Portable Power Systems

advanced energy technologies to power human autonomy

Derek Dunn-Rankin
Mechanical and Aerospace Engineering

University of California, Irvine

UC Riverside, November 24, 2004
A Typical Situation

“More oddities are in the pipeline, including a prototype combat uniform that would give soldiers Superman-style eyesight and jumping ability. The bulletproof suit would also include wrist-mounted weapons fired by voice command and battery-powered T-shirts containing miniature heaters and air-conditioners. Sensors would monitor the soldier’s vital signs, warning him if he gets dehydrated or needs to load up on food.

Some of these gizmos already exist; others await advances in nanotechnology, a budding field in which atoms and molecules are altered to give a material new properties. For instance, clothing fibers could be engineered to sense their surroundings and change colors to blend in. And eyesight could be enhanced by implanting microscopic night-vision devices in human eyes.

The ability to jump over walls in a single bound might come from energy-storing shoes, according to a March press release from the Massachusetts Institute of Technology, which is working on military nanotechnology with Natick, DuPont and Raytheon.”

What supplies the power?

3 kW burst

a few W

10-100 W

From, “The Army’s Mad Lab”
Los Angeles Times, August 25, 2002
New power sources are needed to energize autonomous technologies.
Power Scales

- 10000 W – riding lawnmower ~ elephant
- 1000 W – microwave oven ~ horse
- 100 W – light bulb ~ human
- 10 W – small laptop ~ bat
- 1 W – cell phone ~ hummingbird
- 10 mW – pager ~ blowfly
- 10 µW – pacemaker ~ fruit fly

Portable Power

Images are not to scale
Power and Energy Performance: Current Portable Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Needed (W)</th>
<th>Stored Energy (Whr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pager, pacemaker</td>
<td>&gt; 87,600 hrs</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>micro aircraft</td>
<td>36 sec</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>small personal robot</td>
<td>1 hr</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>artificial heart</td>
<td>6 min</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>cell phone</td>
<td>1 hr</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>4G cell phone</td>
<td>10 hr</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>minimal computer</td>
<td>10 hr</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>wearable</td>
<td>100 hr</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>microclimate</td>
<td>1000 hr</td>
<td>&gt; 1000 hrs</td>
</tr>
<tr>
<td>human endeavor</td>
<td>&gt; 10,000 hrs</td>
<td>&gt; 10,000 hrs</td>
</tr>
</tbody>
</table>

Desired Portable Device Performance

MEMS Power

- pager
- pacemaker: > 87,600 hrs (10 years)
Portable Power System Size

• Simple Assumptions
  – 15% fuel/energy conversion efficiency
  – Fuel specific energy equivalent to liquid hydrocarbons (13 kWh/kg)
  – Fuel occupies 66% of system
  – Combustion can generate 100 W/cc chamber volume

• Compact Geometry and Low Mass
  – 60 g -- 6 kg power source weight
  – 0.01 -- 0.10 m system length scale
  – 60 cc -- 6 liter power source volume

• High Power and Energy
  – 10 W -- 1000 W power output
  – 1 hr -- 10 hr operation
  – 600 -- 6000 Whr/kg specific energy

Power performance 10 times current state-of-the-art batteries is possible.
PPS Concept

Powerpellet: 10 W; 100 Whr

Powercell: 100 W; 1000 Whr

Powerpack: 1000 W; 10000 Whr

Portable Power Systems
“power in the palm of your hand”
Current technology fails to deliver sufficient energy and power density in the size needed for autonomy.
Fuel Storage


Graph showing volumetric energy density and gravimetric energy density for different fuel storage systems, including LH2, CGH2, and Chemical Hydrides. The graph also highlights proposed 2015 and 2010 DOE goals for fuel storage density.
Portable Power Systems
Research Thrusts

Fuel Processing and Storage
- Reforming
- Hydrogen

Advanced Energy and Power
- Engines
- Fuel Cells
- Nanowire TE

Power Integration and Control
- Smart Batteries
- Electronics

Energy Dense Fuel Input
- Clean - Emission Control
- Quiet - Noise Suppression
- Cool - Thermal Management
Fuel Cells

- Rapid refueling
- Low temperature
- Direct conversion to electricity
- High theoretical efficiency

![Diagram of fuel cell components]

- Typical fuel cell efficiency ~50%
- Typical engine efficiency ~25%

![Graph showing the maximum thermodynamic efficiency versus temperature]

Fuel Cell, liquid product
Fuel Cell, steam product
Carnot Limit

Temperature °C
Max. Thermodynamic Efficiency
Fuel Cell Types

Low temperature PEM has high power density and rapid response potential

Courtesy G.S. Samuelsen
Fuel Cell Operation

Cross section of polymer electrolyte hydrogen fuel cell

Anode

\[ \text{H}_2 \rightarrow 2\text{H} + 2e^- \]

Cathode

\[ \text{O}_2 + 4\text{H}^+ + 4e^- \rightarrow 2\text{H}_2\text{O} \]

Load

Anode Feed, \( \text{H}_2 \)

Cathode Feed, \( \text{O}_2 \)

Gas diffusion backing

Polymer electrolyte

Catalyst support

Catalyst

Courtesy F. Prinz
PEM Membrane Electrode Assembly

Three phase zone
- membrane
- catalyst
- gas

Hydrated H⁺ ions move freely as hydronium molecule H₃O⁺

Nafion by DuPont

PTFE

Sulphonation

Sulfonated PTFE Nafion

C₂F₄-O⁻ C₂F₄-SO₃⁻ H⁺
Miniature Combustion Systems

- Volumetric heat release from liquid fuel will be necessary for highest power/mass ratios.
- Combustion is extremely fuel tolerant.
- Challenges include high surface-to-volume ratios (thermal issues, flame quenching, short residence times).
- Two miniature combustion approaches:
  - Fuel film combustors
  - Miniature IC engines
Liquid-fuel Combustion in Small Volumes

Short Residence Time – fast vaporization and mixing are required
- large liquid surface area should be exposed to hot gases
- rapid transport of heat & mass in gas near liquid surface

Efficiency & Quenching Protection
- minimize wall area / volume exposed to hot gases

*Use wall film to maximize surface area and to minimize heat losses*
*Use swirlers and vortex generators to maximize transport rates*
Film Combustor Configuration

Flame

Liquid Film

Streamlines

Swirling Air

Liquid Film

Recirculation Caused by Strong Swirl
Design Estimates

- Liquid / gas density ratios are $O(10^2$ to $10^3\)$ as chamber pressure varies between 1 to 10 atmospheres.
- Air / fuel mass ratios will be $O(10)$; e.g., stoichiometric ratios are 6.435 for CH$_3$OH and 14.71 for C$_n$H$_{2n}$.
- Air / liquid volumetric-flow-rate ratio will be $O(10^3$ to $10^4\)$. 
- If air velocity is $O(1$ to 10 m/sec) and chamber diameter is 5 to 10 mm, then air-volume flow rate is $O(10^{-5}$ to $10^{-3}$ m$^3$/sec) and the liquid-volume flow rate is $O(10^{-9}$ to $10^{-6}$ m$^3$/sec).
- Fuel mass flow rate will vary between 1 mg/sec and 1 gm/sec so power should vary between 10 watts and 10 kilowatts for engine efficiency of 30%. 

Spray versus Film Combustion

\[
(S/V)_{drop} = \frac{4\pi R^2}{(4\pi R^3 / 3)} = \frac{3}{R}
\]

\[
(S/V)_{film} = \frac{\pi dL}{(\pi dLt)} = \frac{1}{t}
\]

\[
(S/V)_{film} / (S/V)_{drop} \sim \frac{(40 / 3) (\rho_l u_l / \rho_g u_g)}{R / d}
\]

As chamber diameter \(d\) decreases, film combustion gains advantage over droplet combustion in terms of total surface area.

By considering laminar transport rates, the length of the film in the streamwise direction can be determined

\[
L / d \sim 10^{-3} \text{Re}_d
\]
Liquid Surface-to-Volume Ratio: Spray versus Wall Film

Film is superior at low chamber diameter and at lower pressure.

Higher Surface-to-Volume for Liquid Film

Higher Surface-to-Volume for Liquid Droplets

\[
\frac{\rho u_i}{\rho g u_g} = \begin{cases} 
10^2 & \text{for Liquid Droplets} \\
1 & \text{for Liquid Film}
\end{cases}
\]

\[
\frac{d(\text{mm})}{R(\mu \text{m})} = 4 \times 10^{-2} \frac{\rho u_i}{\rho g u_g}
\]
Experimental Apparatus

- 20 mm long
- 10 mm diameter
- Fuel inlets 4.5 cm below exit
- Tangential fuel and air

Diagram:
- Emissions probe
- Thermocouples
- Sapphire window
- Heptane from first syringe pump
- Heptane from second syringe pump
- Air
Fuel and Air Parameters

• Heptane flow rate of 50.7 cc/hr from each syringe pump
• Airflow rates between 6.42 and 11.4 liters/min, which is the range within which the flame is relatively stable
• Mean cold flow velocities ranging from 1.35 to 2.3 m/s
• Overall equivalence ratios between 1.26 and 2.24
• Maximum fuel film thickness between 125 and 140 microns
Flame Behavior: Observations

- 35 mm SLR camera and 1600 speed film
- 7.44 to 10.45 l/min airflow
- Equivalence ratios 1.38 to 1.93
- Reynolds numbers 470 to 660 based on tube diameter, air mass flow rate, and viscosity at 1000 K
- Decreasing plume length
- Rising flame anchor point
CARS Measurements
Temperature Profile

![Temperature Profile Diagram](image-url)

- **Temperature Profile**
- **adiabatic flame temperature**
Heptane: 101 cc/hr

flame modes over 5 seconds
Heptane: 101 cc/hr

| Air flow rate (L/min) | 6.42 | 8.46 | 10.45 | 12.36 | 14.40 | 22.65 |
Twin Wall Design

- Porous gauze layer to hold fuel
- Air inlet
- Fuel inlet
- 2.4 cm diameter
- Swirl air inlet
• Four-stroke, compression ignition with resistively heated platinum catalyst glow plug
• Single cylinder, displacement = 4.89 cc
• Carburetor
• Lubrication, oil premixed into fuel
• Weight, 279 g

O.S. Engine FS-30S
Experimental Setup

- Electric motor dynamometer
- Pressure transducer
- Steady state operation
- Range of loads 8 - 60 mN-m
- Range of speeds 3,500 - 13,500 rpm
Power and Efficiency

**Efficiency,**  \[ \eta_f = \frac{\dot{W}_b}{\dot{m}_f (Y_{\text{methanol}} Q_{\text{LHV,methanol}} + Y_{\text{nitromethane}} Q_{\text{LHV,nitromethane}}) } \]

**Equivalence ratio,**  \[ \phi = \frac{(\dot{m}_{\text{methanol}} + \dot{m}_{\text{nitromethane}}) / \dot{m}_{\text{air}}}{(\dot{m}_{\text{methanol}} + \dot{m}_{\text{nitromethane}}) / \dot{m}_{\text{air,stoich}}} \]

<table>
<thead>
<tr>
<th></th>
<th>Mixture A</th>
<th>Mixture B</th>
<th>Mixture C</th>
</tr>
</thead>
<tbody>
<tr>
<td>% CH\textsubscript{3}OH</td>
<td>79</td>
<td>72</td>
<td>62</td>
</tr>
<tr>
<td>% CH\textsubscript{3}NO\textsubscript{2}</td>
<td>3</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>% castor oil</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>(A/F) stoich</td>
<td>6.11</td>
<td>5.43</td>
<td>4.62</td>
</tr>
<tr>
<td>max power, W</td>
<td>48.0</td>
<td>82.9</td>
<td>48.3</td>
</tr>
<tr>
<td>max efficiency, %</td>
<td>5.58</td>
<td>9.33</td>
<td>5.72</td>
</tr>
</tbody>
</table>

Energy density of a nitromethane-air mixture is greater than that of a methanol-air mixture (6.73 versus 3.51 J/cc).
Turbulence Intensity, $v'_{rms}$

At the time of spark, $v'_{rms} \approx v_p/2$ [2] and $l_0 \approx h/2$

$$v_p = 2LN \frac{\pi}{2} \sin \theta \left[ 1 + \frac{\cos \theta}{(R^* - \sin^2 \theta)^{1/2}} \right]$$

$$\frac{h}{h_{TDC}} = 1 + \frac{1}{2} (r_c - 1) [R^* + 1 - \cos \theta - (R^* - \sin^2 \theta)^{1/2}]$$

$\theta = 30^\circ$ before TDC

$L = 16.4$ mm
$N = 166.7$ rev/s (10,000 rpm)
$R^* = \frac{L_{connecting\ rod}}{r_{crankshaft}} = \frac{l}{a} = 3.5$
$r_c = 7.05$
$h_{TDC} = 2.67$ mm

$v'_{rms} = 2.68$ m/s and $l_0 = 1.73$ mm

Turbulence Reynolds Number

Turbulence Reynolds number based upon the integral scale

\[ Re_{l_0} = \frac{\rho v'_{rms} l_0}{\mu} \]

Viscosity and density of working fluid equal to that of air at \( T_2 = 629 \text{ K} \) and \( P_2 = 12.7 \text{ atm.} \)

\[ \mu = 3.15 \times 10^{-5} \text{ N} \cdot \text{s/m}^2 \]

\[ \rho = 7.11 \text{ kg/m}^3 \]

\[ Re_{l_0} = 1048 \]
Laminar Burning Velocity

- Laminar burning velocity is calculated by the empirical correlation [3]:

\[ S_L = S_{L,0} \left( \frac{T_u}{T_0} \right)^{\alpha} \left( \frac{P_2}{P_0} \right)^{\beta} \]

- \( \alpha, \beta, \) and \( S_{L,0} \) depend on fuel type and equivalence ratio

- \( T_0 = 298 \) K and \( P_0 = 1 \) atm.

- Stoichiometric methanol-air mixture at \( T_u = 629 \) K and \( P_2 = 12.7 \) atm.

\[ S_L = 119 \text{ cm/s} \]

The flame thickness is calculated from Spalding’s 1-D laminar premixed flame approach [4].

\[ \delta_L = \frac{2\alpha}{S_L} \]

The value of alpha used is that of air at the mean temperature of \( T_m = (T + T_f)/2 = 1414 \text{ K} \), where \( T = 629 \text{ K} \), \( T_f = 2200 \text{ K} \) and \( P = 12.7 \text{ atm} \),

\( \alpha = 0.241 \text{ cm}^2/\text{s} \).

\[ \delta_L = 40.4 \mu\text{m} \]

\[ Da = \frac{\tau_{flow}}{\tau_{chem}} = \left( \frac{l_0}{\delta_L} \right) \left( \frac{S_L}{v'_{rms}} \right) \]

\[ Da = 19.1 \]

Turbulence in the Centimeter Scale

• The values of $Da = 19.1$ and $Re_{lo} = 1048$ are consistent with those typical of full size IC engines.

• This engine lies on the boundary between the wrinkled laminar flame and the flamelets-in-eddies regimes.

• No turbulence effect of scaling down to the centimeter scale.

Turbulent Burning Velocity

- Wrinkled laminar flame correlation of Klimov [5]

\[
\frac{S_T}{S_L} = 3.15 \left( \frac{v'_{rms}}{S_L} \right)^{0.7}
\]

- \( S_T = 7.37 \text{ m/s} \)
- Residence time

\[
\tau_r = \frac{r_{piston}}{S_T} = 1.3 \text{ ms}
\]

- Assume flame propagation begins 30 deg before TDC and constant rotational speed of 10,000 rpm.

- Crank angle over which combustion occurs.

- Displacement volume over which combustion occurs.

\[
\Delta \theta = 80^\circ
\]
\[
\Delta V = 0.9 \text{ cc}
\]

Summary

• New portable power sources are critical for advancing autonomous devices
• Miniature combustion will be needed for highest power/weight demands, such as micro air vehicles and mobile robots
• Short residence time and thermal control produce very poor efficiency performance currently
• Taking advantage of film combustion offers a possible solution
• Future and current work includes CFD modeling of the film combustor and new swirl enhancement strategies
• Acknowledgments – Prof. W.A. Sirignano; J. Papac, T. Pham, N. Amade Sarzi, NSF, UC Energy Institute
THANK YOU!
Micro Air Vehicles -- Insects

- 100 mg
- 80-150 W/kg
- 100 W/kg system (incl. fuel weight) power demand
- 10 hour operation takes 1000 Whr/kg
- At given scale transmission power would dominate
- Smallest available camera/transmitter is 4000 mg

R. Fearing – UC Berkeley
Wing Muscle vs. Piezoelectric Actuation

- 80-150 W/kg
- resonance is important
- wing efficiency ~ 80%
- piezoelectric efficiency ~ 90%

<table>
<thead>
<tr>
<th>parameter</th>
<th>blowfly</th>
<th>MFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>actuator</td>
<td>muscle</td>
<td>piezoelectric</td>
</tr>
<tr>
<td>Actuator mass (mg)</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Actuator power (mW)</td>
<td>10</td>
<td>12</td>
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<tr>
<td>Wing power (mW)</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Wing inertia (mg-mm²)</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Quality factor Q</td>
<td>1-3</td>
<td>2</td>
</tr>
<tr>
<td>Resonant frequency (Hz)</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Wing stroke/rotation (degrees)</td>
<td>160/120</td>
<td>120/90</td>
</tr>
<tr>
<td>Wing length (mm)</td>
<td>11</td>
<td>10</td>
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<tr>
<td>Mass (mg)</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
Micro Air Vehicles

- Aerovironment’s Black Widow micro air vehicle
  - 2 km communication range
  - 30 mph flight speed
  - 6 inch wingspan
  - 100 grams
  - 2 gram camera; 2 gram downlink transmitter; 5 gram fully proportional radio control system; 0.5 gram actuators
  - Lithium batteries
  - 30 minute operation

www.aerovironment.com
Artificial Organs

www.abiomed.com
Abiocor artificial heart

www.mc3corp.com
MC³ pulmonary assist device

Hattler catheter – University of Pittsburgh