) Maximum structural cruising 140 mph (122 knots) Never exceed 174 mph (151 knots) Flaps extended 100 mph (87 knots)
C.G. Range	Landplane Normal category (+38.5) to (+47.3) at 2300 lbs. (+35.0) to (+47.3) at 1950 lbs. or less Utility category (+35.5) to (+40.5) at 2000 lbs. (+35.0) to (+40.5) at 1950 lbs. or less Seaplane (Edo 89-2000 or 89A2000 floats) Normal category (+39.8) to (+45.5) at 2220 lbs. (+36.4) to (+45.5) at 1825 lbs. or less Straight line variation between points given.

Mission Profile

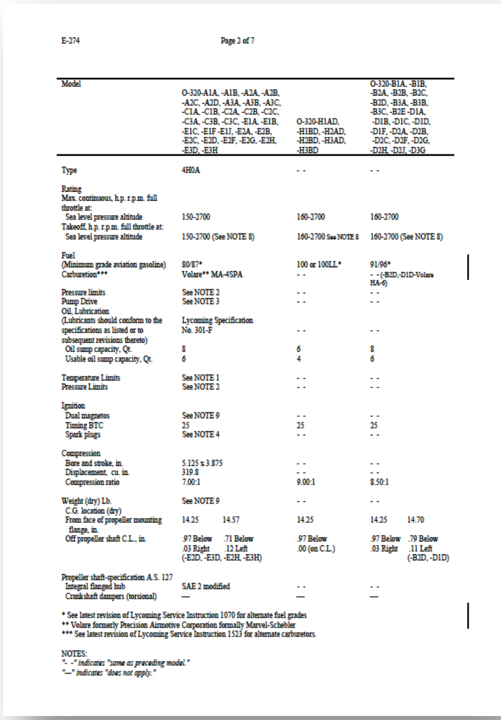
- CAFÉ Foundation: Green Flight Challenge
  - Funded through respectable organizations
  - Accessible and accepted rules/regulations
  - CAFÉ Performance Requirements:
    - Range: 200 statue miles, with 30 min reserve
    - Altitude: Visual Flight Rules (VFR) at $\geq$ 4000 feet
    - Speed: $\geq$ 100 mph average on each of two 200 mile flights
    - Takeoff Distance: $\leq$ 2000 feet from brake release to clear a 50 foot obstacle

Mission Profile

- Cessna 172K with Lycoming O-320-E2D flight characteristics
  - Climb Rate: 721 feet per minute
  - Cruise: 112.5 HP at 130 mph
  - Landing Distance: 150 feet over a 50 foot obstacle
- FAA approved Aircraft Weight and Balance Handbook
  - Standard weight of pilot: 170 lbs

Sampling Approach

- Lycoming O-320-E2D Performance Charts



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Model	O-320-A1A, -A1B, -A2A, -A2B, -A2C, -A2D, -A3A, -A3B, -A3C, -C1A, -C1B, -C2A, -C2B, -C2C, -C3A, -C3B, -C3C, -E1A, -E1B, -E1C, -E1F -E1J, -E2A, -E2B, -E2C, -E2D, -E2F, -E2G, -E2H, -E3D, -E3H	O-320-H1AD, -H1BD, -H2AD, -H2BD, -H3AD, -H3BD	O-320-B1A, -B1B, -B2A, -B2B, -B2C, -B2D, -B3A, -B3B, -B3C, -B2E -D1A, -D1B, -D1C, -D1D, -D1F, -D2A, -D2B, -D2C, -D2F, -D2G, -D2H, -D2J, -D3G
Type	4H0A	- -	- -
Rating			
Max. continuous, h.p. r.p.m. full throttle at:			
Sea level pressure altitude	150-2700	160-2700	160-2700
Takeoff, h.p. r.p.m. full throttle at:			
Sea level pressure altitude	150-2700 (See NOTE 8)	160-2700 See NOTE 8	160-2700 (See NOTE 8)
Fuel			
(Minimum grade aviation gasoline)	80/87*	100 or 100LL*	91/96*
Carburetion***	Volare** MA-4SPA	- -	- - (-B2D,-D1D-Volare HA-6)
Pressure limits	See NOTE 2	- -	- -
Pump Drive	See NOTE 3	- -	- -
Oil, Lubrication (Lubricants should conform to the specifications as listed or to subsequent revisions thereto)	Lycoming Specification No. 301-F	- -	- -
Oil sump capacity, Qt.	8	6	8
Usable oil sump capacity, Qt.	6	4	6
Temperature Limits	See NOTE 1	- -	- -
Pressure Limits	See NOTE 2	- -	- -
Ignition			
Dual magnetos	See NOTE 9	- -	- -
Timing BTC	25	25	25
Spark plugs	See NOTE 4	- -	- -
Compression			
Bore and stroke, in.	5.125 x 3.875	- -	- -
Displacement, cu. in.	319.8	- -	- -
Compression ratio	7.00:1	9.00:1	8.50:1
Weight (dry) Lb.	See NOTE 9	- -	- -
C.G. location (dry)			
From face of propeller mounting flange, in.	14.25 14.57	14.25	14.25 14.70
Off propeller shaft C.L., in.	.97 Below .03 Right; .71 Below .12 Left (-E2D, -E3D, -E2H, -E3H)	.97 Below .00 (on C.L.)	.97 Below .03 Right; .79 Below .11 Left (-B2D, -D1D)
Propeller shaft-specification A.S. 127			
Integral flanged hub	SAE 2 modified	- -	- -
Crankshaft dampers (torsional)	—	—	—

* See latest revision of Lycoming Service Instruction 1070 for alternate fuel grades
** Volare formerly Precision Airmotive Corporation formally Marvel-Schebler
*** See latest revision of Lycoming Service Instruction 1523 for alternate carburetors.

NOTES:
"- -" indicates "same as preceding model."
"—" indicates "does not apply."

- Electric Motor/Power Storage Specifications

Medium Duty Permanent Magnet Motor/Generator "HPM450"

US Hybrid

ISO 9001:2008 REGISTERED FIRM

PRODUCT OVERVIEW:

The HPM450 is a permanent magnet motor designed for medium duty electric and hybrid vehicles and mobile generator applications. High torque and power density with excellent energy efficiency. When used in conjunction with our Integrated Power Unit it can be operated over a wide dynamic range. It can operate in either torque or speed control mode with full control of DC current, power and operating voltage. The system offers extensive J1939 CAN compliance and RS232 diagnostics. It can be used as a hybrid drive motor or generator with command and control via CAN/J1939.

FEATURES:

- Input voltage: 250 - 450Vdc or 550 - 700Vdc
- High Torque/power Density,
- Efficiency: 96% Motor, 98% Controller.
- CAN command, control and diagnostics.
- Output voltage can be regulated via CAN/Analog command.
- Vector controlled Torque or Speed Command.
- Motoring and Generation Capability

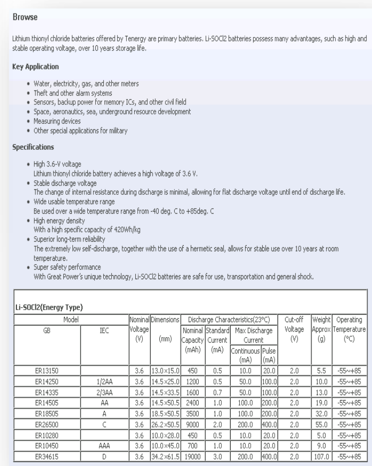
APPLICATIONS:

Electric and Fuel Cell Vehicles drive or APU and Stationary Power Systems.

Motor Type	Permanent magnet
Torque (Max)	450Nm
Power (Max)	120kW
Speed (Max)	4500 rpm
Weight	65 kg
Input Voltage	Med V: 250Vdc-450Vdc High V: 450Vdc-700Vdc
Cooling	Liquid cooling, 60C
Shaft	SAE / Custom
Efficiency	Motor > 96%
Isolation resistance	> 1 MΩ at 700Vdc

www.ushybrid.com DATA SHEET REV: 1001, Specifications subject to change.

Integrated Solutions for Clean Mobility & Energy Conservation



Browse

Lithium thionyl chloride batteries offered by Tenergy are primary batteries. Li-SOCl2 batteries possess many advantages, such as high and stable operating voltage, over 10 years storage life.

Key Application

- Water, electricity, gas, and other meters
- Theft and other alarm systems
- Sensors, backup power for memory ICs, and other civil field
- Space, aeronautics, sea, underground resource development
- Measuring devices
- Other special applications for military

Specifications

- High 3.6-V voltage
  Lithium thionyl chloride battery achieves a high voltage of 3.6 V.
- Stable discharge voltage
  The change of internal resistance during discharge is minimal, allowing for flat discharge voltage until end of discharge life.
- Wide usable temperature range
  Be used over a wide temperature range from -40 deg. C to +85deg. C
- High energy density
  With a high specific capacity of 420Wh/kg
- Superior long-term reliability
  The extremely low self-discharge, together with the use of a hermetic seal, allows for stable use over 10 years at room temperature.
- Super safety performance
  With Great Power's unique technology, Li-SOCl2 batteries are safe for use, transportation and general shock.

Li-SOCl2(Energy Type)

Model		Nominal Voltage (V)	Dimensions (mm)	Discharge Characteristics(23°C)				Cut-off Voltage (V)	Weight Approx (g)	Operating Temperature (°C)
GB	IEC			Nominal Capacity (mAh)	Standard Current (mA)	Max Discharge Current Continuous (mA)	Max Discharge Current Pulse (mA)			
ER13150		3.6	13.0×15.0	450	0.5	10.0	20.0	2.0	5.5	-55~+85
ER14250	1/2AA	3.6	14.5×25.0	1200	0.5	50.0	100.0	2.0	10.0	-55~+85
ER14335	2/3AA	3.6	14.5×33.5	1600	0.7	50.0	100.0	2.0	13.0	-55~+85
ER14505	AA	3.6	14.5×50.5	2400	1.0	100.0	200.0	2.0	19.0	-55~+85
ER18505	A	3.6	18.5×50.5	3500	1.0	100.0	200.0	2.0	32.0	-55~+85
ER26500	C	3.6	26.2×50.5	9000	2.0	200.0	400.0	2.0	55.0	-55~+85
ER10280		3.6	10.0×28.0	450	0.5	10.0	20.0	2.0	5.0	-55~+85
ER10450	AAA	3.6	10.0×45.0	700	1.0	10.0	20.0	2.0	9.0	-55~+85
ER34615	D	3.6	34.2×61.5	19000	3.0	200.0	400.0	2.0	107.0	-55~+85

Deliverables

- Final Outcome
  - Potentially viable option for electrical propulsion using commercially available technologies
  - Explain capabilities of selected motors and power storage devices
  - Center of gravity analysis
  - Benefits of electrical propulsion in comparison to internal combustion engines

Results

Pugh Matrices

Mission Profile

Center of Gravity Analysis

Electric vs. Piston Application

Financial Analysis

Motor Pugh Matrix

Scale: (0) to (10)		BASELINE Lycoming O-320-E2D		Raser Tech G100		Lange EA42	
Criteria	Importance	Measured	Weight	Measured	Weight	Measured	Weight
Horsepower	10.0	150.0	.0	160.0	10.0	51.6	5.0
RPM @ Max Horsepower	8.0	2700.0	.0	4000.0	7.0	1800.0	9.0
Power Consumption (Amp-hour)	7.0	N/A	.0	160.0	9.0	133.0 to 202.0	8.0
Weight (lbs)	9.0	268.0	.0	172.0	8.0	64.2	10.0
Volume/ L x OD (in^3)	7.0	29.6 x 32.2 x 23.2	.0	9.5 x 13.5	10.0	10.7 x 9.8	10.0
TOTAL			**.0**		**361.0**		**338.0**

Scale: (0) to (10)		BASELINE Lycoming O-320-E2D		Tesla Motors		U.S. Hyrbid HPM 450	
Criteria		Measured	Weight	Measured	Weight	Measured	Weight
Horsepower		150.0	.0	288.0	10.0	161.0	10.0
RPM @ Max Horsepower		2700.0	.0	5000.0 to 6000.0	7.0	2500.0 to 4000.0	10.0
Power Consumption (Amp-hour)		N/A	.0	573.0	4.0	171.0 to 267.0	9.0
Weight (lbs)		268.0	.0	115.0	10.0	143.0	9.0
Volume/ L x OD (in^3)		29.6 x 32.2 x 23.2	.0	<O-320	10.0	7.0 x 17.0	10.0
TOTAL			**.0**		**344.0**		**394.0**

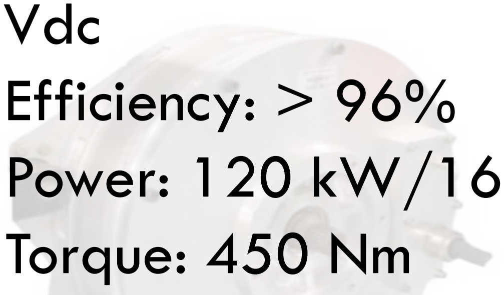
Battery Pugh Matrix

Scale: (-10) to (10)		BASELINE						
		100LL	Tenergy				A123 Systems	
			Li-Polymer		$Li\text{-}SOCl_2$		Prismatic	
Criteria	Importance	Weight	Measured	Weight	Measured	Weight	Measured	Weight
Power Capacity/Weight (Watt-hour/lbs)	10.0	5849.0	64.500	-4.0	230.000	0.0	62.300	-4.0
Power Delivery Capability (1 = Yes/0 = No)	7.0	1.0	1.000	10.0	1.000	10.0	1.000	10.0
Power Capacity/Volume (Watt-hour/in^3)	7.0	5109.0	.005	-2.0	.024	0.0	.001	-6.0
TOTAL		**.0**		**16.0**		**70.0**		**-12.0**

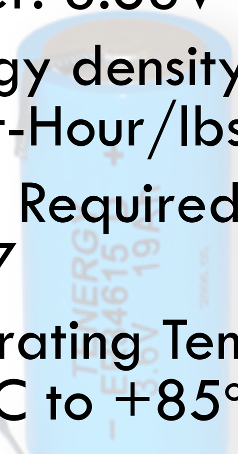
Scale: (-10) to (10)		BASELINE						
		100LL	Valence		Saft			
			LiFe $MaPIO_4$		VL45E Fe		VL-52E	
Criteria		Weight	Measured	Weight	Measured	Weight	Measured	Weight
Power Capacity/Weight (Watt-hour/lbs)		5849.0	41.100	-6.0	68.700	-4.0	84.900	-2.0
Power Delivery Capability (1 = Yes/0 = No)		1.0	1.000	10.0	1.000	10.0	1.000	10.0
Power Capacity/Volume (Watt-hour/in^3)		5109.0	.004	-3.0	.006	-2.0	.008	-1.0
TOTAL		**.0**		**-11.0**		**16.0**		**43.0**

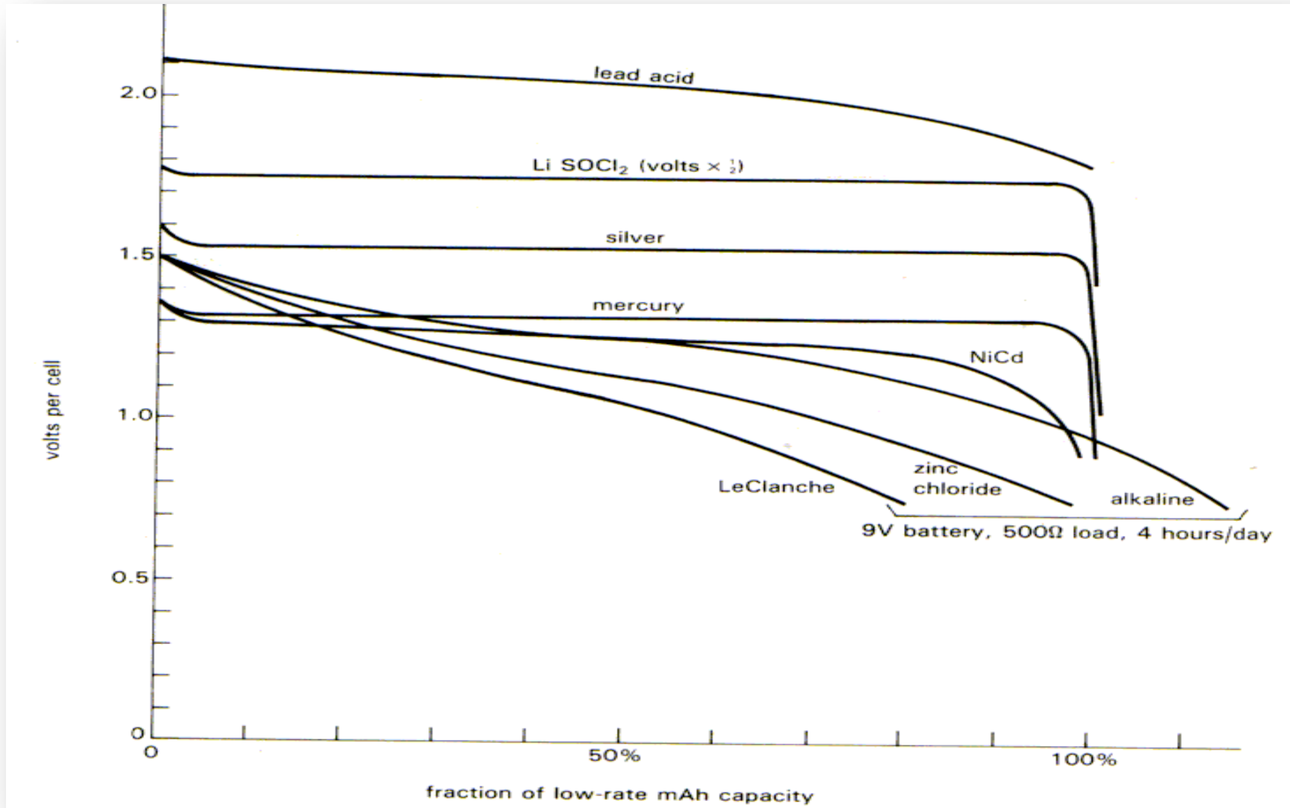
Motor & Battery Selection Review

- U.S. Hybrids: HPM 450 Motor
  - Voltage: 450 Vdc to 700 Vdc
  - Efficiency: > 96%
  - Power: 120 kW/161 HP
  - Torque: 450 Nm
  - Weight: 143 lbs
  - RPM @ Max Horsepower: 2500 RPM
  - Utilized in Sikorsky Firefly helicopter



- Tenergy: Li-$SOCL_2$ Batteries
  - Power: 3.63V ; 19Ah
  - Energy density: 926 Watt-Hour/lbs
  - Total Required Batteries: 2637
  - Operating Temperature: -40°C to +85°C
  - Shelf Life: 10+ years
  - Total Weight: 622 lbs
  - Intended for Aviation/ Aerospace applications





(Purdue University College of Technology, 2010)

Battery Discharge Rate

Mission Profile

Electric Flight Profile Breakdown

	Electric Flight Profile Breakdown		
Flight Operation	**Amps Used**	**Minutes**	**Amp-Minute**
Takeoff	200	6	1200
Cruise	150	109	16350
Landing Approach	128	6	768
Landing Approach	112	8	896
Taxi	64	3	192
30 Minute Reserve	150	30	4500
	TOTAL		**23906**
	Amp-Minutes Available		Amps in Range?
		24000	Yes

Speed/Distance Analysis

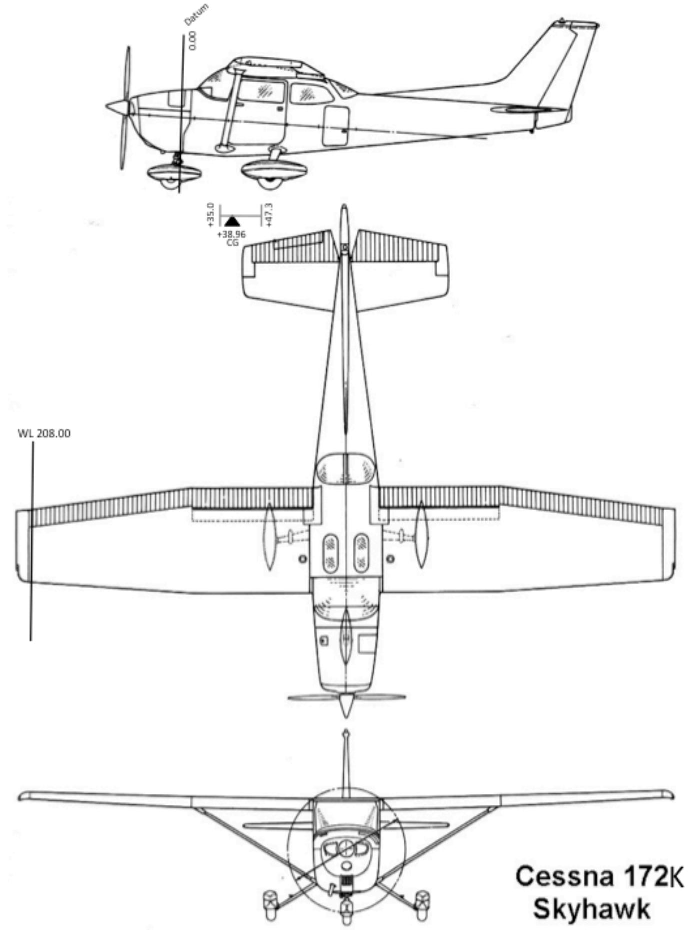
	Speed (MPH)	Hours	Distance Traveled
Takeoff	87.50	0.10	8.75
Cruise	140.00	1.82	254.33
Landing Approach	102.00	0.10	10.20
Landing Approach	89.00	0.13	11.87
	TOTAL	**2.15**	**285.15**
	Average Speed		**132.63**

Mission Profile/Electric Solution Comparison

	Requirements	Electric Solution
Range (miles)	200.0	**285.0**
Fuel Reserve (min)	30.0	30.0
Altitude (ft)	≥ 4000.0	4000.0
Average Speed (mph)	≥ 100.0	**132.6**
Takeoff Distance (ft)	≤ 2000.0	1685.0
Clear 50 ft obstacle?	Yes	Yes
Pilot Weight (lbs)	170.0	170.0
Climb Rate (ft/min)	721.0	721.0
Cruise (hp)	112.5	**120.6**
Cruise (mph)	130.0	**140.0**
Landing Distance (ft)	1500.0	1340.0
Clear 50 ft obstacle?	Yes	Yes

Baseline Measurement

- Datum:
  +38.96”
- Empty Weight:
  1386.48 lbs
- Maximum Gross Weight:
  2300 lbs
- Center of Gravity Envelope:
  +35.0” to 47.3”

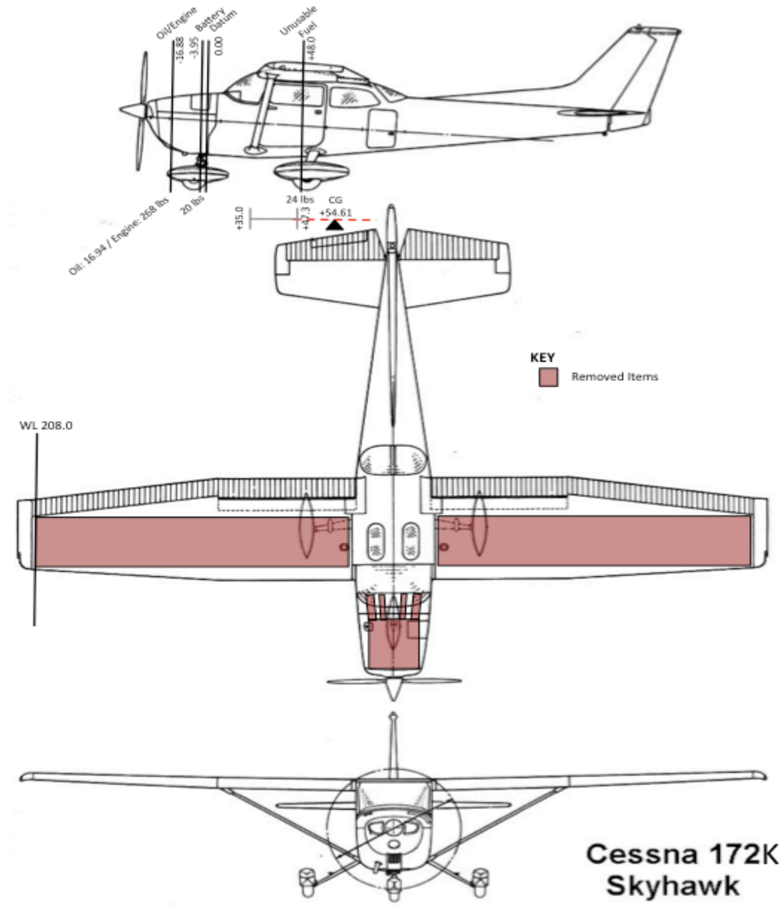


Baseline Cessna 172K Center of Gravity

Empty Weight Calculation

- Lycoming O-320-E2D:
  268 lbs at -16.88"
- SAE 50 Engine Oil:
  16.94 lbs at -16.88"
- Original Battery:
  20 lbs at -3.95"
- Unusable Fuel:
  24 lbs at +48.00"

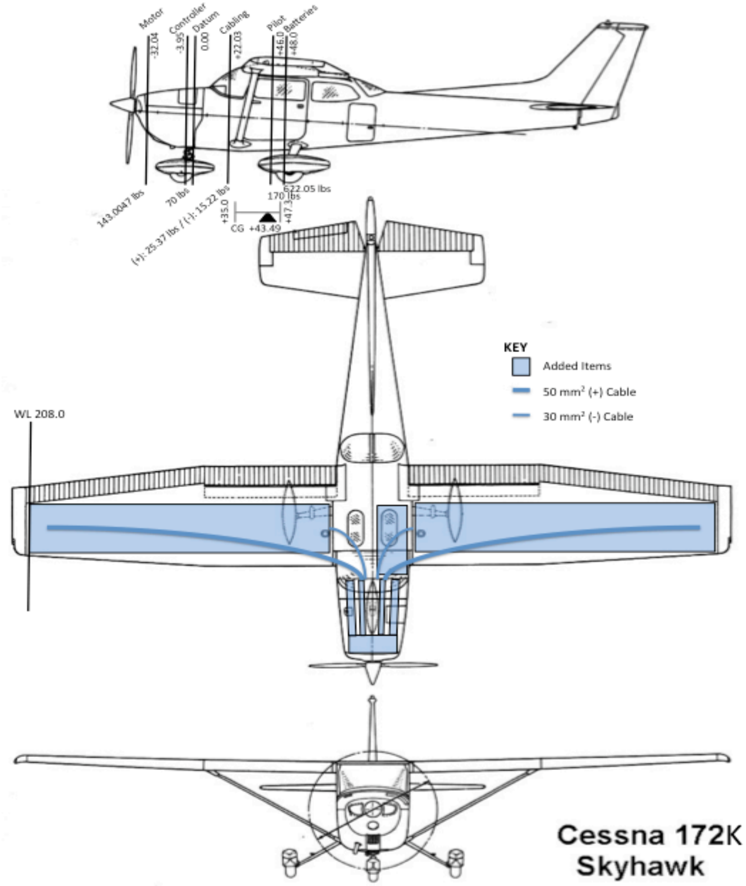
Final CG Location: +51.61"
Total Aircraft Weight: 1058 lbs



Empty Weight Cessna 172K Center of Gravity

Electrical Solution

- Electric Motor:
  143 lbs at -32.04”
- Motor Controller:
  70 lbs at -3.95”
- 50 mm^2 Battery (+) Cable:
  25.4 lbs at +22.03”
- 30 mm^2 Battery (-) Cable:
  15.22 lbs at +22.03”
- Batteries:
  622.05 lbs at +48.00”
- Pilot at Full Seat Extension:
  170 lbs at +46.00”



Electrical Solution Cessna 172K Center of Gravity

Final CG Location: +43.49”
Total Aircraft Weight: 2103 lbs

Center of Gravity Envelope: +35.0” to 47.3”
Maximum Gross Weight: 2300 lbs

Electrical vs. Piston Application

Piston Engine	Electric Motor
Potential Efficiency: 20-40%	Potential Efficiency: >94%
Max Torque: several thousand RPM	Max Torque: Instantaneous
Multiple moving parts	Single moving part
CG changes	CG stationary
Pollutants	Lack of emissions

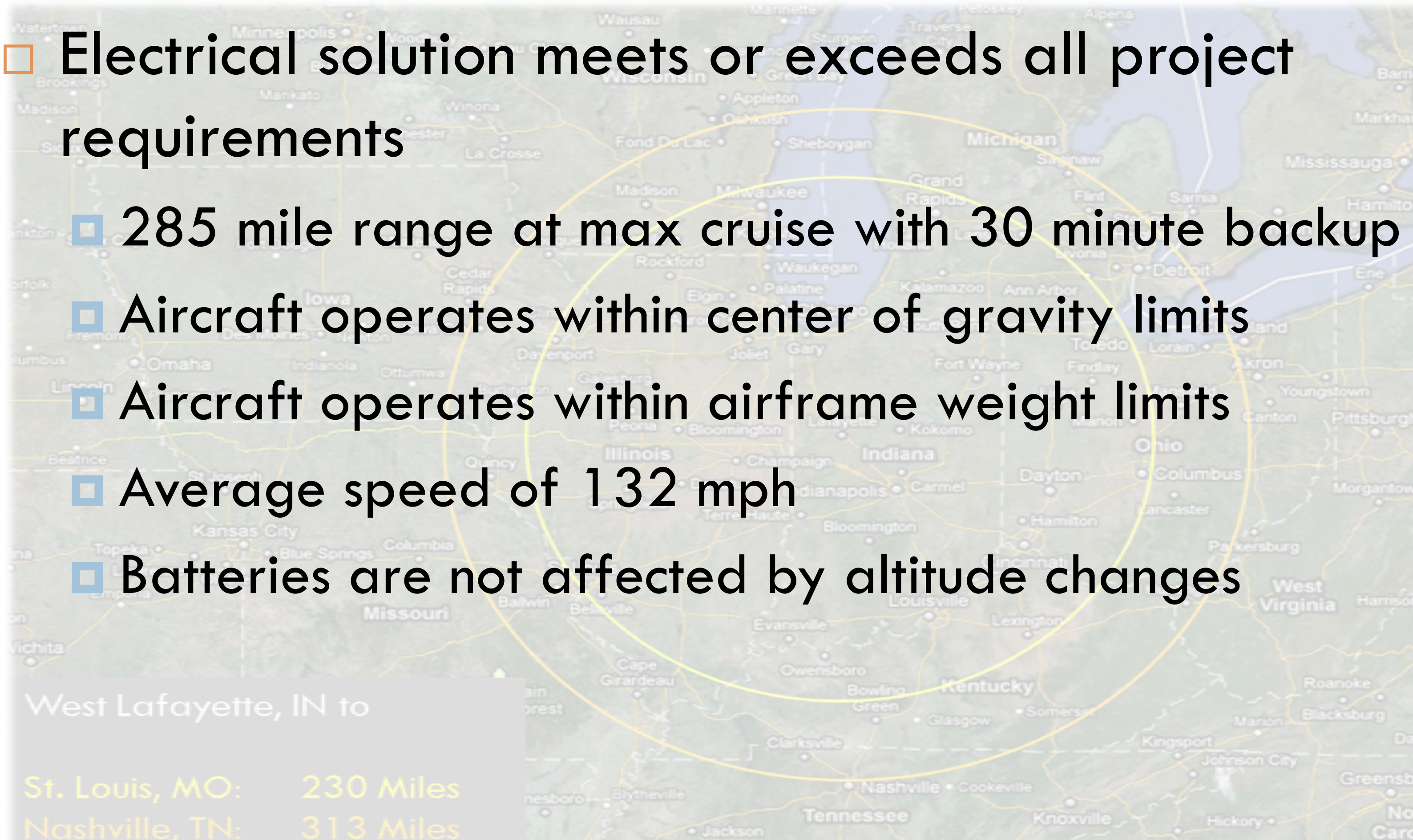
Financial Analysis

- For this research, cost is a deliverable, not a driver
- Total cost of electrical solution: $118,308
  - Electrical motor: $68,000
  - Batteries: $19.00/ battery
- Estimated profit from sold components: $13,097
- Total cost of electrical implementation: $105,211

Conclusion/Considerations

Conclusions

- Electrical solution meets or exceeds all project requirements
  - 285 mile range at max cruise with 30 minute backup
  - Aircraft operates within center of gravity limits
  - Aircraft operates within airframe weight limits
  - Average speed of 132 mph
  - Batteries are not affected by altitude changes



Future Research

Fuel Cell Integration

Solar Cell Integration

Capacitor Integration

Fuel Cell Integration

- Solid Oxide Fuel Cell (SOFC)
  - Delphi to be commercially available in 2012
    - 5 kW Output
    - SOFC Emissions (per kWh):
      - CO: < 8 grams
      - NMHC: < 0.2 grams
    - Lycoming IO-320 Emissions at takeoff (per hour):
      - CO: 2205 grams
      - NMHC: 49578 grams
    - Operating Temperature: 800°C-1000°C
      - No use of precious metals

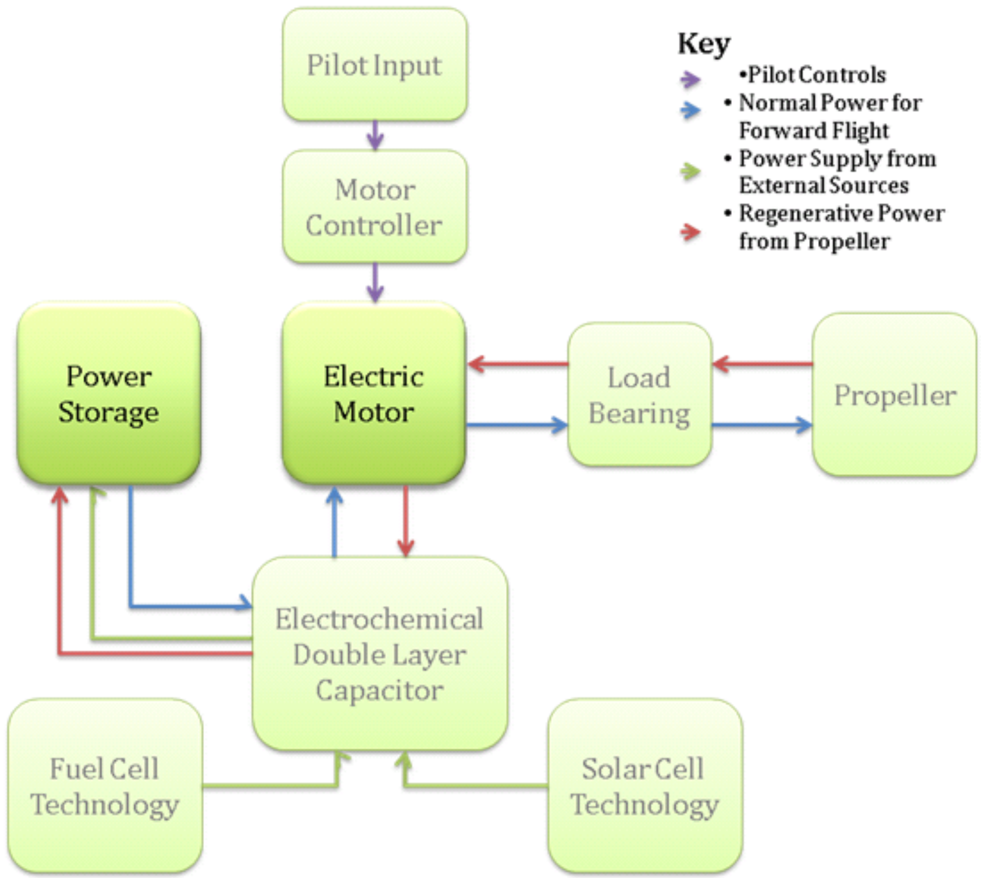
Solar Cell Integration

- Companies
  - First Solar
  - Sanyo Electric
  - Sunpower Corporation
  - Suntech
  - Sharp
- Sharp
  - 142 Watt/1000 Volt Output
  - 10.0% efficiency
  - Extracts light from a wider solar spectrum
  - 25-year warranty

Capacitor Integration

- Electrochemical Double Layer Capacitors (EDLC)
  - Companies
    - Maxwell Technologies
    - The Tecate Group
  - Reduce battery deep cycle damage
    - Wired between batteries and motor to provide a buffer
  - Potential for regenerative power

Future Research



Outline

- Introduction
- Literature Review
- Methodology
- Results
- Conclusion/Considerations
- Future Research

Questions