Development of Superconducting and Cryogenic Power Systems and Impact for Aircraft Propulsion

Energy Materials and Applications
Orlando FL, 25 Jan 2013

Timothy J. Haugan, Ph.D.
Research Physicist
Propulsion Directorate
Air Force Research Laboratory
Outline

• Introduction

• Hybrid-Electric Aircraft
  – 2 passenger, YUNTEC Int. e430 0.045 MW
  – 4 passenger, Pipestrel G4 Taurus 0.145 MW
  – 38 passenger de-Havilland Dash 8 3.2 MW
  – 400 passenger, NASA NSX-3 45 MW

• Cryo-Electric Power Systems: Superconducting,
  Hyperconducting, Cryo-cooled Semiconductor
  – Generators/Motors
  – Power Transmission Cables
  – SMES energy storage
  – Power Electronics (Inverters, Busbars, FCL, Switches…)
Aviation Jet-Fuel Costs: 2012

$187 B  Worldwide Other
$54 B  U.S. Commercial
$5.0 B  U.S. Air Force Mobility
$3.3 B  U.S. Air Force Other
Total = $246 B/yr

<table>
<thead>
<tr>
<th>Year</th>
<th>Jet Fuel Cost ($/gal)</th>
<th>U.S. Airline Consumption (Billions gal/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>$2.24</td>
<td>17.3</td>
</tr>
<tr>
<td>2011</td>
<td>$2.82</td>
<td>17.6</td>
</tr>
<tr>
<td>2012</td>
<td>$3.05</td>
<td>17.9&lt;sup&gt;est&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

http://www.military.com/features/0,15240,177545,00.html
http://www.indexmundi.com/commodities/?commodity=jet-fuel&months=12
4,5-Passenger Auto Vehicles

Combustion Vehicle (CV)
2013 Chevy Eco Cruze

City = 28 mpg
Hwy = 42 mpg

Energy Efficiency ~ 25%
(limited by thermodynamics)

Hybrid-Electric Vehicle (HEV)
2012 Toyota Prius

City = 51 mpg\(_e\)
Hwy = 48-50 mpg\(_e\)

Energy Efficiency ~ 30%
- Regenerative braking
- “Smart” use of electric power

Electric Vehicle (EV)
2013 Honda Fit EV

City = 132 mpg\(_e\)
Hwy = 118 mpg\(_e\)

Energy Efficiency ~ 90%

Auto Vehicle Comparison: Electric vs. Hybrid DriveTrains

### LEAF
- 107-hp / 207 lb-ft traction motor
- 24.0 kW-hr Li-ion battery

### PRIUS
- 1.8-liter 98-hp engine
- 56-hp motor / generator
- 80-hp traction motor
- Planetary gearset

### VOLT
- 1.4-liter 84-hp engine
- 72-hp motor / generator
- 149-hp / 368 lb-ft traction motor
- Clutch
- Planetary gearset

### Battery (lbs)
- **LEAF or TESLA**: 990
- **PRIUS**: 50
- **Volt**: 330

### Engine + Gear (lbs)
- **LEAF or TESLA**: 200
- **PRIUS**: ~ 900 (est.)
- **Volt**: ~ 700 (est.)

### Totals (lbs)
- **LEAF or TESLA**: ~ 1200
- **PRIUS**: ~ 950 ?
- **Volt**: ~ 1000 ?

Electric Vehicle Power Performance
Tesla Roadster

- “Acceleration is perfectly linear, with no dead spots in the rev range… ***”
- Always instant torque at any speed or rpm
- Instant switching to reverse motor direction for highly efficient re-gen
- No need for transmission gears and only one gear needed

http://www.teslamotors.com/roadster/technology/motor
Tesla Roadster Electric Vehicle (EV)

Li Battery Pack (DC output)
- 202 MJ
- 990 lb

Drivetrain Efficiencies

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiencies (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Battery Pack</td>
<td>97-98 %</td>
</tr>
<tr>
<td>Electric Power Control</td>
<td>97-98 % (peak)</td>
</tr>
<tr>
<td>Electric Motor</td>
<td>93 %</td>
</tr>
<tr>
<td>Total Drivetrain+Fuel</td>
<td>88 % (from Tesla)</td>
</tr>
</tbody>
</table>

Electric Power Control
- (DC to AC inverters, replaces transmission)
- 90 lb

Electric Motor (AC)
- 215 kW
- 115 lb
- 4.1 kW/kg

Electric Motor (DC output)
- 202 MJ
- 990 lb

http: www.teslamotors.com

www.autoblog.com
2-Passenger Aircraft

<table>
<thead>
<tr>
<th>Combustion Vehicle (CV)</th>
<th>Hybrid-Electric Vehicle (HEV)</th>
<th>Electric Vehicle (EV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liberty XL2</td>
<td>Siemens DA36 E-Star</td>
<td>YUNeeq Int. e430</td>
</tr>
</tbody>
</table>

**Flight Efficiency**

- **Combustion Vehicle (CV)**: Flight = 24.4 mpg, Passenger = 49 pmpg, Fuel Cost = $26/hr (@ Cruise_{eff} = 121 mph)
- **Hybrid-Electric Vehicle (HEV)**: Flight Efficiency = 25% higher, Energy Efficiency = 30%?
- **Electric Vehicle (EV)**: Flight ~ 150 mpg_e, Passenger ~ 300 pmpg_e, Fuel Cost = $0.9/hr (@ Cruise_{eff} = 40 mph)

**Energy Efficiency**

- **Combustion Vehicle (CV)**: ~ 12% (limited by thermodynamics)
- **Hybrid-Electric Vehicle (HEV)**: ~ 90%
- **Electric Vehicle (EV)**: ~ 90%

http://www.libertyaircraft.com/  
http://www.siemens.com/  
http://www.yuneec.com/
40 kW Electric-Aircraft
YUNneec Int. e430, 2 Passenger Aircraft

- flight-time 1.5–3 hr
- 48 MJ Li-Polymer battery pack @ 83.5 kg
  (~160 Wh/kg)
- “reliability and maintenance like nothing ever seen before”!

Source: http://yuneecouk.site.securepod.com/Aircraft.html

Impacts:
- **Maintenance**: only a few moving parts
- **Maintenance Cost**: virtually zero
- **Noise**: ultra-quiet
- **Other**: vertical lift, distributed propulsion, low cooling drag, remote charging, other

<table>
<thead>
<tr>
<th>Specifications</th>
<th>All-Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive-Train Efficiency</td>
<td>~ 85-90 %</td>
</tr>
<tr>
<td>Motor Density</td>
<td>2.1 kW/kg</td>
</tr>
<tr>
<td>Energy Source</td>
<td>Li-Polymer Battery</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$3.37 / 121.2MJ (U.S.Gal equiv)</td>
</tr>
<tr>
<td></td>
<td>@ $0.10 / kWh</td>
</tr>
<tr>
<td>Fuel Burn*</td>
<td>32 MJ/hr</td>
</tr>
<tr>
<td>Fuel Weight*</td>
<td>~ 123 lbs/hr</td>
</tr>
<tr>
<td>Fuel Cost*</td>
<td>$0.9/hr</td>
</tr>
</tbody>
</table>

* Estimate cruise ~ 22% of full power and 90% energy efficiency = 10.4 kW avg use.
“Siemens scientists of the global research department Corporate Technology are currently working on a **new electric motor that is expected to be five times lighter than conventional drives.** In two years, another aircraft is expected to be equipped with **an ultra-light electric drive.**”

from http://www.siemens.com/
4-Passenger Aircraft

Combustion Vehicle (CV)  
Cessna 182 Skylane

- Flight = 12.8 mpg
- Passenger = 51 pmpg
- Fuel Cost* = $44/hr (100 miles @ 100 mph)

Hybrid-Electric Vehicle (HEV)

- Flight = ?

Electric Vehicle (EV)  
Pipestrel G4 Taurus

- Flight = 100.9 mpg_{pe}
- Passenger = 403.5 pmpg_{pe}
- Fuel Cost* = $3.38/hr ! (100 miles)

Energy Efficiency ~ 12% (limited by thermodynamics)

*Fuel Cost
- Aviation Gas (Avgas) = $5.6/gal
- Jet Fuel = $3.05/gal
- Electricity = $3.37 gal_e (121.2 MJ @ $0.10/kW*hr)

Energy Efficiency ~ 90%
Electric, Combustion Comparison
4 Passenger ~ 150 kW

Pipestrel G4 Taurus

Battery Energy Burn = 1.07Gal$_e$/hr
Fuel Cost ~ $2/hr

Cessna 172 Skyhawk

Fuel Burn ~ 9 Gal/hr (AvGas)
Fuel Cost ~ $50/hr

http://caefoundation.org/v2/main_home.php
http://www.wired.com/autopia/2011/08/pipistrel-taurus-g4-electric/, http://wikipedia.com, other
145 kW Electric Aircraft 
Pipestrel G4 Taurus

Battery Energy Burn = 129 MJ/hr \( (1.07 \text{Gal}_e/\text{hr}) \)
Fuel Efficiency = 100.9 miles-per-gallon-equivalent \( (\text{MPG}_e) \)
\[ = 403.5 \text{ passenger MPG equivalent (PMPG}_e) \]
\[ \sim 4x \text{ higher per passenger than Boeing 787 Dreamliner} \]
Fuel Cost = $3.4/hr (!)

NASA $1.35M Winner Green Flight Challenge
Largest prize in aviation history
“I think we’re sort of in the dawn of electric flight..”

<table>
<thead>
<tr>
<th>Pipestrel G4Taurus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
</tr>
<tr>
<td>Empty Weight</td>
</tr>
<tr>
<td>Typical Payload</td>
</tr>
<tr>
<td>Max. Weight</td>
</tr>
<tr>
<td>Range</td>
</tr>
<tr>
<td>Cruise Speed</td>
</tr>
<tr>
<td>Electric Motor</td>
</tr>
<tr>
<td>Motor Efficiency</td>
</tr>
<tr>
<td>Battery Type</td>
</tr>
<tr>
<td>Battery Size</td>
</tr>
<tr>
<td>Battery Weight</td>
</tr>
</tbody>
</table>

http://cafefoundation.org/v2/main_home.php
http://www.wired.com/autopia/2011/08/pipistrel-taurus-g4-electric/, other...
145 kW Electric Aircraft, Pipistrel G4 Taurus
“World record fuel efficient aircraft, 4 passenger”

NASA $1.35M Winner Green Flight Challenge
- Largest prize in aviation history

“I think we’re sort of in the dawn of electric flight..”

Battery Energy Burn = 129 MJ/hr \( (1.07 \text{Gal}_e/\text{hr}) \)

Fuel Efficiency = 100.9 miles-per-gallon-equivalent (MPG\(_e\)!) = 403.5 passenger MPG equivalent (PMPG\(_e\)!)!

~ 4x higher per passenger than Boeing 787 Dreamliner

Fuel Cost ~ $2/hr

http://cafefoundation.org/v2/main_home.php
http://www.wired.com/autopia/2011/08/pipistrel- taurus-g4-electric/, other...
## 300-Passenger Aircraft

<table>
<thead>
<tr>
<th></th>
<th>Combustion Vehicle (CV)</th>
<th>Hybrid-Electric Vehicle (HEV)</th>
<th>Electric Vehicle (EV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing 787-9 Dreamliner</td>
<td></td>
<td></td>
<td>EADS Volt-Air</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Feature</th>
<th>CV</th>
<th>HEV</th>
<th>EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight mpg</td>
<td>~ 0.4</td>
<td>?</td>
<td>2 $\text{mpg}_e$ (?)</td>
</tr>
<tr>
<td>Passenger mpg</td>
<td>~ 110</td>
<td>?</td>
<td>400 $\text{pmpg}_e$ (?)</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>$11.4$/mile</td>
<td>?</td>
<td>$3.1$/mile (?)</td>
</tr>
<tr>
<td>Energy Efficiency</td>
<td>40%*</td>
<td>55% (?)</td>
<td>~ 90%</td>
</tr>
</tbody>
</table>

*thermodynamic limit

Boeing SUGAR Volt. “The team is looking at various… technology options… These include hybrid battery-gas turbine propulsion, fuel cells, fuel cell–gas turbine hybrid propulsion systems, cryogenic fuels, cryogenically cooled engines and associated technologies, advanced batteries and open rotor/turboprop technologies.”


Electric-Aircraft: EADS VoltAir

“EADS VoltAir all-electric aircraft concept unveiled in Paris”
European Aeronautic Defense and Space Company N.V. (EADS) – parent company of Airbus

Battery Size: 100-300 GJ

- “VoltAir’s two next-generation lithium-air batteries would power two highly efficient superconducting motors…which would in turn dive two coaxial, counter-rotating shrouded propellers. Energy densities ~ 7-8 kW/kg expected with almost no losses.”
- “High-temperature-superconductor (HTS) wiring would take the place of …copper coils”
- “… as batteries approach and exceed energy densities of 1000 Wh/kg within the next two decades.”

“Conventional electric engines… generally do not offer the power densities… required for large airborne missions…
- The necessary cooling of these engines to reach superconducting temperature can be realised with low-cost and environmentally friendly liquid nitrogen.”

http://evworld.com/news.cfm?newsid=25993
**2011_0222**

**Boeing B777-200LR**
Two Turbofans GE90-115B

<table>
<thead>
<tr>
<th></th>
<th>B777-L200LR Turbine-Engine (lb)</th>
<th>N3-X Hybrid-Electric (HEDP) with Cryogenic Power (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Wt</td>
<td>340,800</td>
<td>267,400</td>
</tr>
<tr>
<td>Payload Wt</td>
<td>118,100</td>
<td>118,100</td>
</tr>
<tr>
<td>Block Fuel Wt</td>
<td>279,800</td>
<td>88,000</td>
</tr>
<tr>
<td>TOGW</td>
<td>768,700</td>
<td>473,500</td>
</tr>
</tbody>
</table>

Reduce > 70%

**N3-X, H. Kim, NASA-Glenn, A5M 2011_0222**

<table>
<thead>
<tr>
<th>Benefit</th>
<th>~ Fuel Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Lift Body</td>
<td>35%</td>
</tr>
<tr>
<td>Maximize Fan</td>
<td>8-10%</td>
</tr>
<tr>
<td>By-Pass Ratio</td>
<td></td>
</tr>
<tr>
<td>Reduce Drag</td>
<td>18-20%</td>
</tr>
<tr>
<td>Other System</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>72%</strong></td>
</tr>
</tbody>
</table>

**N3-X, H. Kim, NASA-Glenn, A5M 2011_0222**

*J. Felder et al, NASA-Glenn, ISABE_2011_1340*

http://en.wikipedia.org/
**45 MW Hybrid-Electric Distributed Propulsion (HEDP): NASA N3-X**

- **Specifications**
  - **Cu Wire or PM @ 293K**
  - **All-Superconductor or Cryogenic**
  - **Motor/Generator Power Density (kW/kg)**
    - 3 - 7
    - 40 - 65
  - **Efficiency (%)**
    - 85%
    - 99%
  - **Heat Loss**
    - 6.8 MW
    - 0.45 MW
  - **Mass**
    - 146 klb
    - 11 klb
  - **TRL Level - Airborne**
    - 9
    - 1 - 6

**Reduces fuel from 279,800 lbs to 88,000 lbs**

**45 MW Electrical Propulsion System – 1st order estimate**

**Erases gains from HEDP drag reduction**

**Higher than payload = 118 klb!**

**GOTCHA: Cryogenics enabling technology for HEDP**

J. Felder et al, NASA-Glenn, ISABE_2011_1340
Future Concept: 12 MW Hybrid-Electric C-130J

For C-130J
- 3 MW Cryo-electric-props ~ 140 lbs ea
  > 10x lighter than turbo-props

GOTCHA: Vertical lift enabled by ultra-light electric distributed propulsion (?)
Outline

• Introduction

• Hybrid-Electric Aircraft
  – 2 passenger, YUNTEC Int. e430  0.045 MW
  – 4 passenger, Pipestrel G4 Taurus  0.145 MW
  – 38 passenger de-Havilland Dash 8  3.2 MW
  – 400 passenger, NASA NSX-3  45 MW

• Cryo-Electric Power Systems
  (Superconducting, Hyperconducting, Cryo-cooled Semiconductor)
  – Generators/Motors
  – Power Transmission Cables
  – SMES energy storage
  – Power Electronics (Inverters, Busbars, FCL, Switches…)

Wire Device Efficiency

\[ P_{\text{loss}} = I^2 R \]

or

\[ P_{\text{loss}} = \alpha \rho_{\text{wire}} P_{\text{Device}} \]

where \( \alpha = (L J_e)/270V \)

\( L = \) wire length

\( J_e = \) current density

\[ RRR = \text{residual resistivity ratio (to room temperature)} \]

Using International Annealed Copper Standard (IACS)
Composite Aluminum Conductor – 8000 Amps!

- Residual-Resistivity Ratio (RRR) = 400-500
  (H = 0-10T)
  (Cu ~ 10 for standard wires, P-doped for high H fields)

- $J_e(20K,H=1-2T) = 45,000 \text{ A/cm}^2$

- Yield Strength = 0.35 Gpa

- Mech. Strength Limit = 0.1-0.2%

- Fe = 8.4 Wt%, Ce = 3.6 Wt%

- Al Weight Density = 2.70 g/cm$^3$ (Cu = 8.96 g/cm$^3$)
  > 3x lighter than Cu!

Comparing 8000 A wires
Water-cooled Cu, Al 99.999% hyperconductor

Superconductor or Al Hyperconductor Km-length Wires

For Cu, $J_e (293K) = 275 \text{ A/cm}^2$ and resistivity International Annealed Copper Standard (IACS) = $1.724 \text{ cm} @ 293K$
20 MW DC Co-axial Power Transmission Cable

For 270 V Aircraft Power

<table>
<thead>
<tr>
<th></th>
<th>76K $I_c$ (A)</th>
<th>76 K @ 270V P (MW)</th>
<th>55K @270V P (MW)</th>
<th>20 K @270V P (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC single-phase</td>
<td>7,561</td>
<td>2.04</td>
<td>~ 6</td>
<td>~ 18 !</td>
</tr>
<tr>
<td>DC Co-Axial Two-phase</td>
<td>8,324</td>
<td>2.25</td>
<td>~ 6.7</td>
<td>~ 20 !</td>
</tr>
<tr>
<td>Specific Power (MW/kg*m)</td>
<td>4.7</td>
<td>14.1</td>
<td>42.3</td>
<td></td>
</tr>
</tbody>
</table>

Winding for 1MW @76K

GOTCHA: Cable Mass = 0.97 lb/m !

20 MW Power Transmission Cables

<table>
<thead>
<tr>
<th></th>
<th>4/0 Cu-Wire @ 60°C (x322)</th>
<th>Y-Ba-Cu-O Cable @ 20K</th>
<th>Improve Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>1,585 lbs/m</td>
<td>~3 lbs/m</td>
<td>530x</td>
</tr>
<tr>
<td>Heat Loss</td>
<td>7,000 W/m</td>
<td>3.8 W/m (cryo-cool+liquid N₂)</td>
<td>1,840x</td>
</tr>
<tr>
<td>X-sect Area</td>
<td>1170 cm²</td>
<td>5.0 cm²</td>
<td>230 x</td>
</tr>
</tbody>
</table>

Y-Ba-Cu-O Cable @ 20K
Weight = 0.97 lb/m

Cu-Wire MCM 750 Gauge Cable @ 60°C
Weight = 1,429 lb/m

Cryoflex Tubing
Heat Loss @ 20-77K ~ 0.5 W/m
Weight = 1 lb/m

Cryo-cooler
Cools 30-m @ 77K
Weight = 0.23 lb/m
State-of-Art Superconducting AC Cables Worldwide

- Superconducting quench never reported in years of operation and 30 cables worldwide
- Cryocooler problems ~ 1 or 2 times per year using COTS cryocoolers not designed for long-term operation
1 MW Motors or Generators*  

<table>
<thead>
<tr>
<th>Weight Device (lbs)</th>
<th>Weight reduced &gt; 10x</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Power Density (cont.)</th>
<th>MEPS 1/2-Supercond HTS @ 77K</th>
<th>Full-Supercond @ 20K</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 kW/kg</td>
<td>8.8 kW/kg</td>
<td>50 kW/kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Machine Efficiency (%)</th>
<th>99.97</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Waste Heat (cont.)</th>
<th>Waste Heat / Mass (per hr)</th>
<th>Waste Heat / Mass (MJ/kg*h)</th>
<th>CryoCooler Mass @ 1 MW (cont.)</th>
<th>Liquid Cooling @ 1MW (cont.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kW</td>
<td>180 MJ</td>
<td>0.37</td>
<td>22 lbs</td>
<td>7.9 lbs/h Liquid H₂</td>
</tr>
<tr>
<td>30 kW</td>
<td>108 MJ</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 kW</td>
<td>1.1 MJ</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Assuming the motors scale ~ with different power levels  
** Cryogenic, J. Felder et al, NASA-Glenn, ISABE_2011_1340
Motor Efficiency at Low Speeds: 5-36 MW for Navy

Savings for USN electric ship during normal operating profile ~$450,000 per ship per year

Courtesy: Dr. D. Gubser, Naval Research Laboratory
3.2 MW Electric Aircraft: de Havilland Bombadier Dash 8

Pratt-Whitney PW110, 1.4 MW continuous
- PW121  Mass = 425 kg
- Power = 1.603 MW continuous
- Power density = 3.77 kW/kg

http://en.wikipedia.org/wiki/Pratt_%26_Whitney_Canada_PW100
http://en.wikipedia.org/wiki/Turbo

<table>
<thead>
<tr>
<th></th>
<th>DHC-8-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>37-39 passengers</td>
</tr>
<tr>
<td>Typical Payload</td>
<td>7511 lbs</td>
</tr>
<tr>
<td>Range</td>
<td>1174 miles</td>
</tr>
<tr>
<td>Motors</td>
<td>2 PW121</td>
</tr>
<tr>
<td>Motor Weight</td>
<td>1874 lbs</td>
</tr>
<tr>
<td>Max. Fuel Size</td>
<td>1003 U.S. gal</td>
</tr>
<tr>
<td>Max. Fuel Weight</td>
<td>6039 lbs</td>
</tr>
<tr>
<td>Maximum Weight</td>
<td>36661 lbs</td>
</tr>
</tbody>
</table>

de Havilland Canada Bombadier Dash 8: DHC-8-100 series
3.2 MW Hybrid-Electric Aircraft (Prius Style)

Pratt-Whitney PW110, 1.4 MW continuous
- PW121  Mass = 425 kg
- Power = 1.603 MW continuous
- Power density = 3.77 kW/kg

3.2 MW Prius-Style Hybrid

<table>
<thead>
<tr>
<th></th>
<th>DHC-8-100</th>
<th>Hybrid Cu-Wire*</th>
<th>Hybrid Cryo</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2 MW Engine</td>
<td>1874 lbs</td>
<td>1874 lbs</td>
<td>1874 lbs</td>
</tr>
<tr>
<td>(2 PW121)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.83 MW Electric Motor/Generator</td>
<td>1010 lbs*</td>
<td>101 lbs</td>
<td></td>
</tr>
<tr>
<td>2.6 MW Electric Motor</td>
<td>1439 lbs*</td>
<td>144 lbs</td>
<td></td>
</tr>
<tr>
<td>227 MJ Li Battery</td>
<td>1100 lbs ?**</td>
<td>1100 lbs ?</td>
<td></td>
</tr>
<tr>
<td>Extra Machine Weight</td>
<td>0</td>
<td>3549 lbs</td>
<td>1349 lbs</td>
</tr>
<tr>
<td>Fuel Weight (Max.)</td>
<td>6039 lbs</td>
<td>2593 lbs</td>
<td>4794 lbs</td>
</tr>
</tbody>
</table>

* Assume power density = 4 kW/kg
** Energy density = 150 Wh/kg
3.2 MW Hybrid-Electric Aircraft (Chevy Volt Style)

Pratt-Whitney PW110, 1.4 MW continuous
- PW121  Mass = 425 kg
- Power = 1.603 MW continuous
- Power density = 3.77 kW/kg

3.2 MW Prius-Style Hybrid

<table>
<thead>
<tr>
<th></th>
<th>DHC-8-100</th>
<th>Hybrid Cu-Wire*</th>
<th>Hybrid Cryo</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8 MW Engines</td>
<td>1874 lbs</td>
<td>1054 lbs</td>
<td>1054 lbs</td>
</tr>
<tr>
<td>(3.2 MW)</td>
<td>(1.8 MW)</td>
<td>(1.8 MW)</td>
<td>(1.8 MW)</td>
</tr>
<tr>
<td>1.55 MW Electric Motor/Generator</td>
<td>855 lbs*</td>
<td>86 lbs</td>
<td></td>
</tr>
<tr>
<td>2.6 MW Electric Motor</td>
<td>1645 lbs*</td>
<td>165 lbs</td>
<td></td>
</tr>
<tr>
<td>Battery &gt; 2x heavier than fuel load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.8 GJ Li Battery</td>
<td>13690 lbs</td>
<td>13690 lbs</td>
<td></td>
</tr>
<tr>
<td>Machine Weight (w/o battery)</td>
<td>1874 lbs</td>
<td>3554 lbs</td>
<td>1305 lbs</td>
</tr>
<tr>
<td>Fuel Weight (Max.)</td>
<td>6039 lbs</td>
<td>? lbs</td>
<td>? lbs</td>
</tr>
</tbody>
</table>

* Assume power density = 4 kW/kg
** Energy density = 150 Wh/kg
Li-Battery Requirements for Electric Propulsion

Battery Size (GJ)

Battery Weight (lbs)

Li-Battery Size for Cruise $\eta_{\text{eff}}$ @ 22% of Full Power
(use $\varepsilon = 150$ Wh/kg)

Li-Battery Weight for Cruise $\eta_{\text{eff}}$
@ 22% of Full Power
(use $\varepsilon = 150$ Wh/kg)

Payload Weight

Li-Batteries for Electric Propulsion - Restrictions

<table>
<thead>
<tr>
<th>Battery Size (GJ)</th>
<th>Battery Weight (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
</tr>
<tr>
<td>1000</td>
<td>100</td>
</tr>
<tr>
<td>10000</td>
<td>1000</td>
</tr>
<tr>
<td>100000</td>
<td>10000</td>
</tr>
</tbody>
</table>

Storage Device Weight (kg) vs. Power (MW)

- **Li Batteries** (actual systems)
  - \( P = 1 \text{ kW/kg} \)  
  - \( E = 40 \text{ Wh/kg} \)

- **Li Batteries** (lower weight limit)
  - \( P = 1 \text{ kW/kg} \)  
  - \( E = 40 \text{ Wh/kg} \)

- **SMES, 70 MJ Solenoid, 5 MW Design**
  - \( P = 18 \text{ kW/kg} \)  
  - \( E = 70 \text{ Wh/kg} \)

Superconducting Magnetic Energy Storage (SMES)
Energy Storage Devices for Electric Propulsion: Ragone Plot

- **SMES**: NbTi, or BSCCO Wire
- YBCO, other Wire
- **SMES**: 100-900 MJ

- **Li-Battery**: 0.2-200 MJ (discharge)
- **NiH Battery**: Boeing 18 MJ

- **Super-Capacitors**

- **Fuel Cells**

- **Jet-Fuel Combustion**: (useable)

- **Liquid H₂ Combustion**: (useable)

- **All-Electric Aircraft Goals**: 0.05 - 400 GJ

**Specific Power (kW/kg)** vs. **Specific Energy (Wh/kg)**

**DISTRIBUTION A: Approved for public release. Distribution unlimited.**
SMES, Flywheel Energy Storage Systems

Flywheel Storage

Superconducting Magnetic Energy Storage (SMES)

18 MJ system, Boeing Inc.

2 GJ system, Japan

Superconducting magnets can store energy with zero loss for 10+ yrs

Strasik et al, SuST 23, 0340212 (2010)

M. Noe, ISS 2011

Figure 1. Overall design of flywheel energy storage, showing several critical components.
SMES Energy Density – Limiting Factors

• Limiting Factors setting Upper Bounds
  1. $J_e$ vs H properties
  2. Lorentz Forces – Virial Theorem
  3. AC losses during charge/discharge
     - cabling and magnet
  4. Minimum Quench Energy
  5. Cabling and Stability
  6. Quench Protection
Maximum Energy Density Solenoid

• Determine limits from $J_e(H)$ and coil design

If $I_c$ were independent on $B$ the coil with largest inductance (for given wire length) has the largest energy density $\varepsilon$. If $I_c = I_c(B)$, solve the constraint optimization problem:

$$\text{maximize} \quad \frac{1}{2} L(a,b,l) I_c^2 \left( B_c^{(\text{max})} (a,b,l) \right)$$

under a constraint:

$$\frac{\pi \left( b^2 - a^2 \right) l}{wt} = l_{\text{wire}}$$

$l, a, b$ are the length, inner & outer radii of the solenoid, $w, t$ are the wire’s width and thickness

<table>
<thead>
<tr>
<th>Model</th>
<th>Coil</th>
<th>Length, $l$</th>
<th>Outer radius, $b$</th>
<th>Energy Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_c$ independent of $B$</td>
<td>Single layer</td>
<td>0.9$a$</td>
<td>N/A</td>
<td>$\varepsilon = \alpha M^{1/3}$</td>
</tr>
<tr>
<td></td>
<td>Multilayer</td>
<td>0.95$a$</td>
<td>1.86$a$</td>
<td>$\varepsilon = \alpha M^{2/5}$</td>
</tr>
<tr>
<td>$I_c = I_c(B)$</td>
<td>Multilayer</td>
<td>Least</td>
<td>2$a$</td>
<td>$\varepsilon = \alpha M^{1/3}$</td>
</tr>
</tbody>
</table>

Courtesy: D. Latypov, T. Haugan, manuscript in preparation
1. If $J_c$ is independent of $H$: 

2. If $J_c$ is dependent on $H$: ring-shaped

GOTCHA: Energy Density (250 MJ) = 110 Wh/kg for YBCO

- Superconductor Wire = YBCO limited by $H//c$
- Stress Limit = not calculated
- $I_{op} = 970A$

D.M. Latypov, T. J.Haugan, SuST, draft
• Virial Theorem

\[ \varepsilon = \frac{E}{m} = \frac{\sigma_{max}}{3600 \cdot Q_{max} \cdot \rho_{str}} \]

– Volume, I, H integrated out

\[ \varepsilon = \text{Energy Density (Wh/kg)} \]
\[ \rho = \text{density structure (kg/m}^3\text{)} \]
\[ \sigma_{max} = \text{maximum stress (MPa)} \]
\[ Q_{max} = \text{structure factor} \]

- 0.5 Toroid
- 1.0 Optimized Solenoid
- 1-2 Solenoid
-> 2 Toroid field coils
(SI units)

Possible Near Future with MgB\(_2\) Composite !?

YBCO Test, Japan 2012, ASC 2012!

X. Wang, Mat. Res. Lett, iFirst 1-7 (2012)
Force Balance Coils – 360 MJ

Virial Theorem Limit can be achieved (?)

- MgB$_2$ wire: support = 1:1
- $\varepsilon = 27$ Wh/kg ($\rho_{str} = 8000$ kg/m$^3$, Stress = 0.4 GPa)
- $\varepsilon = 500$ Wh/kg !! ($\rho_{str} = 2100$ kg/m$^3$, Stress = 3.8 GPa)

TABLE II
KEY PARAMETERS OF THE 360-MJ SMES COILS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FBC</th>
<th>Solenoid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum magnetic field (T)</td>
<td>5.0</td>
<td>10</td>
</tr>
<tr>
<td>Coil outer diameter (m)</td>
<td>7.0</td>
<td>4.4</td>
</tr>
<tr>
<td>Coil height (m)</td>
<td>1.4</td>
<td>0.89</td>
</tr>
<tr>
<td>Ampere-meters ($\times 10^8$ Am)</td>
<td>2.8</td>
<td>2.2</td>
</tr>
<tr>
<td>10-kA class conductor (km)</td>
<td>28</td>
<td>22</td>
</tr>
<tr>
<td>50-kA class conductor (km)</td>
<td>5.6</td>
<td>4.5</td>
</tr>
<tr>
<td>Mass of the structure* ($\times 10^3$ kg)</td>
<td>3.6</td>
<td>10</td>
</tr>
</tbody>
</table>

(*mass density $\rho_{str}$: $8.0 \times 10^3$ kg/m$^3$, allowable stress $\sigma_\alpha$: 400 MPa)

70 MJ SMES – Present and Future

Present

[Diagram showing a cylinder with 70 MJ, H = 0.012 m, D = 2.0 m]

Future > 5 yrs

[Diagram showing a cylinder with 70 MJ, H = 0.012 m, D = 1.0 m]

<table>
<thead>
<tr>
<th></th>
<th>2-3 Yrs</th>
<th>4-5 Yrs (?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor Wire</td>
<td>MgB$_2$ or Nb$_3$Sn</td>
<td>MgB$_2$ or (YBCO)</td>
</tr>
<tr>
<td>$I_{op}(A)$</td>
<td>970 A</td>
<td>3700 A</td>
</tr>
<tr>
<td>Wire Length</td>
<td>25 km</td>
<td>5km</td>
</tr>
<tr>
<td>Wire Cost</td>
<td>$0.3M</td>
<td>$0.06M ($0.5M)</td>
</tr>
<tr>
<td>Wire Mass</td>
<td>240 kg</td>
<td>&lt; 50 kg</td>
</tr>
<tr>
<td>Energy Density</td>
<td>75 Wh/kg</td>
<td>375 Wh/kg</td>
</tr>
</tbody>
</table>
**J_e(H) Properties – Update 2012**

![Graph showing J_e(H) properties for various materials.](image)

- **MgB_2**

- **YBCO**
  - Braccini et al, SuST v24 p035011 (2011)

- **Nb_3Sn**
  - Tube-Type for HEP Fusion, Sumption et al, Cryogenics v52

---

**Graph Details**:

- **YBCO H//ab**
- **YBCO H//ab-5°**
- **Nb_3Sn HEP Fusion**
- **Hypertech (46.5 % fill)**
- **MgB_2 IMD Method (assume 30% fill)**
## Hybrid-Electric Aircraft Summary

<table>
<thead>
<tr>
<th></th>
<th>Combustion</th>
<th>Hybrid-Electric</th>
<th>Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Passenger Auto</td>
<td>Chevy Eco Cruze 42 mpg, 208 ppmg</td>
<td>Toyota Prius 51 mpg, 255 ppmg</td>
<td>Honda EV Fit 132 mpg&lt;sub&gt;e&lt;/sub&gt;, 660 ppmg&lt;sub&gt;e&lt;/sub&gt;</td>
</tr>
<tr>
<td>2 Passenger Aircraft</td>
<td>Liberty XL2 24 mpg, 49 ppmg</td>
<td>Siemens DA36 E-Star 30 mpg&lt;sub&gt;est&lt;/sub&gt;, 60 mpg&lt;sub&gt;est&lt;/sub&gt;</td>
<td>YUNeeq e430 150 mpg&lt;sub&gt;e&lt;/sub&gt;, 300 ppmg&lt;sub&gt;e&lt;/sub&gt;</td>
</tr>
<tr>
<td>4 Passenger Aircraft</td>
<td>Cessna 182 13 mpg, 26 ppmg</td>
<td>?</td>
<td>Pipestrel G4 Taurus 101 mpg&lt;sub&gt;e&lt;/sub&gt;, 404 ppmg&lt;sub&gt;e&lt;/sub&gt;</td>
</tr>
<tr>
<td>290-400 Passenger Aircraft</td>
<td>Boeing 787-9 0.4 mpg, 110 ppmg</td>
<td>NASA N3-X 1.2 mpg, 490 ppmg</td>
<td>EADS Volt-Air ?</td>
</tr>
</tbody>
</table>

- **Cryogenic Power Systems:** critical enabling technology, many pieces tested and ‘ultra-safe’ designs expected
- **Energy Storage Devices:** energy densities $\varepsilon = 200 – 1000$ Wh/kg critical for future developments
- **SMES Devices:** $\varepsilon = 500 - 1000$ Wh/kg possible !?
Development of Superconducting and Cryogenic Power Systems for Aircraft Propulsion

16th US-Japan Workshop on Advanced Superconductors
Dayton OH, 11 Jul 2013

Timothy J. Haugan, Ph.D.
Research Physicist
Propulsion Directorate
Air Force Research Laboratory
Outline

• Hybrid-Electric Vehicle (HEV) Aircraft
  – 38 passenger, de-Havilland Dash 8 3.2 MW
  – 400 passenger, NASA N3-X 45 MW

• Electric Vehicle (EV) Aircraft
  – 290 passenger, Boeing 787 EV Concept 40 MW

• Cryogenic/Superconducting Power Systems
  (Superconducting, Hyperconducting, Cryo-cooled Semiconductor)
  – Generators/Motors
  – Power Transmission Cables
  – SMES energy storage
  – Power Electronics (Inverters, Busbars, FCL, Switches…)
  – Cryogenics
Electric Power Source Efficiencies

http://www.ibiblio.org/hyperwar/NHC/CRS/propulsion.htm

Li-Battery and SMES?
Aviation Jet-Fuel Costs: 2012

- $187 B Worldwide Other
- $54 B U.S. Domestic Commercial
- $5.0 B U.S. Air Force Mobility
- $3.3 B U.S. Air Force Other

Total = $246 B/yr

<table>
<thead>
<tr>
<th>Year</th>
<th>Jet Fuel Cost ($/gal)</th>
<th>U.S. Airline Consumption (Billions gal/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>$2.24</td>
<td>17.3</td>
</tr>
<tr>
<td>2011</td>
<td>$2.82</td>
<td>17.6</td>
</tr>
<tr>
<td>2012</td>
<td>$3.05</td>
<td>17.9 &lt;sup&gt;est&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

http://www.military.com/features/0,15240,177545,00.html
http://www.indexmundi.com/commodities/?commodity=jet-fuel&months=12
Hybrid-Electric Vehicle (EV) Aircraft
“Similar to General Motors' Chevy Volt drive train, the DA36 E-Star uses a serial hybrid electric drive train…”

“Siemens scientists of the global research department Corporate Technology are currently working on a new electric motor that is expected to be five times lighter than conventional drives. In two years, another aircraft is expected to be equipped with an ultra-light electric drive.”

http://www.siemens.com/
### 3.2 MW Hybrid-Electric Aircraft (Chevy Volt Style, 500 km Range)

**de Havilland DHC-8-100**

Pratt-Whitney PW121, 1.603 MW continuous
- Mass = 425 kg
- Power density = 3.77 kW/kg

**3.2 MW Chevy-Volt-Style Power System**

<table>
<thead>
<tr>
<th></th>
<th>DHC-8-100B</th>
<th>Hybrid Cu-Wire*</th>
<th>Hybrid Cryo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Engines</td>
<td>1874 lb (3.2 MW)</td>
<td>1054 lb (1.8 MW)</td>
<td>1054 lb (1.8 MW)</td>
</tr>
<tr>
<td>1.55 MW Electric Motor/Generator</td>
<td>855 lb*</td>
<td>86 lb</td>
<td></td>
</tr>
<tr>
<td>3.2 MW Elec-Motor</td>
<td>1645 lb*</td>
<td>165 lb</td>
<td></td>
</tr>
<tr>
<td>Cooling</td>
<td>Cryo 3x lighter</td>
<td>58 lb N₂-liq/hr</td>
<td></td>
</tr>
<tr>
<td>Machine Weight</td>
<td>1874 lb</td>
<td>3554 lb</td>
<td>1363 lb</td>
</tr>
<tr>
<td>Fuel Mix Max.</td>
<td>6039 lb gas</td>
<td>1990 lb gas 2369 lb battery</td>
<td>1990 lb gas 4560 lb battery</td>
</tr>
<tr>
<td>Machine+Fuel Max.</td>
<td>7913 lb</td>
<td>7913 lb</td>
<td>7913 lb</td>
</tr>
<tr>
<td>Range @ CruiseAvg 70% Power</td>
<td>944 miles gas</td>
<td>311 miles ** elec</td>
<td>311 miles ** gas</td>
</tr>
<tr>
<td>Fuel Cost @ Cruise (per 1000 miles*passenger)</td>
<td>$59.6</td>
<td>$20.6</td>
<td>$18.7</td>
</tr>
</tbody>
</table>

* Assume power density = 4 kW/kg
** Energy density = 400 Wh/kg, Cu-wire efficiency = 90%, HTS efficiency = 99%
### Boeing B777-200LR
Two Turbofans GE90-115B

<table>
<thead>
<tr>
<th></th>
<th>B777-L200LR Turbine-Engine (lb)</th>
<th>N3-X Hybrid-Electric (HEDP) with Cryogenic Power (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empty Wt</td>
<td>340,800</td>
<td>267,400</td>
</tr>
<tr>
<td>Payload Wt</td>
<td>118,100</td>
<td>118,100</td>
</tr>
<tr>
<td>Block Fuel Wt</td>
<td>279,800</td>
<td>88,000</td>
</tr>
<tr>
<td>TOGW</td>
<td>768,700</td>
<td>473,500</td>
</tr>
</tbody>
</table>

N3-X
H. Kim, NASA-Glenn, ASM 2011_0222

- The ‘cold’ fan discharge enables much simpler thrust vectoring for S&C.
- Partially embedded (w/ high eBPR) distributed fans present LO characteristics.
- Core engine/generator could be embedded within the airframe for survivability.
- One–fan-inoperative (OFI) has minimal impact to overall thrust.
- OEI is not detrimental to mission success.

### N3-X Benefit ~ Fuel Reduction

- High-Lift Body: 35%
- Maximize Fan By-Pass Ratio: 8-10%
- Reduce Drag: 18-20%
- Other System: 7%
- Total: 72%

J. Felder et al, NASA-Glenn, ISABE_2011_1340

http://en.wikipedia.org/

45 MW Hybrid-Electric Distributed Propulsion (HEDP): NASA N3-X

Reduces fuel from 279,800 lbs to 88,000 lbs

45 MW Electrical Propulsion System – 1st order estimate

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Cu Wire or PM @ 293K</th>
<th>Partial-Superconductor (state-of-art)</th>
<th>All-Superconductor or Cryogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor/Generator Power Density (kW/kg)</td>
<td>3 - 7</td>
<td>6 – 9</td>
<td>40 - 65</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>85 %</td>
<td>96 %</td>
<td>99 %</td>
</tr>
<tr>
<td>Heat Loss</td>
<td>6.8 MW</td>
<td>1.8 MW</td>
<td>0.45 MW</td>
</tr>
<tr>
<td>Mass</td>
<td>154 klb</td>
<td>33.2 klb</td>
<td>11 klb</td>
</tr>
<tr>
<td>TRL Level - Airborne</td>
<td>9</td>
<td>6</td>
<td>1 - 6</td>
</tr>
</tbody>
</table>

Erases gains from HEDP drag reduction

Higher than payload = 118 klb!

GOTCHA: Cryogenics enabling technology for HEDP

J. Felder et al, NASA-Glenn, ISABE_2011_1340
Electric Vehicle (EV) Aircraft
40 kW Electric-Aircraft
YUNeecc Int. e430, 2 Passenger

- flight-time 1.5–3 hr
- 48 MJ Li-Polymer battery pack @ 83.5 kg (~160 Wh/kg)
- “reliability and maintenance like nothing ever seen before”!

Source: http://yuneecouk.site.securepod.com/Aircraft.html

**Impacts:**
- **Maintenance:** only a few moving parts
- **Maintenance Cost:** virtually zero
- **Noise:** ultra-quiet
- **Other:** vertical lift, distributed propulsion, low cooling drag, remote charging, other

<table>
<thead>
<tr>
<th>Specifications</th>
<th>All-Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive-Train Efficiency</td>
<td>~ 85-90 %</td>
</tr>
<tr>
<td>Motor Density</td>
<td>2.1 kW/kg</td>
</tr>
<tr>
<td>Energy Source</td>
<td>Li-Polymer</td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$3.37 / 121.2MJ (U.S.Gal equiv) @ $0.10 / kWh</td>
</tr>
<tr>
<td>Fuel Burn*</td>
<td>32 MJ/hr</td>
</tr>
<tr>
<td>Fuel Weight*</td>
<td>~ 123 lbs/hr (Li-Polymer)</td>
</tr>
<tr>
<td>Fuel Cost*</td>
<td>$0.9/hr</td>
</tr>
</tbody>
</table>

* Estimate cruise ~ 22% of full power and 90% energy efficiency = 10.4 kW avg use.
145 kW Electric Aircraft
Pipestrel G4 Taurus

Battery Energy Burn = 129 MJ/hr  (1.07Gal/hr)
Fuel Efficiency = 100.9 miles-per-gallon-equivalent (MPG_e)!
   = 403.5 passenger MPG equivalent (PMPG_e)!
~ 4x higher per passenger than Boeing 787 Dreamliner
Fuel Cost = $3.4/hr (!)

NASA $1.35M Winner Green Flight Challenge
Largest prize in aviation history
“I think we’re sort of in the dawn of electric flight..”

Battery Type: Li-Polymer, (Non-insurable fire hazard)

<table>
<thead>
<tr>
<th></th>
<th>Pipestrel G4 Taurus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>4 passenger</td>
</tr>
<tr>
<td>Empty Weight</td>
<td>1250 lbs</td>
</tr>
<tr>
<td>Typical Payload</td>
<td>950 lbs</td>
</tr>
<tr>
<td>Max. Weight</td>
<td>3300 lbs</td>
</tr>
<tr>
<td>Range</td>
<td>&gt; 215 miles</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>107.4 mph</td>
</tr>
<tr>
<td>Electric Motor</td>
<td>145 kW</td>
</tr>
<tr>
<td>Motor Efficiency</td>
<td>95-96%</td>
</tr>
<tr>
<td>Battery Size</td>
<td>&gt; 270 MJ</td>
</tr>
<tr>
<td>Battery Weight</td>
<td>1100 lbs (~ 150 Wh/kg)</td>
</tr>
</tbody>
</table>

http://cafefoundation.org/v2/main_home.php
http://www.wired.com/autopia/2011/08/pipistrel-taurus-g4-electric/, other...
- “VoltAir’s two next-generation lithium-air batteries would power two highly efficient superconducting motors…which would in turn dive two coaxial, counter-rotating shrouded propellers…
- The necessary cooling of these engines to reach superconducting temperature can be realised with low-cost and environmentally friendly liquid nitrogen.”

http://evworld.com/news.cfm?newsid=25993
Tesla Roadster Electric Vehicle (EV)  0.215 MW

Drivetrain Efficiencies

<table>
<thead>
<tr>
<th></th>
<th>Efficiencies (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Battery Pack</td>
<td>97-98 %</td>
</tr>
<tr>
<td>Electric Power Control</td>
<td>97-98 % (peak)</td>
</tr>
<tr>
<td>Electric Motor</td>
<td>93 % est</td>
</tr>
<tr>
<td><strong>Total Drivetrain+Fuel</strong></td>
<td><strong>88 % (from Tesla)</strong></td>
</tr>
</tbody>
</table>

Electric Power Control (replace transmission) 90 lbs

Electric Motor 215 kW 115 lbs

Li Battery Pack 202 MJ 990 lbs

www.teslamotors.com
# Boeing 787-9 EV (Concept)

45 MW 290-Passenger

## Boeing 787-9 Dreamliner

### GEnx-1B64 Engine

45 MW Tesla-Roadster-Style Power System

<table>
<thead>
<tr>
<th></th>
<th>787-9 Combustion</th>
<th>787-9 EV EV Cu-Wire</th>
<th>787-9 EV Cryo**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Weight (total 2 ea)</td>
<td>28,538 lb (GEnx)</td>
<td>24,197 lb*</td>
<td>2,420 lb</td>
</tr>
<tr>
<td>Electric Power Controller</td>
<td></td>
<td>18,937 lb</td>
<td>1,894 lb</td>
</tr>
<tr>
<td>Cable + Current-Leads</td>
<td></td>
<td>57,825 lb</td>
<td>1,337 lb</td>
</tr>
<tr>
<td><strong>Machine Weight</strong></td>
<td>28,538 lb</td>
<td>100,959 lb</td>
<td>5,651 lb</td>
</tr>
<tr>
<td>Fuel/Energy Weight Max.</td>
<td>247,693 lb</td>
<td>193,457 lb</td>
<td>270,581 lb</td>
</tr>
<tr>
<td><strong>Machine+Fuel Max.</strong></td>
<td>276,231 lb</td>
<td>276,231 lb</td>
<td>276,231 lb</td>
</tr>
<tr>
<td>Battery/SMES Size (Max.)</td>
<td></td>
<td>114 GJ*</td>
<td>177 GJ**</td>
</tr>
<tr>
<td>Drivetrain Efficiency</td>
<td>35%</td>
<td>90%</td>
<td>99+ %</td>
</tr>
<tr>
<td>Range @ Avg. Power</td>
<td>9780 miles</td>
<td>599 miles</td>
<td>1015 miles</td>
</tr>
</tbody>
</table>

* - Power Density = 4.1 kW/kg  
  - Li-battery = 400 Wh/kg

**J. Felder et al, NASA-Glenn, ISABE_2011_1340

** Cryo Range elec 70% longer

Cryo 20x lighter

MW-Class Power System Components
DC Co-axial Power Transmission Cable: 2.3 MW @ 76K (~20 MW @ 20K)

For 270 V Aircraft Power

<table>
<thead>
<tr>
<th></th>
<th>76K Ic(A)</th>
<th>76K @ 270V P (MW)</th>
<th>55K @ 270V P(MW)</th>
<th>20K @ 270V P(MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC single-phase</td>
<td>7,561</td>
<td>2.04</td>
<td>~ 6</td>
<td>~ 18 !</td>
</tr>
<tr>
<td>DC Co-Axial Two-phase</td>
<td>8,324</td>
<td>2.25</td>
<td>~ 6.7</td>
<td>~ 20 !</td>
</tr>
<tr>
<td>Specific Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(MW/kg*m)</td>
<td>4.7</td>
<td>14.1</td>
<td>42.3</td>
<td></td>
</tr>
</tbody>
</table>

GOTCHA: Cable Mass = 0.97 lb/m !

## 20 MW Power Transmission Cables

### Y-Ba-Cu-O Cable @ 20K
- Weight = 0.97 lb/m

### Cu-Wire MCM 750 Gauge Cable @ 60° C
- Weight = 1,429 lb/m

### Y-Ba-Cu-O Cable
- **Weight**: 0.97 lb/m
- **Heat Loss**: 7,000 W/m
- **Cryo-cooler**
  - Cools 30-m @ 77K
  - Weight = 0.23 lb/m

### Cu-Wire MCM 750 Gauge Cable
- **Weight**: 1,429 lb/m
- **X-sect Area**: 5.0 cm²

### Improvement Factors

<table>
<thead>
<tr>
<th>Cables</th>
<th>Weight</th>
<th>Heat Loss</th>
<th>X-sect Area</th>
<th>Improve Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/0 Cu-Wire @ 60°C (x322)</td>
<td>1,585 lbs/m</td>
<td>~ 3 lbs/m</td>
<td>1170 cm²</td>
<td>530x</td>
</tr>
<tr>
<td>Y-Ba-Cu-O Cable @ 20K</td>
<td>~ 3 lbs/m</td>
<td>3.8 W/m (cryo-cool+liquid N₂)</td>
<td>5.0 cm²</td>
<td>1,840x</td>
</tr>
<tr>
<td>Cryoflex Tubing</td>
<td>Heat Loss @ 20-77K ~ 0.5 W/m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryo-cooler</td>
<td>Cools 30-m @ 77K</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Heat Loss
- **Cryoflex Tubing**: ~ 0.5 W/m
- **Cryo-cooler**: ~ 3.8 W/m (cryo-cool+liquid N₂)

### Weight
- **Cryoflex Tubing**: 1 lb/m
- **Cryo-cooler**: 0.23 lb/m
Li Batteries reach 400 Wh/kg!

- Limited to 500 cycles
- Efficiency (charging?) ~ 75%
- Ref: Motor Trend p. 34, June 2012

http://enviasystems.com
SMES – Virial Theorem Limit

• Virial Theorem

\[ \varepsilon = \frac{E}{m} = \frac{\sigma_{\text{max}}}{3600 \cdot Q_{\text{max}} \cdot \rho_{\text{str}}} \]

– Volume, I, H integrated out

\[ \varepsilon = \text{Energy Density (Wh/kg)} \]
\[ \rho = \text{density structure (kg/m}^3\text{)} \]
\[ \sigma_{\text{max}} = \text{maximum stress (MPa)} \]
\[ Q_{\text{max}} = \text{structure factor} \]

- 0.5 Toroid
- 1.0 Optimized Solenoid
- 1-2 Solenoid
- \( > 2 \) Toroid field coils

(SI units)

Possible Near Future with MgB\(_2\) Composite !?

Energy Density (Wh/kg)

Maximum Stress (GPa)

X. Wang, Mat. Res. Lett, iFirst 1-7 (2012)
Summary

• 1-50 MW Hybrid-Electric or All-Electric Propulsion Aircraft
  – Cryogenic/Superconducting Power Systems critical enabling technology?
  – Many pieces tested and ‘ultra-safe’ designs expected

• Potential Huge Impact $100B-$200B per year!

• Energy Storage Devices
  – $\varepsilon = 400 – 1000$ Wh/kg critical for future developments
  – For SMES, $\varepsilon = 500 – 1000$ Wh/kg possible from Virial Theorem !?
3.2 MW Electric Aircraft: de Havilland Bombadier Dash 8

### de Havilland Canada Bombadier Dash 8: DHC-8-100 series

<table>
<thead>
<tr>
<th>Capacity</th>
<th>DHC-8-100B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Payload</td>
<td>37-39 passengers</td>
</tr>
<tr>
<td>Range</td>
<td>7511 lbs</td>
</tr>
<tr>
<td>Motors</td>
<td>1174 miles</td>
</tr>
<tr>
<td>Motor Weight</td>
<td>2 PW121</td>
</tr>
<tr>
<td>Max. Fuel Size</td>
<td>1874 lbs</td>
</tr>
<tr>
<td>Max. Fuel Weight</td>
<td>1003 U.S. gal</td>
</tr>
<tr>
<td>Maximum Weight</td>
<td>6039 lbs</td>
</tr>
<tr>
<td>Power density</td>
<td>36661 lbs</td>
</tr>
</tbody>
</table>

**Pratt-Whitney PW110, 1.4 MW continuous**
- PW121 Mass = 425 kg = 937 lbs
- Power = 1.603 MW continuous
- Power density = 3.77 kW/kg

[http://en.wikipedia.org/wiki/Pratt_%26_Whitney_Canada_PW100](http://en.wikipedia.org/wiki/Pratt_%26_Whitney_Canada_PW100)
Ion Tiger UAV – U.S. Navy

- Aircraft = 37 lbs
- Payload = 6 lbs
- Power = 550 W
- Loft Duration = 48 hrs current record
  - (3 days planned)
- Fuel Cell PEM – Liquid H₂
  - 2500 Wh/kg
  - ~ 50% efficiency (~4x higher than gas)
  - 2.5 lbs (0.5 kW/kg)

Liquid H₂ = 3.3 lbs
Dewar ≤ 4.8 lbs
Volume = 5.5 gallons
Total = 8.1 lbs
Liquid H₂ εeff = 14,300 Wh/kg

Figure 1. Liquid hydrogen flight dewar for Ion Tiger. (left) schematic of cross section of conceptual dewar, (right) prototype aluminum dewar with the fueling interface.