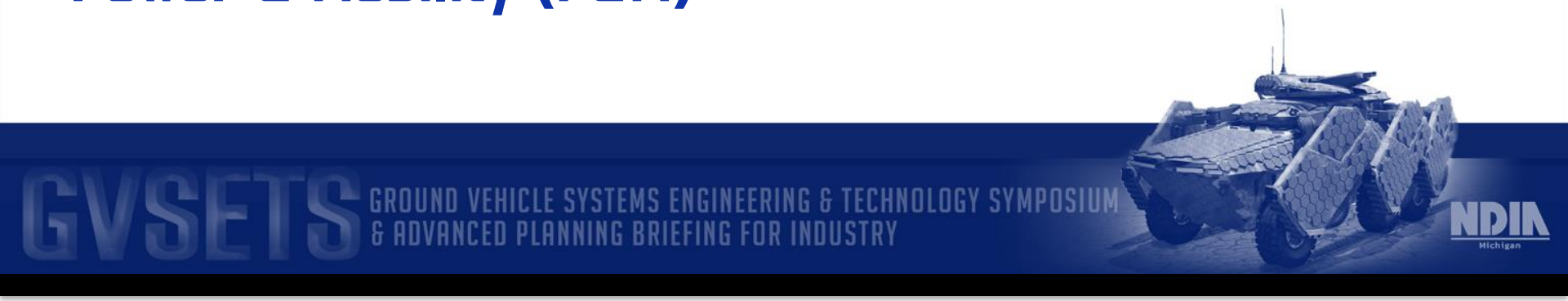
Power & Mobility (P&M)



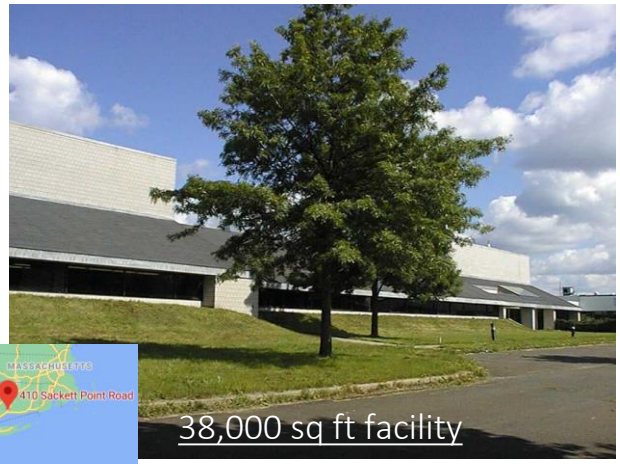
JP-8 Fuel Cell Electric Vehicle

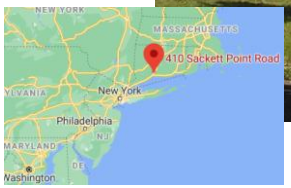
Saurabh A. Vilekar[1], Christian Junaedi[1], Eric Allocco[1], Francesco Macri[1], Kyle Hawley[1], Max Plajer[1], Phil Blaze[1], Tim LaBreche[1], Carlos Martinez Baca[1], Rich Mastanduno[1], **Subir Roychoudhury**[1], Jarrod Hoose[2], Kevin Centeck[2]

[1]Precision Combustion, Inc., North Haven, CT
[2]Ground Vehicle Systems Center, Warren, MI

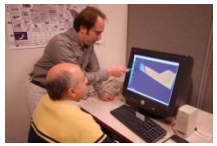
Precision Combustion, Inc.

We create, develop, manufacture, and market sustainable solutions for energy and environmental sectors.





- Located in North Haven, CT
- Privately-held small business; established 1986
- *~50 employees; 11 PhDs*
- Focus on *innovation and product development*
- Core technologies: *Materials, Reactors, Systems*



From Concept to Fielded Prototypes

Extended Range, Silent SMET

DECIF & GVSC investment

- SOFC replaces diesel generator
- Provides 10 kW (electric, steady state) for propulsion, export power
- MIL-SPEC power out (28 V DC, 120 V AC)
- Battery hybridized for peak loads
- Increased range & lower carbon footprint
- Low thermal & acoustic signature (~60 dB @ 1 m.)
- Demonstrated with F-24/JP-8
- Produces clean surplus water
- *Weight, efficiency & start-up time remain to be optimized*

Semi-autonomous, off-road, battery-hybridized electric vehicle demonstrated

Operating Concept

Conventional or Sustainable fuels

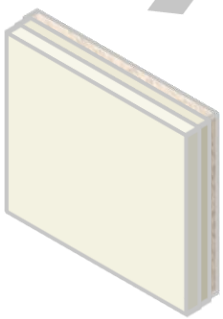
JP-8

Reformer

Air

H_2/CO

CO_2, Water

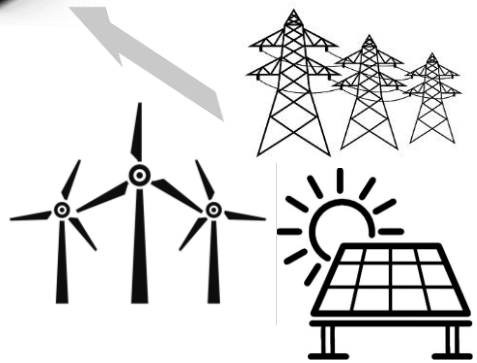


Solid Oxide Fuel Cell

Electricity

Battery

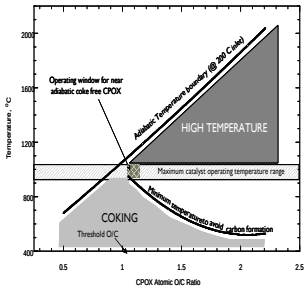
MIL-SPEC Power



Grid/Renewables

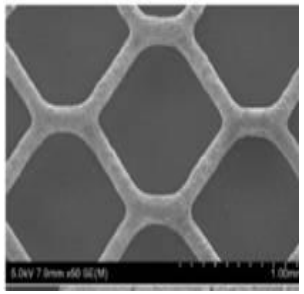
Concept being matured for DoD, Space, & Commercial applications

IP Examples



Novel control algorithms to avoid coking (*PCI Patent #US 8,337,757 B2 & others*)

Low cost, Ultra-compact, efficient H_2 generator (*PCI Patent #US 7,976,594 & others*)

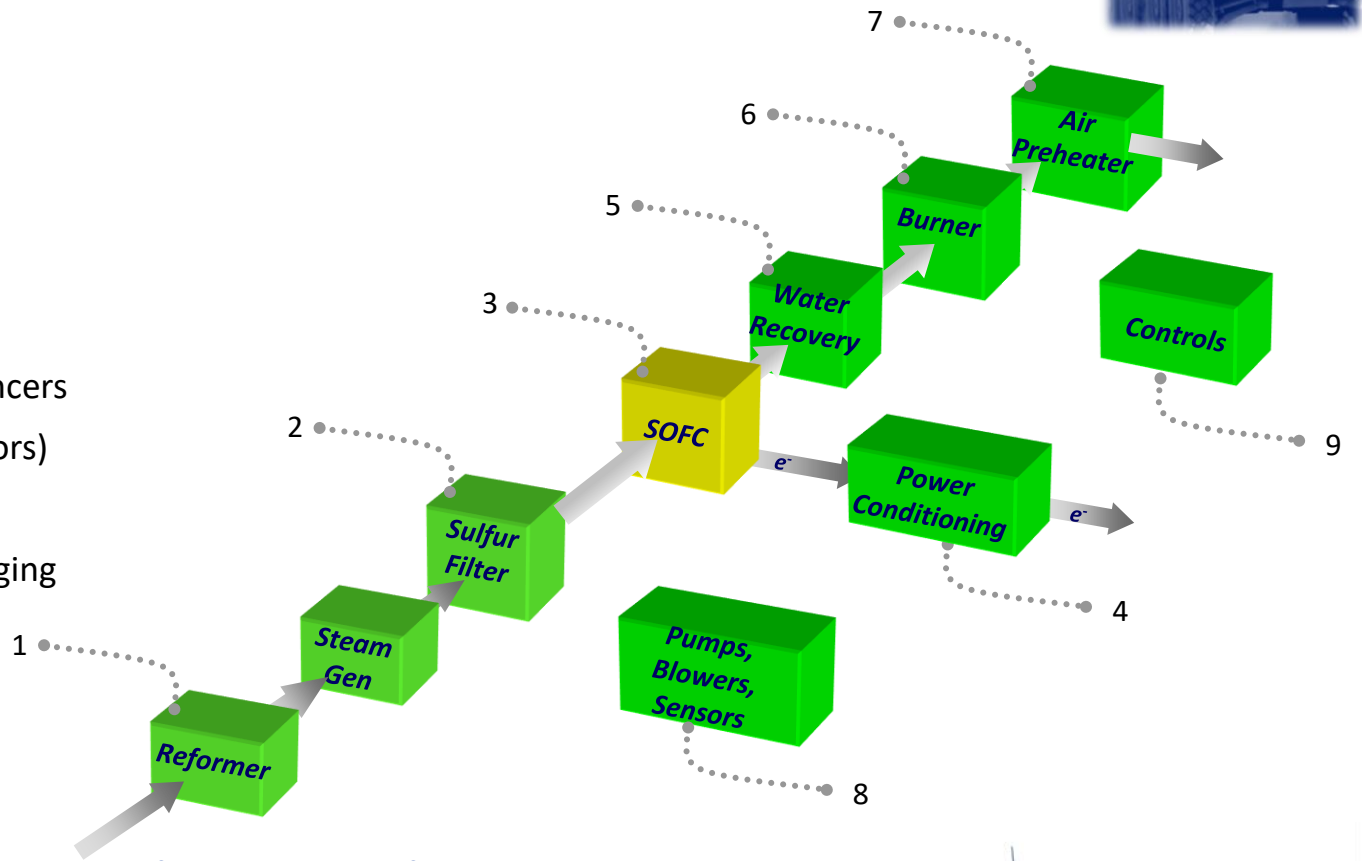


PCI's short contact time Microlith® catalyst (*PCI Patent #US 5,051,241 & others*)

Portfolio of patents on substrate, reactor, and systems

SOFC Generator Approach

1. Reformer
2. Desulfurization
3. SOFC (*from various OEM's*)
4. Power Conditioning
5. Water recovery
6. Start/tail-gas burner
7. Heat exchangers, flow balancers
8. BOP (Pumps, blowers, sensors)
9. Controls
10. System integration & packaging



PCI develops turnkey fuel cell and reformer subcomponents and systems

(1) Reformer + (2) Sulfur Filter

Challenges:

- Reform Jet fuels and diesels w. sulfur
- Remove the sulfur in fuels
- Produce SOFC quality reformate
- In a small, lightweight package

10 kWe F-24/JP-8 Reformer

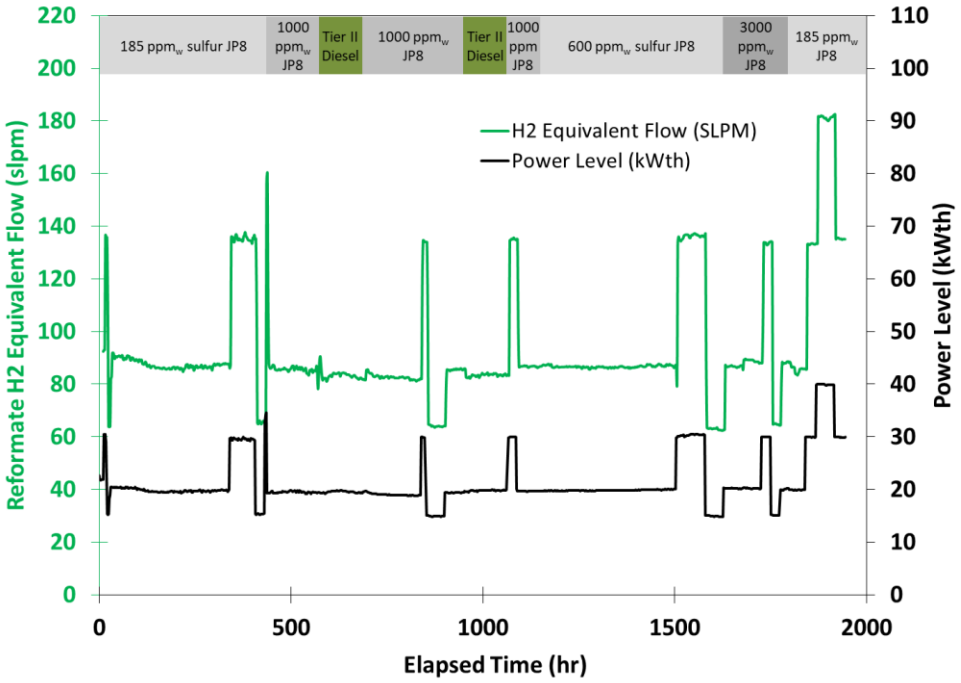
Approach:

- Use PCI's patented catalysts & sorbents
- Use PCI's patented process-intensified reactor design
- Use PCI's patented sulfur removal approach

Sulfur filter

Experimentally Validated & Patented by PCI

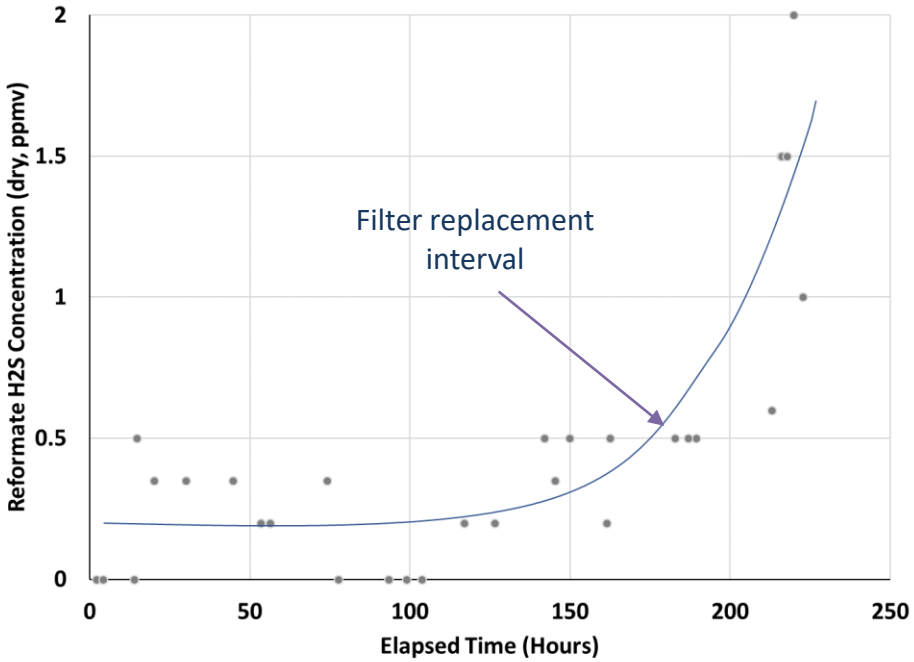
(1) Reformer Performance



- 30+ thermal cycles
- High fuel conversion >99.9%
- Converts fuel-bound sulfur to H_2S
- LHV-based reforming efficiency >80%
- Equilibrium reforming efficiency >95%
- Reformer startup to steady state <15 mins
- Reformer successfully implemented in generators
- Degradation rate of <5% observed over 2000 hours
- 2000-hour test w. Jet fuels (w. 185, 600, & 3000 ppm_w Sulfur) & Tier II Diesel

2000-hour reformer durability with Jet fuels/Diesel demonstrated

(2) Sulfur Filter Performance



Sulfur filter performance w. high bed utilization

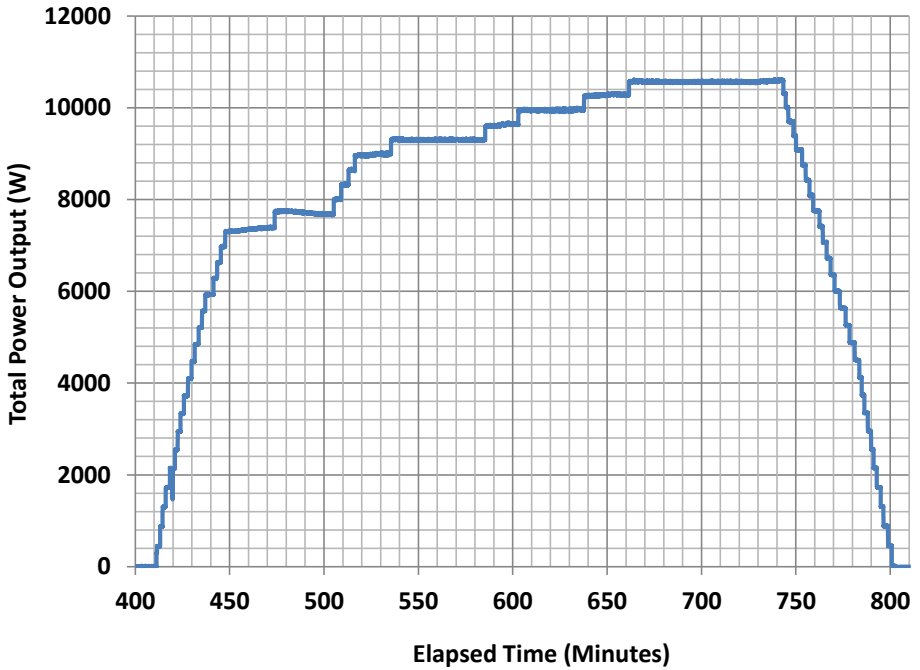
Mesh-supported sorbent (PCI patented design) w. high capacity

Sulfur cleanup to <0.2 – 0.5 ppm_v with high sulfur Jet fuels

Ability to effectively remove sulfur demonstrated

(3) Solid Oxide Fuel Cell (SOFC)

- Robust and durable SOFC sourced from OEMs
- Stack examined for:
  - Repeatability
  - Performance & stability over time
  - Stability over multiple start/stop cycles
  - Low cathode air requirement for lower weight & parasitics
  - Manifolded cathode and anode for simplified integration

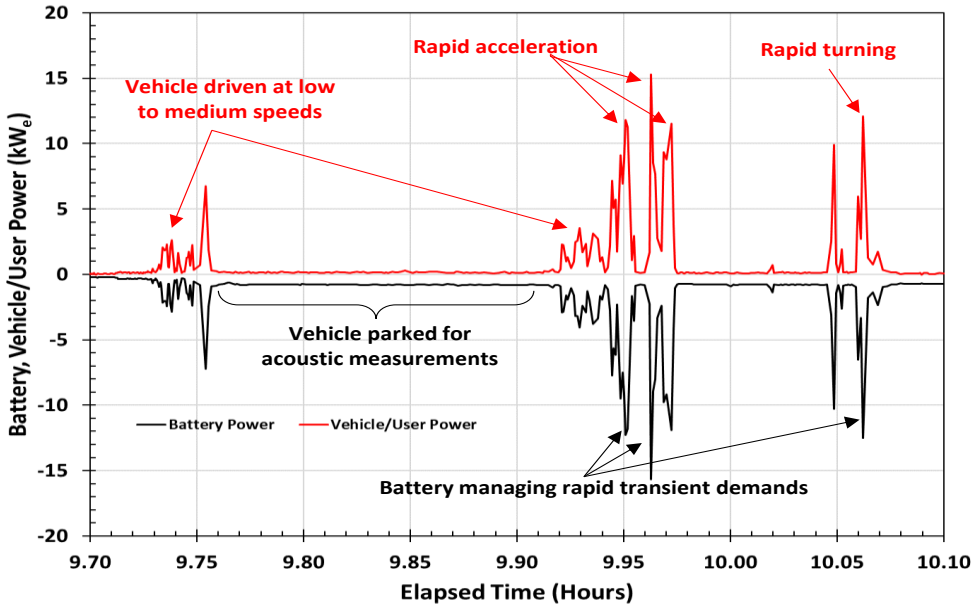


- We work closely w. stack OEMs to implement startup/transient/shutdown protocols

Stable SOFC operation in generator
SOFC related risks significantly mitigated

(4) Power Conditioning

- Challenges:
  - Convert stack voltage to 28 – 32 VDC (nominal)
  - Meet power quality requirements
  - Enable seamless hybridization with COTS batteries
  - Load balancing to allowable SOFC *slew rate*
  - Load shunting capability during down transients
  - Implement SOFC protection protocols w. dynamic loads
  - Minimize power conditioning losses
  - PCB design for compact footprint
  - Battery sizing to meet start, load requirements



- Approach:
  - Designed and fabricated power conditioning system (in-house, with external PCB fabrication)
  - Novel and simplified approach with built in safeties implemented
  - Designed PCB with provisions for individual SM-Bus monitoring (track SOH of each battery)

Power conditioning board designed and experimentally verified; startup/transient/shutdown protocols implemented

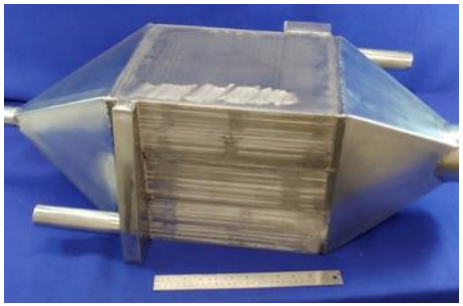
(6) Start/Tail-gas Burner

- Challenges:
  - Reliable start-ups with consistent temperature profile
  - Single lightweight burner for startup (JP-8/F-24) and/or tail gas (H_2 + CO) combustion
  - Integrate burner with heat exchangers to meet ΔP and ΔT requirements for SOFC

Single Burner design developed & implemented

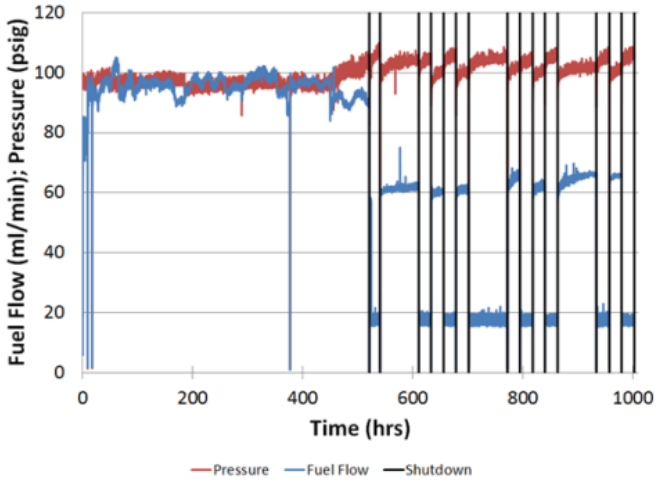
(7) HX: Performance Validation

- Multiple Custom HEXs (including 3D printed) for:
  - Cathode/anode inlet/outlet
  - Reformer inlet
  - Steam generation, etc.
- Performance validated and tested



All HEXs met thermal performance & pressure drop targets

(8) BOP (pumps, blowers, sensors)



- All fuel/air pumps/blowers/sensors rigorously tested over 1000s of hours
- Availability, cost, weight, parasitic power, fuel-compatibility assessed
- Service life estimated based on performance
- Fuel delivery system test example shown

Rigorous performance and durability assessment of pumps, blowers, sensors

(9) Controls: Data Acquisition & Feedback

Challenges :

- Properly and safely operate the SOFC system:
  - All process parameters must be monitored
    - Temperatures, pressures, voltages, and a variety of other sensors to collect system information
    - Each parameter must be properly received and scaled
  - Control signals must be sent to the various BOP components to provide user-flexibility
    - Including pumps, valves, and other electronic relays
- All input and output variables are interrelated via a system of PID control loops
- Over 150 values are logged, graphed in real time, & examined

(10) System Integration & Packaging

- Detailed P&ID of system created
- Detail CAD models created
- Components fabricated, tested, & assembled
- Controls & power conditioning implemented
- Performance tested w. target fuel
- Confirmed water neutrality, sulfur tolerance, power out, etc.
- MIL-SPEC power validated for communication equipment
- Weight, efficiency, start-up time remain to be optimized

Standalone prototype, inclusive of all components.

JP-8 fueled, SOFC + Battery hybridized system for Silent-Mobility, Silent-Watch, Export-Power

Operational Benefits

- Fuel flexibility for increased resilience
  - Use scavenged fuels
  - Batteries can be charged via renewable/grid power
  - Can use future carbon-neutral sustainable-fuels for lower carbon footprint
- High efficiency
  - Reduced average fuel consumption
  - Lower GHG emissions and supports anti-idle technology
- Capability enhancement
  - Tactical vehicles as distributed power generators & microgrid compatible
  - Power other assets (SMETS, UAS, weapons, soldier needs, comms, payloads)
  - Minimal moving parts for long MTBF
  - Avoids compromises endemic with battery-only solutions
  - Provides more on-board electric output & produces clean surplus water
  - Low thermal and acoustic signatures enables full-time silent operation

Advances Climate & Operational Energy Strategy

Next Steps

- Smaller, lighter, more efficient, faster startup, MIL SPEC compliance
- Implement SOFC auxiliary power in Robotic Combat Vehicle
- Meet Key Performance Parameter associated with military systems
- Scale for target applications (mobility, soldier power, UAS)
- Examine microgrid compatibility
- Ongoing work for commercial applications
- Ongoing work for space applications (NASA, others)

Component & system development ongoing for broader utility

Thank You!

These results were made possible through the dedicated efforts of the engineers & technicians at PCI.

We are grateful to the DoD, DoE, and NASA for supporting the development efforts.

sroychoudhury@precision-combustion.com; aanderson@precision-combustion.com

http://www.precision-combustion.com

Twitter: @_PCI Linked In: www.linkedin.com/company/precision-combustion-inc.