Protonex™

Fuel Flexible Portable SOFC Generators

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THE NEXT GENERATION OF PORTABLE POWER.™

PROTONEX OVERVIEW

- Leading provider of 100 - 1000 watt fuel cell power solutions
  - *Utilizing advanced PEM and SOFC technologies*
  - *Focused on a broad range of applications under-served by batteries and generators*
- Targeting a set of high-value Commercial and Military markets
  - *Clean, quiet, efficient, and lightweight power solutions*
  - *Offering customers high performance and low cost over time*
- Commercial & government partnerships

  Cummins Parker Raytheon TOTO CBC GROUP

  - *Over $46m* in development contracts to date from U.S. Air Force, Army, Navy, SOCOM, DARPA, DOE, NASA…*
- Publicly traded on the AIM market of the LSE

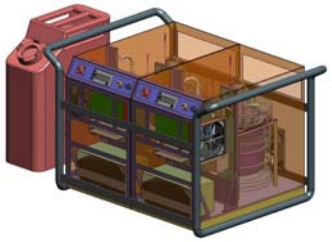
** Contract value including programs awarded to Mesoscopic Devices before acquisition in April 2007*

Current company platforms

M250-B – Battery Tender

- Targeted mainly at recreation and renewable market
- Provides clean quiet power
- Methanol fuel

500/1000 W – APU/Tender



- Targeted mainly at vehicle APU/portable generator
- Provides clean quiet power
- Kerosene or butanol

M250-G – Generator

- Targeted at recreation and emergency responder markets
- Operates indoors or outdoors
- Methanol fuel

P125 – Generator/Tender

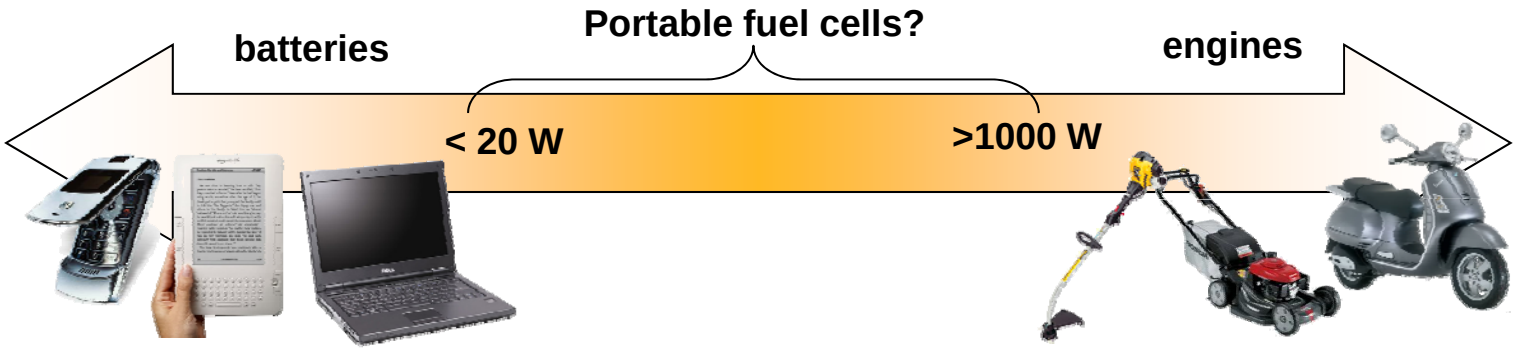
- Targeted at recreation and commercial battery charging market
- Compact and easy to use
- Propane fuel
- Liquid fueled military prototypes in progress

Future products to follow with higher power levels and different fuel types

Why portable fuel cells?

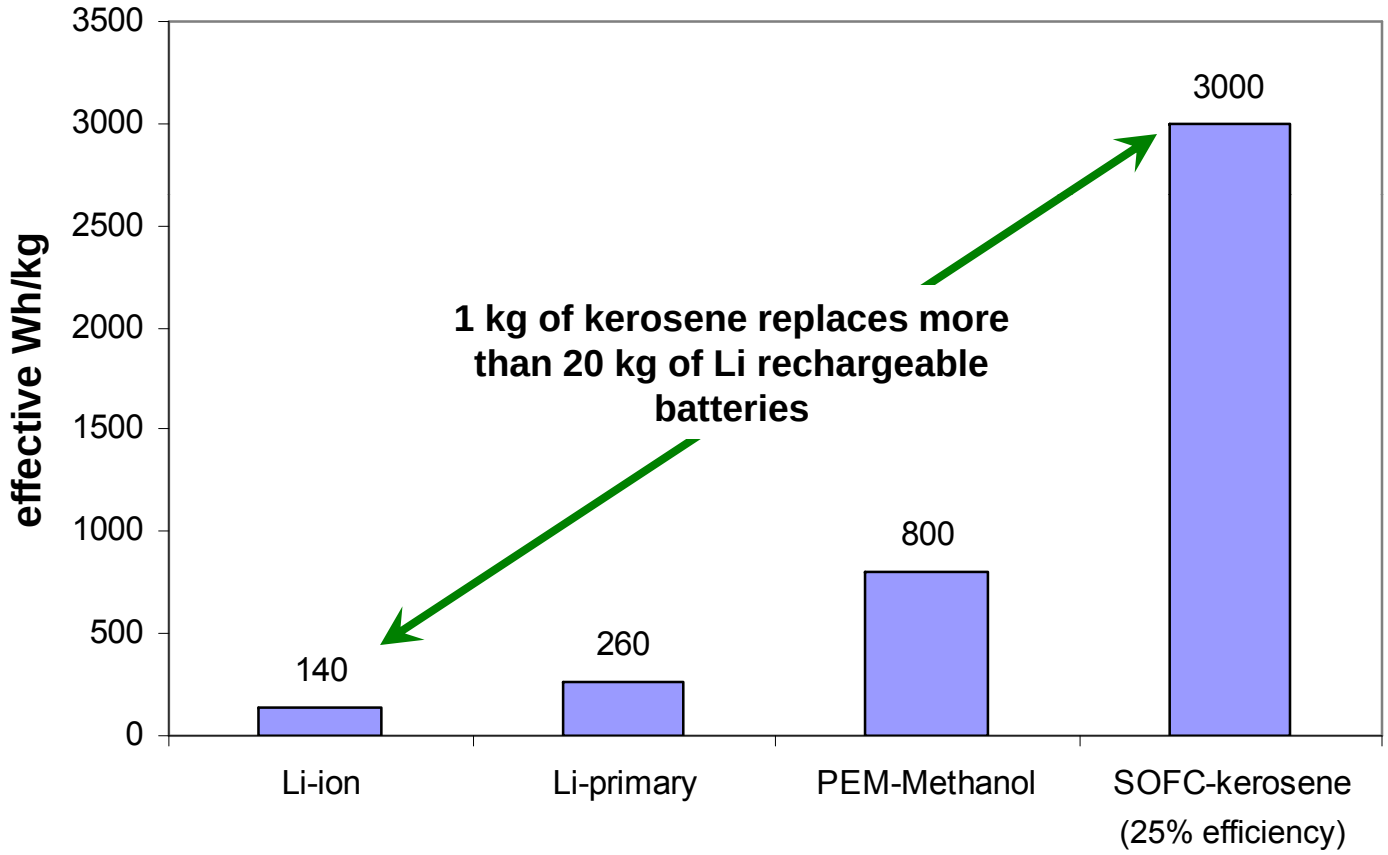
- **Wired-equivalent performance from wireless devices**

- **Performance gap between batteries and small engines in the 50–1000 W, 1000–10 000 Wh range**
  - Batteries are too heavy (many kg)
    - Insufficient run time
  - Engines are too loud, too polluting
    - Particularly a problem for small engines under 1 kW
- **Fuel cells offer 2–10 times the run time for the same weight**

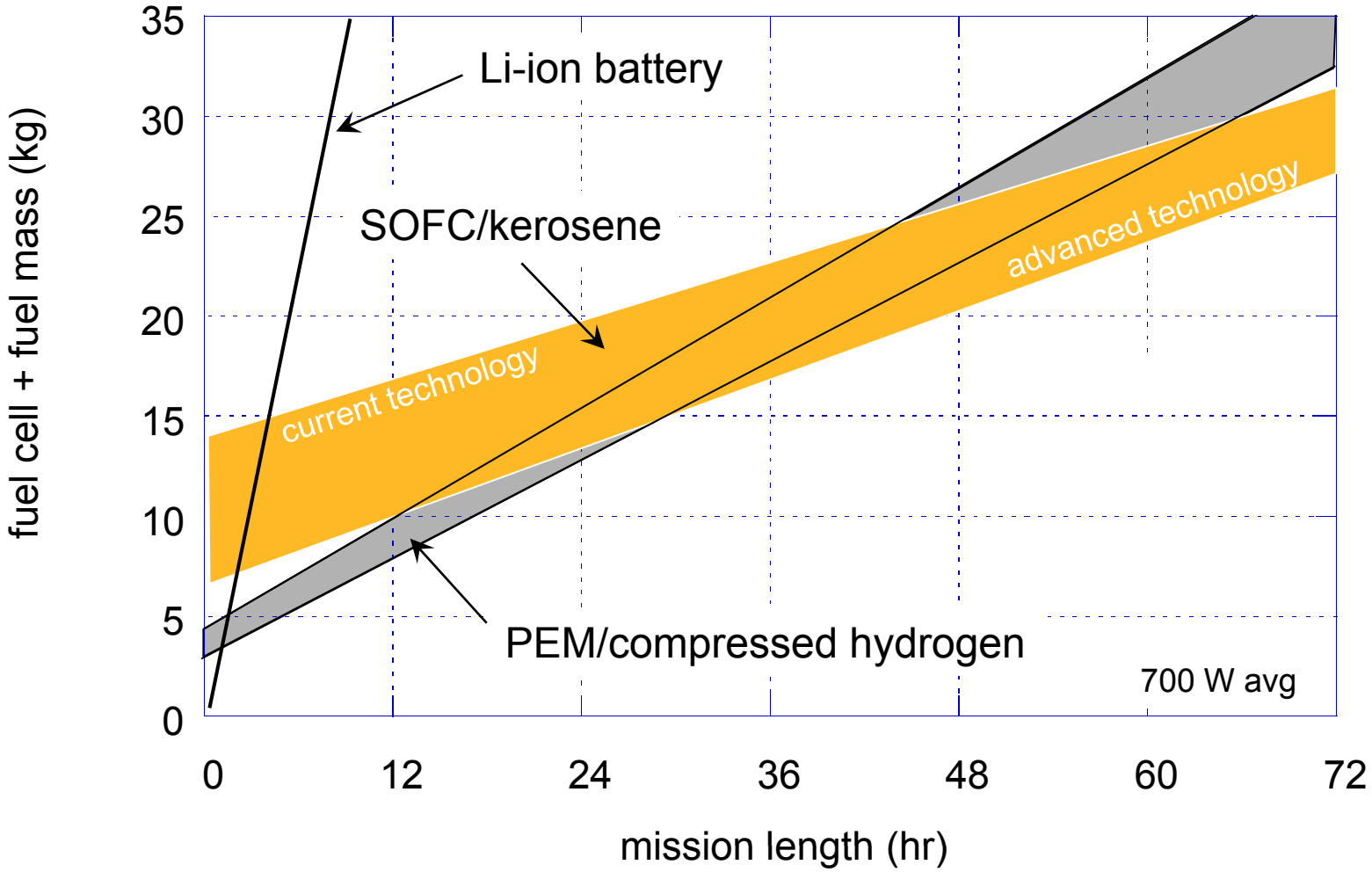


Fuel cells enable long run time portable devices

- **High specific energy available**
  - Much greater than primary or rechargeable lithium batteries

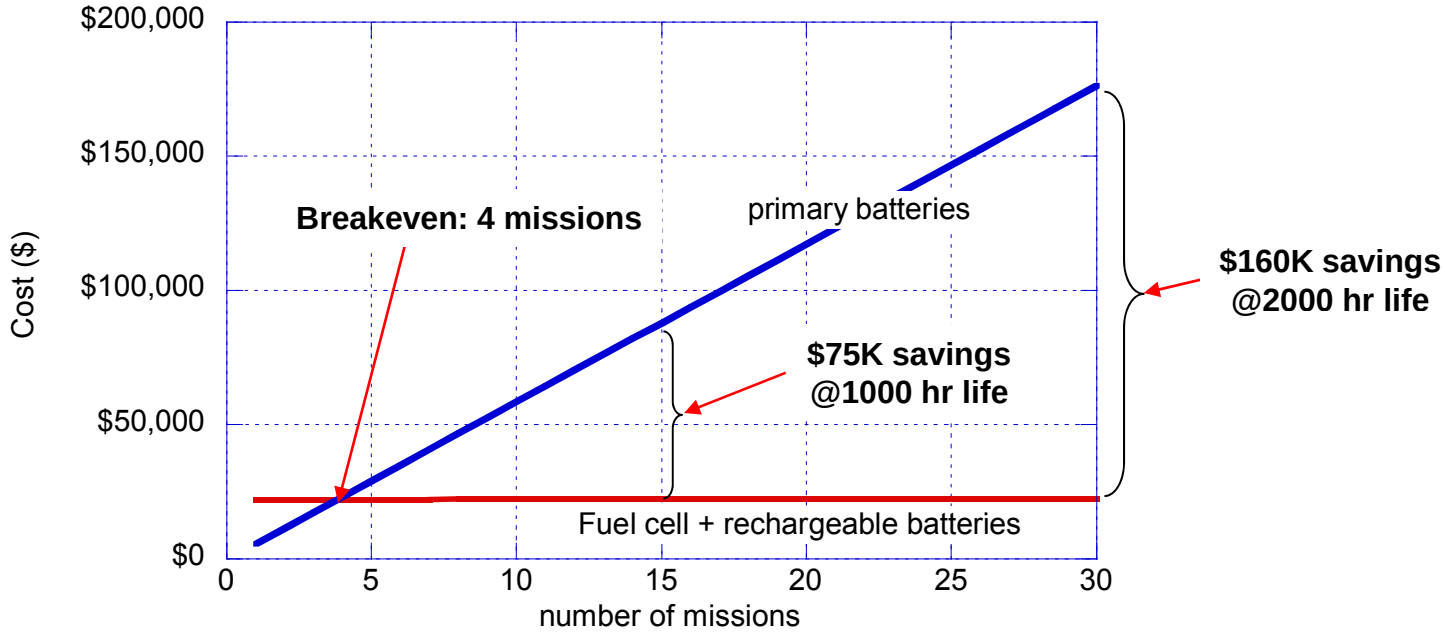


Fuel cell mass vs. time [scaled to 700W average]



Compelling value proposition today

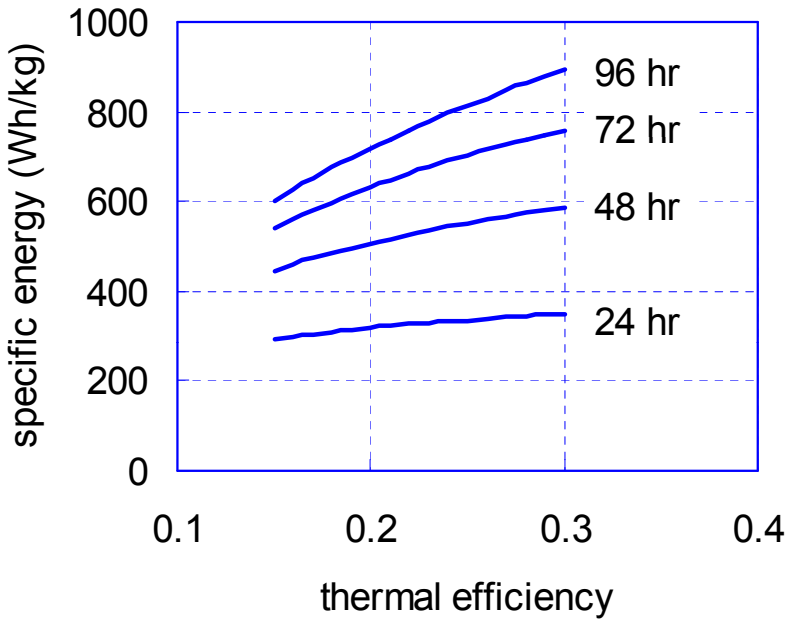
- **Military squad battery charger**
  - Primary batteries: $120/ea
  - Fuel cell battery charger + rechargeable batteries: ~$12,000
  - 72 hour, 120 W total mission, 6 soldiers @ 20 W ea



- **Commercial recreational vehicles**
  - Hybridized battery charge controller
  - >10,000 fuel cell generators already sold (Smart Fuel Cell)

Requirements of portable power applications

- **Efficiency?**
  - Fuel cost is insignificant
  - 100 W 25% efficient system consumes 30 gallons in 3000 hour lifetime
  - Increased efficiency costs weight and complexity



- **Weight – the user must carry the generator and fuel**
  - Specific energy (generator + fuel)
  - Fuel must include weight of packaging
- **Cost**
- **Noise**

Why liquid fuel?

- **Weight: liquids have lighter packaging**
- **Volume: liquids have higher volumetric energy density**

Container weight (kg)	**0.21**	**4.8**	**0.38**	**8.2**
Fuel weight (kg)	**0.78**	**15**	**0.47**	**9.1**
Container weight fraction	**27%**	**31%**	**83%**	**90%**

	Propane	**Kerosene**
Energy density (Wh/liter)	**6600**	**9500**
		44% less volume

Liquid fuel tradeoffs

✓ **Positive**

- Non-pressurized (safety, temperature range)
- Availability
- Bio-derived fuels
- Any size fuel tank available
- Easily refilled by user even while running
- Easier to sense low fuel

× **Negative**

- Orientation dependence
- Metering and mixing more difficult
- More difficult to reform (maybe lower efficiency)
- More expensive system?

Types of fuels

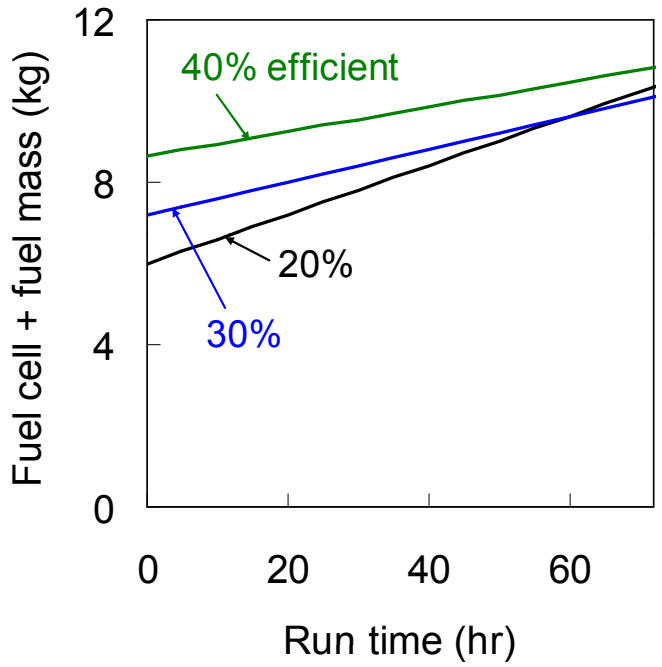
- **Propane**
  - Readily available commercial fuel
  - Easy to meter and reform
- **Kerosene (low sulfur)**
  - Safe
  - Similar to military JP-8
- **Diesel (ULSD)**
  - Common commercial fuel with well controlled sulfur content
  - Challenging to reform
- **Butanol**
  - Biobutanol
  - Oxygenated (impacts fuel processing)

Fuel processing for portable SOFC

	Reformer thermal efficiency	Required equipment	Relative size
Steam reforming w/water recovery	**>100%**	✓ Fuel & water metering - Thermally integrated reformer ✖ Condenser	**Large**
Autothermal reforming	**>80%**	✓ Simple reformer - Fuel, air, water metering ✖ Condenser	**Large**
Anode recycle	**~100%**	? Fuel & recycle metering ? High T pump	**Medium**
CPOX	**~70%**	✓ Fuel & air metering ✓ Reformer	**Small**

Portable SOFC systems design

- **Fuel processing method is a tradeoff between efficiency and weight + complexity + cost**



CPOX catalyst for
125 W SOFC generator

- **What about:**
  - Cost?
  - Startup and shutdown?
  - Ambient conditions (-20 ° C and 60 ° C)?

CPOX fuel processing

- **Reaction stoichiometry**
  - $C_xH_yO_z + \frac{x-z}{2}O_2 \rightarrow xCO + \frac{y}{2}H_2$
  - Ideal O/C ratio = 1
  - Excess air suppresses carbon formation & lowers efficiency
  - Short residence time (<20 ms)
- **Reaction conditions**
  - Selectivity increases with temperature
  - Small reactors are not adiabatic
  - Oxygenated fuels have lower dH_{rxn}
- **Control is critical**
  - Too much air can overheat reformer
  - Too little air can coke system
  - Fuel and air pulsations must be controlled

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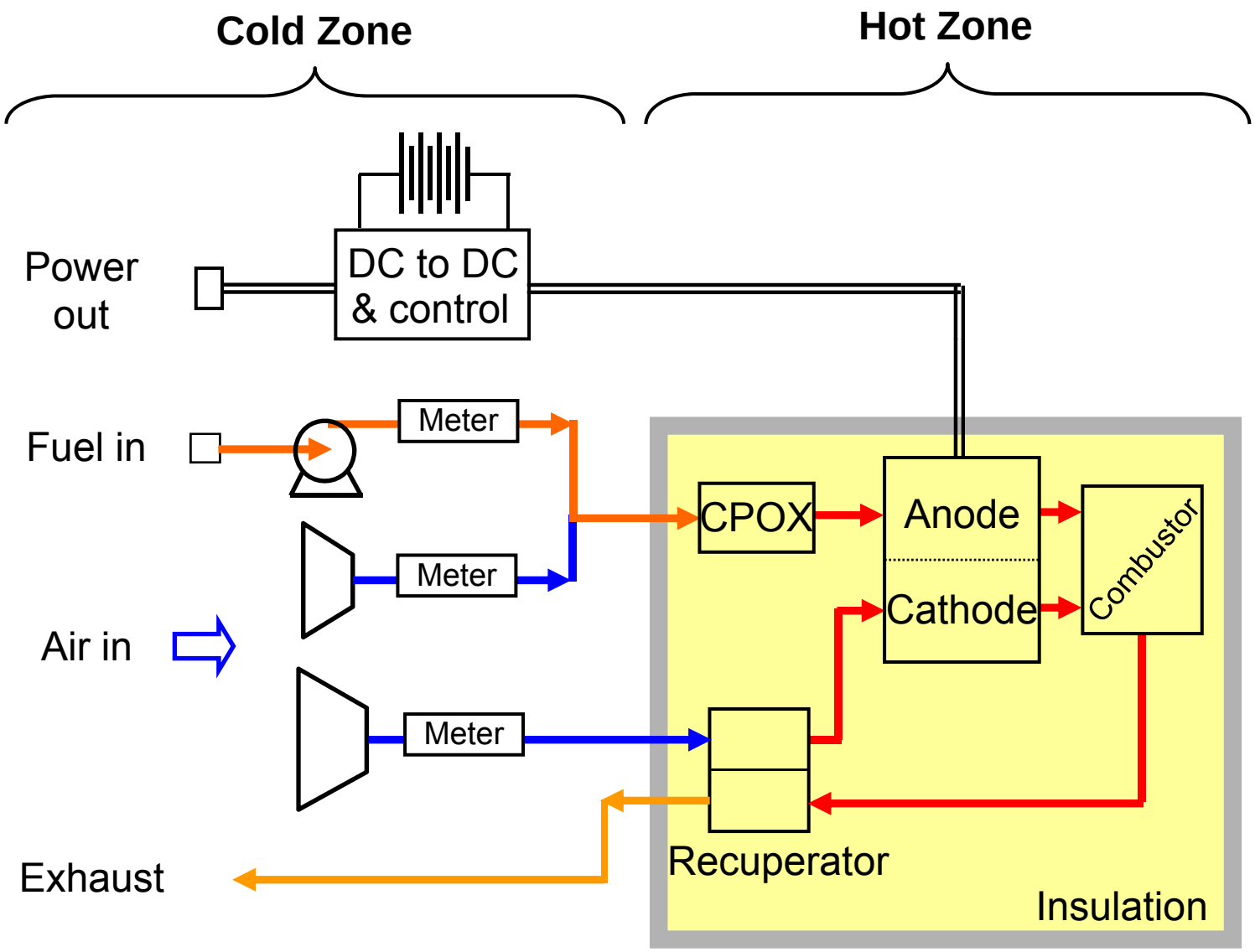
Portable SOFC system

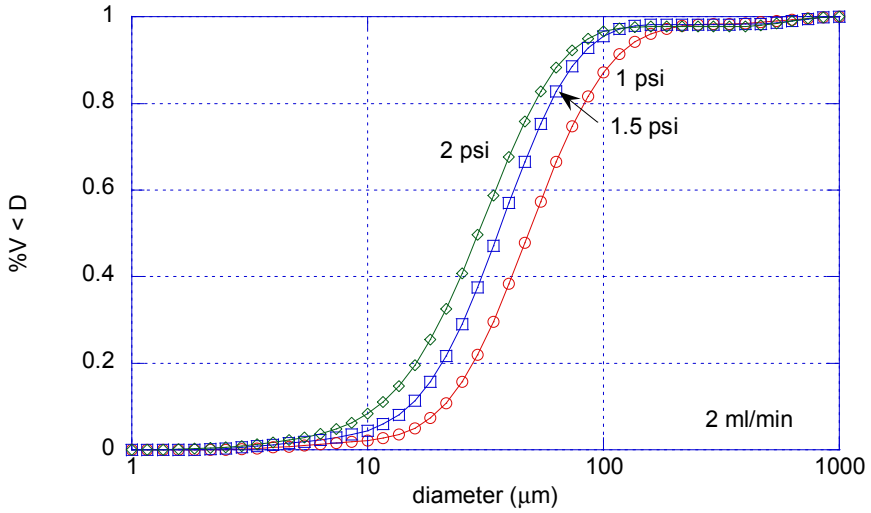


Practical fuel processing challenges

- **Startup**
  - Cold start
  - Low energy requirement
  - Exothermic CPOX lights off in seconds
- **Shutdown**
  - Ni anodes require reducing environment at high T
  - High turndown ratio (10:1)
- **Liquids**
  - Orientation dependence
  - Metering and bubbles
  - Stability over turn down ratio
  - Feeding the reformer: atomization or vaporization

Atomization

- **Advantages**
  - Potentially better lifetime
  - Instant on
- **Challenges**
  - Low pressure drop is required
  - Less than 2 psi
  - Turn down ratio
- Patent-pending ultra-low pressure drop atomizer yields < 20 µm droplets at < 2 psi

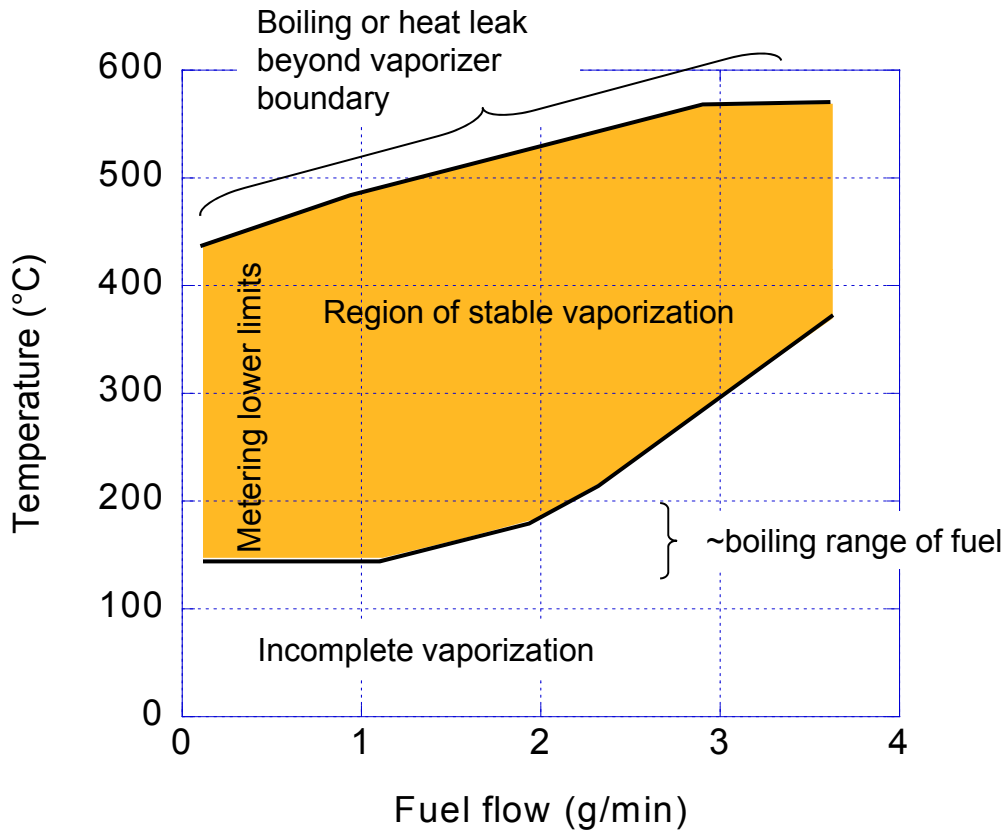


Vaporization

- **Advantages**
  - Low pressure drop
  - High turndown ratio
- **Challenges**
  - Provides steady vapor: avoid boiling, spitting, surging
  - Tolerate residue from incomplete vaporization
  - Cold start capability: include a heater
  - Thermal integration: heat sources range up to 100's ° C
- **Patent-pending vaporizer extends life and operating window**
  - Is stable over range of temperatures
  - No small passages

Vaporizer stability window

- **Patent-pending vaporizer extends operating window and lifetime**

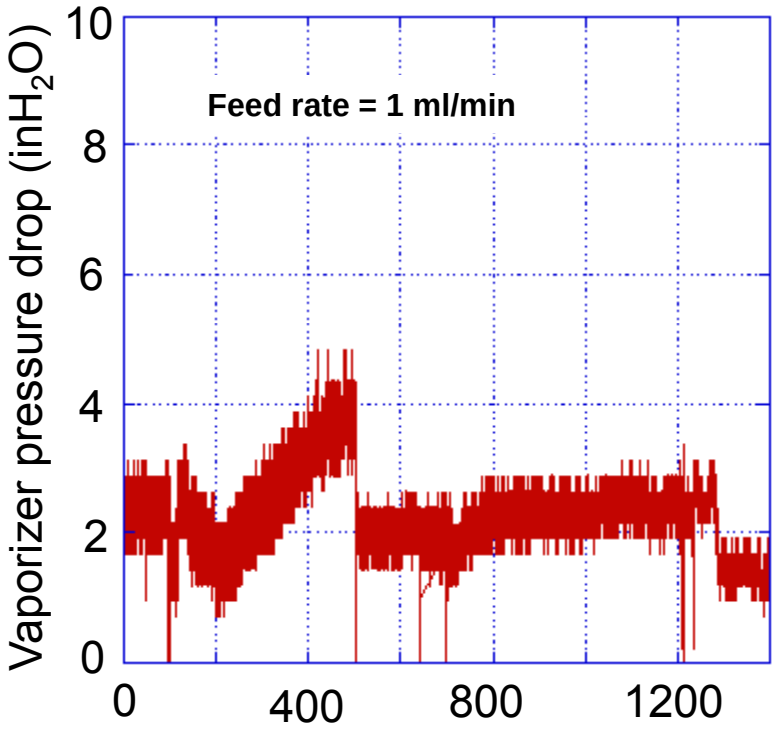


- **Vaporization bounded by practical limits**
- **Stability does not ensure long vaporizer lifetime**

Vaporizer + CPOX lifetime

- **Low sulfur kerosene**
- **Tolerant to deposits**
- **1000 hr between maintenance**

1200 hours = 20 gallons (76 L)



SOFC stack for 100 W system

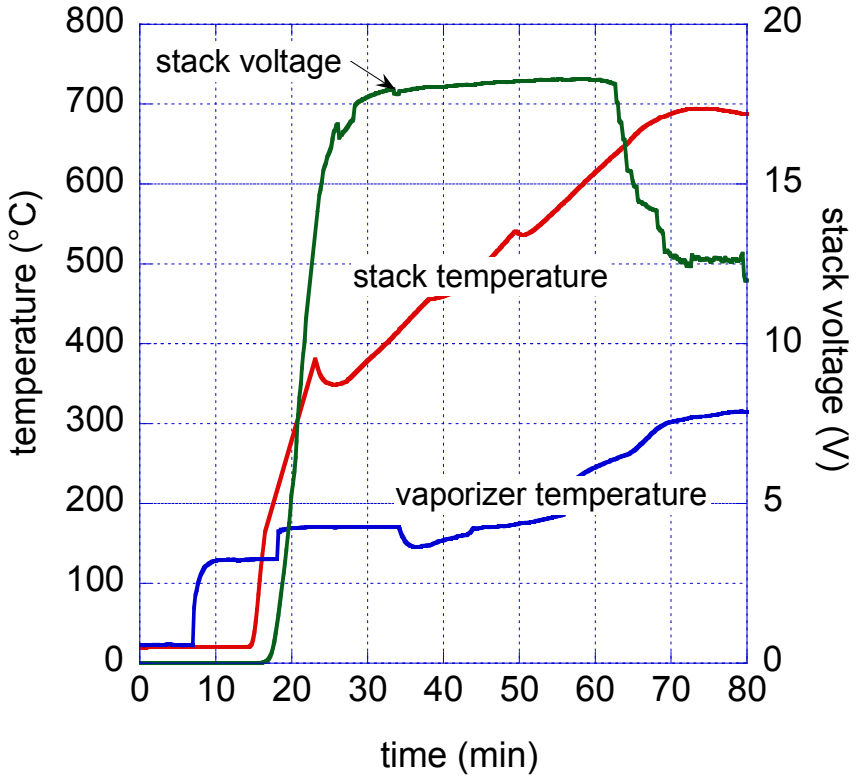
- **Tubular cells**
  - Cycles better than planar stacks
  - High hot zone power density
- **18 cells**
  - 12 V at 0.7 V/cell
- **Thermal regulation**
  - Small SOFC's difficult to keep hot
  - Use inefficiencies to maintain temperature
  - Minimize insulation and exhaust heat losses

Liquid fueled SOFC generator

- **First steps towards JP-8**
- **Low-sulfur kerosene systems in lab testing**
- **State of the art:**
  - 50 W/kg
  - 25% efficient
  - ~1.5 liters per day (125 W)
  - Specific energy >1000 Wh/kg at 72 hours
- **Military prototypes to be delivered in 2010**

Prototype liquid fueled system operation

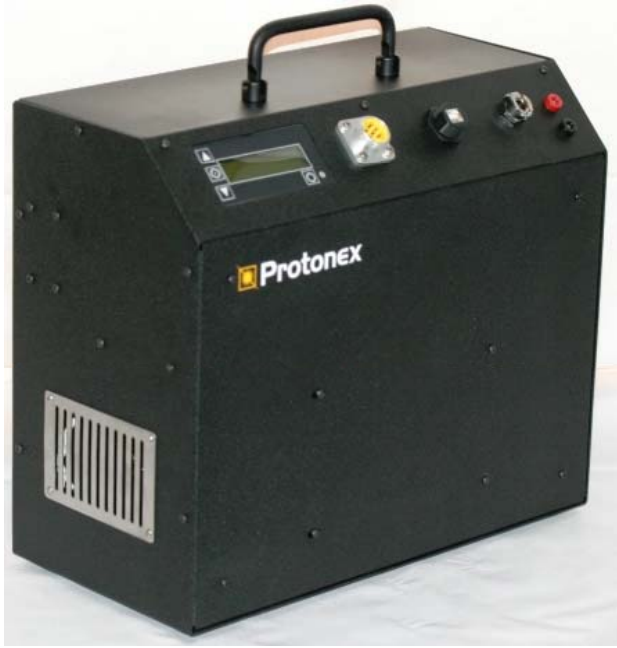
- **Startup**
  - Cold start on battery power
  - 60 min heatup
  - New systems with equivalent startup as propane
- **Power**
  - 100 W net
  - Thermally self sustaining (including vaporizer)



Propane fueled SOFC generator

- **Military units delivered in 2009**

Output	**12 VDC**
Power	**100 W**
Peak power	**200 W**
Dry weight	**6.8 kg**

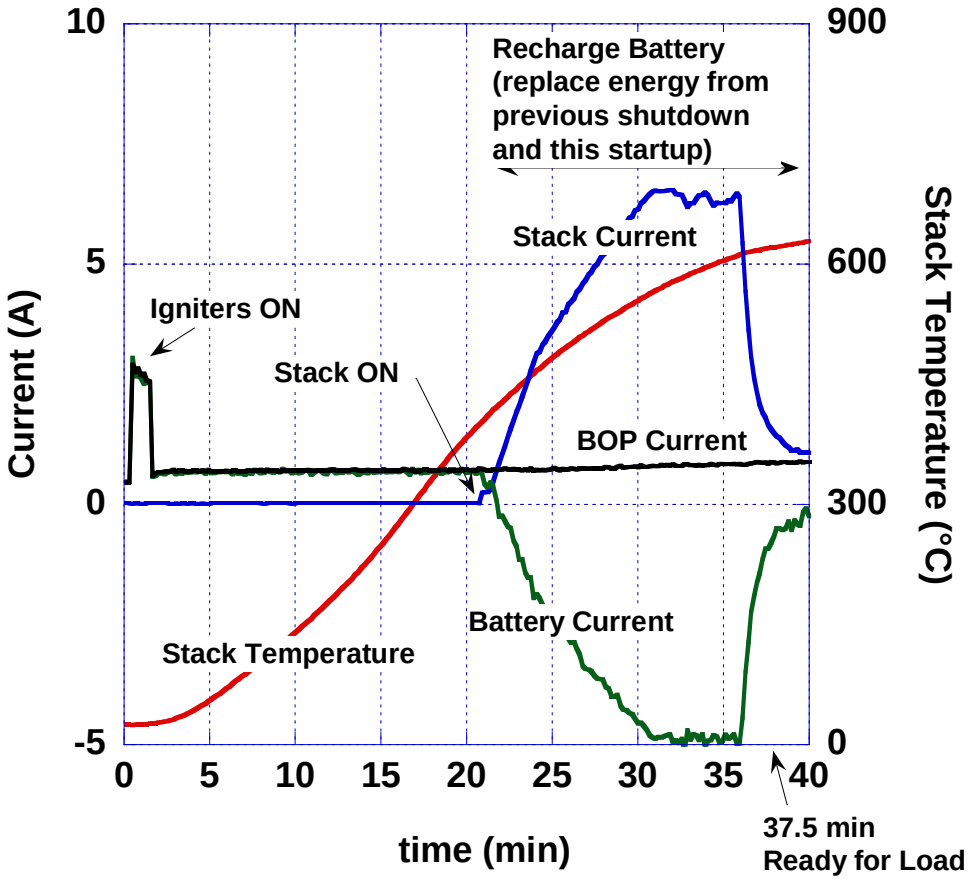


= 10 day run time

= 12 hour run time

Propane system operation

- **Startup**
  - Single button start
  - 38 minutes to full power
- **Instant-on capability**
  - 38 min @ 100 W = 4.4 Ah
  - Increase battery mass by 0.5 kg
- **Run**
  - 100 W net
  - 200 W peak (15 min)
  - Battery management
- **Shutdown**
  - Single button shutdown



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