Hydrogen on Demand™ Fuel Systems for Military Applications

Military Fuel Cells 2003 Presentation
October 20-21, 2003

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Outline

- Millennium Cell – company overview
- Hydrogen on Demand™ Process
  - Hydrogen storage/generation via sodium borohydride
  - Description of hydrogen generation reaction
  - How the HOD™ system works
- Utility for Military Applications
  - Examples of technology applications and performance
- Summary

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Millennium Cell Company Overview

- We are a development stage, intellectual property company that licenses enabling technologies for the hydrogen economy
  - 20 patents issued to date
  - 35 patent applications submitted to date
- Public offering in August 2000 (NASDAQ: MCEL), currently 40 employees located in Eatontown, NJ
  - 27 in Product Development organization, including 10 Ph.D.s
- Announced commercial relationships with market leaders:

DaimlerChrysler
Rohm and Haas
Borax
Ballard®
PSA Peugeot Citroën
Air Products
Duffy Electric Boat Company
Samsung
U.S. Department of Energy
Energy Efficiency and Renewable Energy

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Hydrogen Generation from Sodium Borohydride (SBH)

Hydrogen on Demand™ Process

$$NaBH_4\,(aq) + 2\,H_2O \xrightarrow[cat]{} 4\,H_2 + NaBO_2\,(aq) + heat$$

An energy-dense water-based fuel (e.g., 30 wt% $NaBH_4$ holds 6.7 wt% H_2)	Proprietary catalyst induces rapid H_2 production	Pure humidified H_2 delivered to engine or fuel cell	Borate can be recycled into $NaBH_4$	Exothermic reaction requires no heat input

- Hydrogen is generated in a controllable, heat-releasing reaction
- Fuel is a room-temperature, non-flammable liquid under no pressure
- Hydrogen generated via the HOD™ process is of high purity (no carbon monoxide or sulfur) and is humidified (heat generates some water vapor)
- U.S. Patent 6,534,033: "System for Hydrogen Generation"

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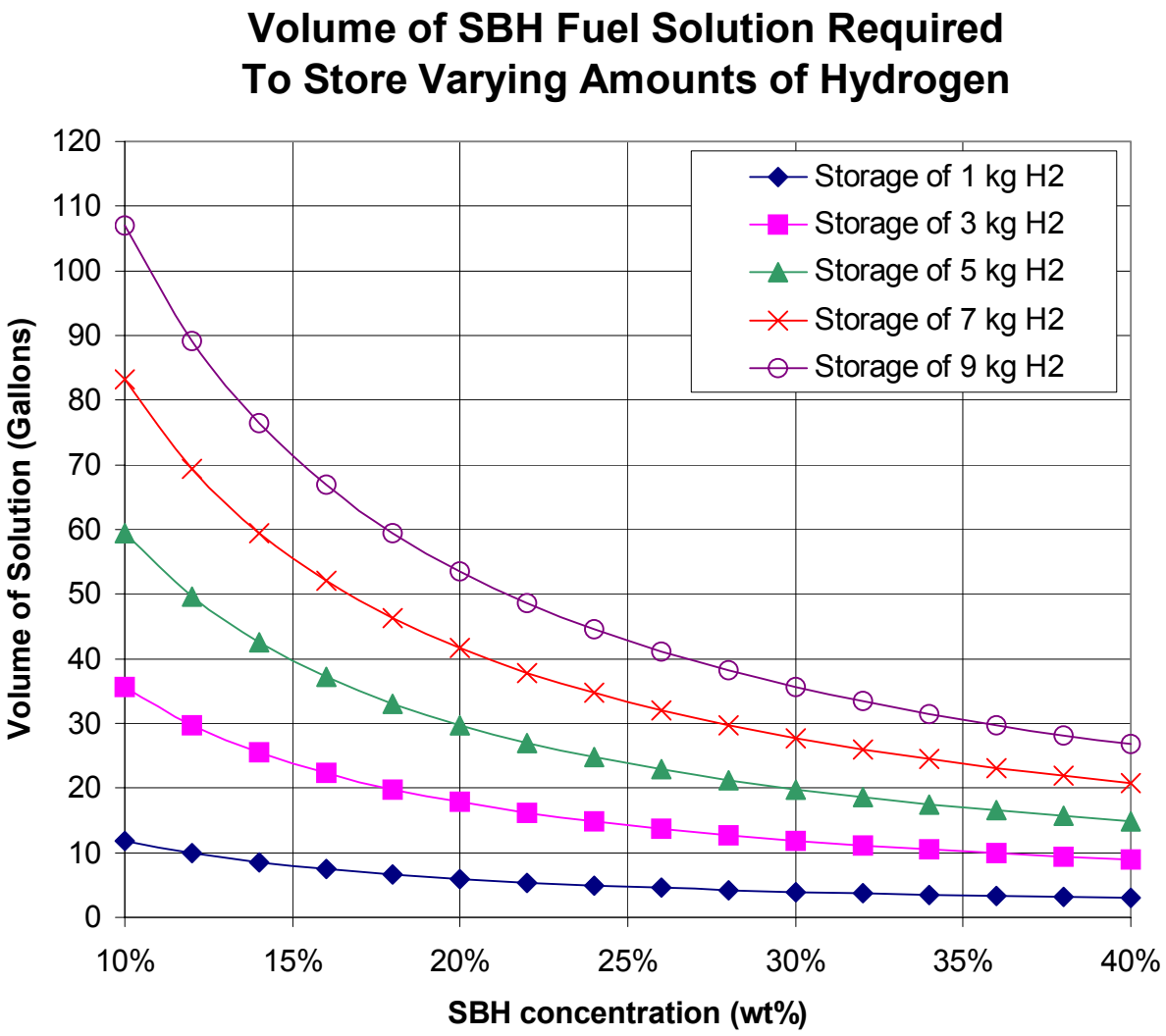
Volumetric Storage Efficiency



Volumetric storage:

30 wt% fuel = ~63 g H_2/L

For comparison:

Liquid H_2 = ~71 g H_2/L

5000 psi = ~23 g H_2/L

10000 psi = ~39 g H_2/L

For a practical system, balance of plant (both volumetrically and gravimetrically) is key to energy density

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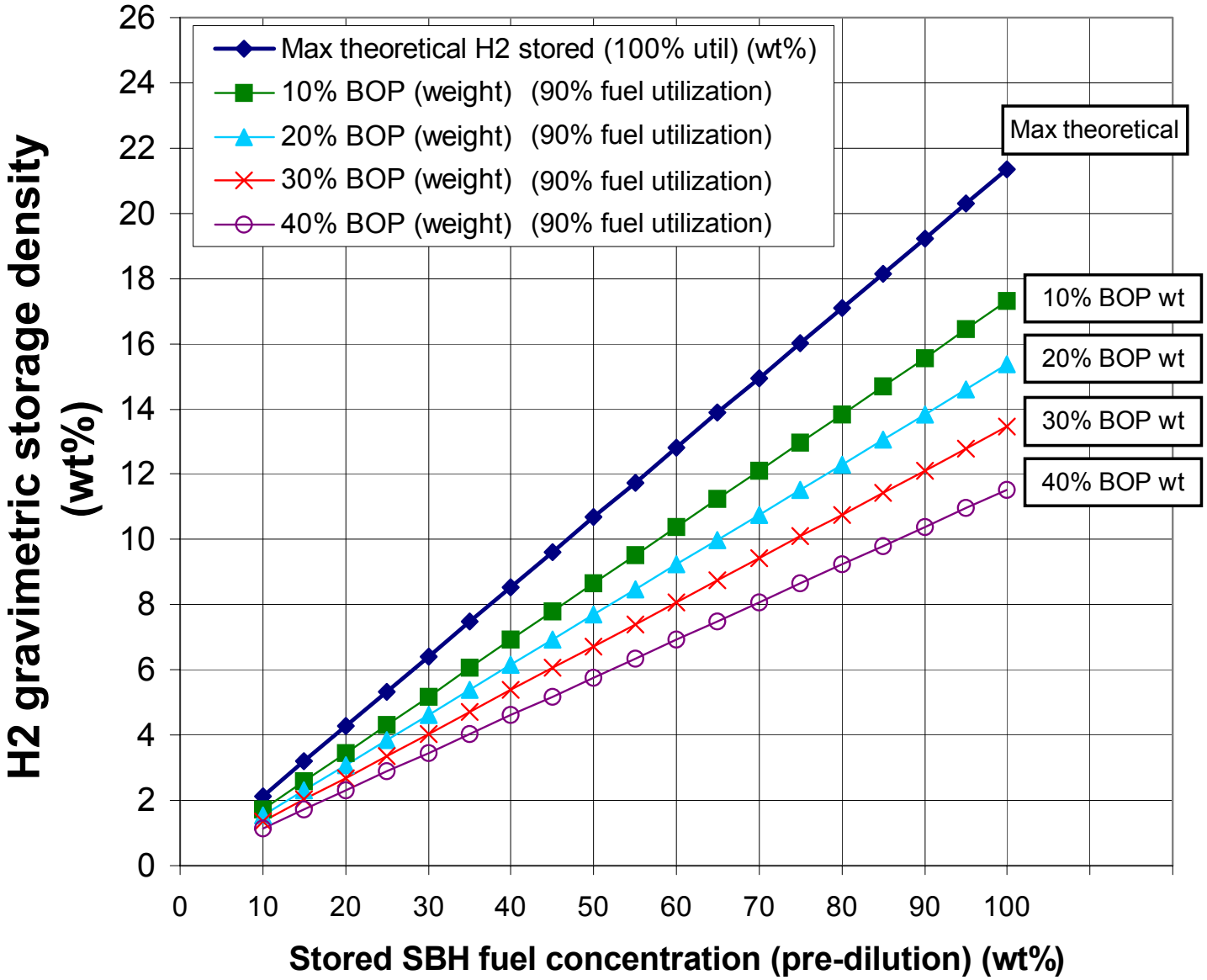
Gravimetric Storage Efficiency of SBH

Fuel Cell Water Integration



SBH has the intrinsic energy density to be a competitive hydrogen source

Challenges:

- Water management
- Thermal management
- Fuel/borate handling

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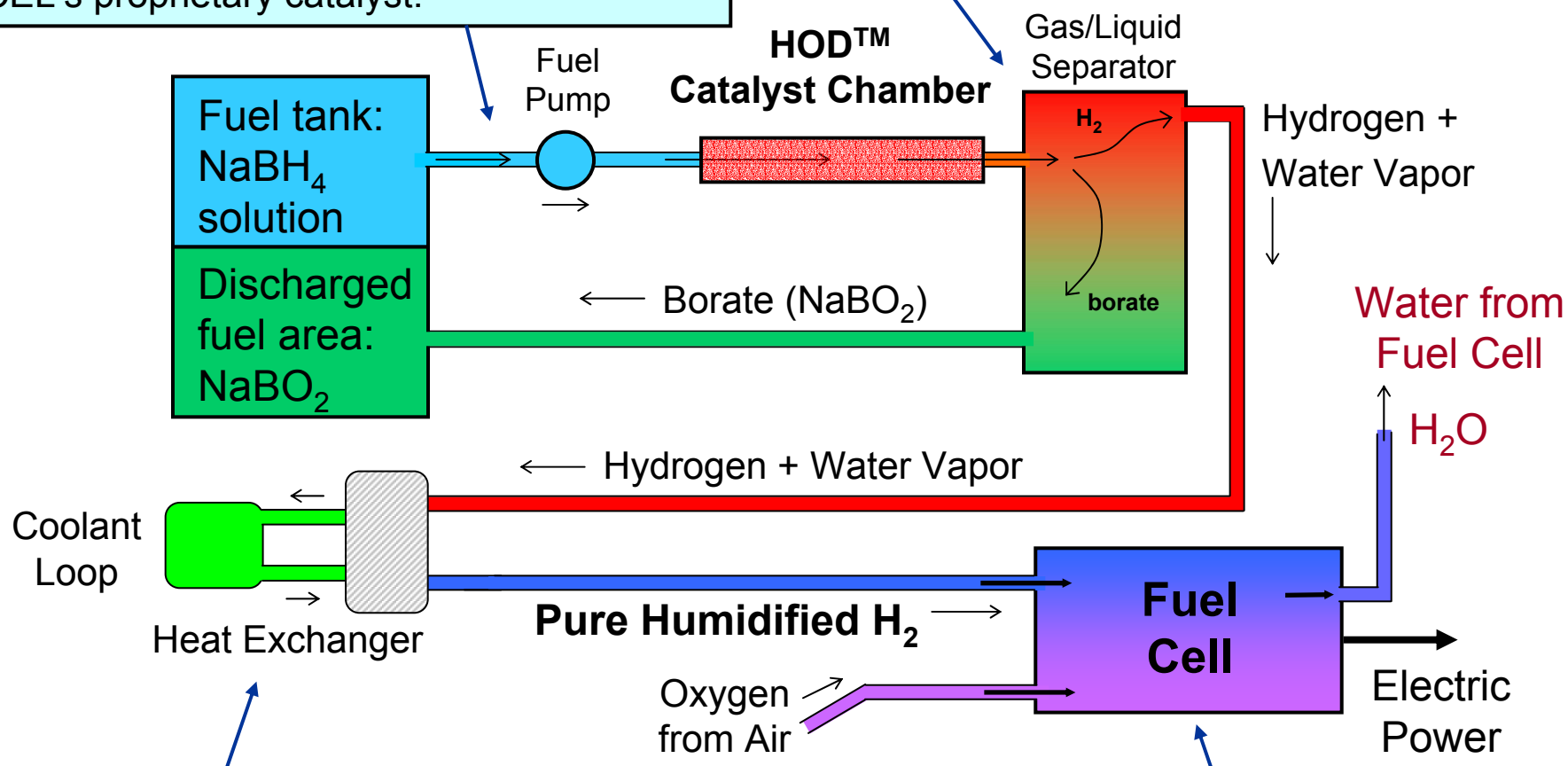
How Hydrogen on Demand™ Works

1. Borohydride Fuel is pumped or moved from a tank through a chamber containing MCEL's proprietary catalyst.

2. The fuel is converted into pure hydrogen, water vapor, and borate ($NaBO_2$).



3. The temperature and humidity of the hydrogen stream are adjustable. Humidified hydrogen is sent to the fuel cell.

4. The fuel cell creates **power** and **water**. This water can be recycled within the HOD system. Allows for higher fuel concentrations.

Utility for Military Applications

- Sodium borohydride is unique in that it has strong performance metrics at multiple power levels:
  - Transportation (ground, maritime) (50-100 kW)
  - Auxiliary power generation, UUV (5-10 kW)
  - Battery chargers, standby power (1-5 kW)
  - Battery replacement, man-portable (<100 W)
- Small logistical footprint: SBH can be transported or air-dropped as a solid, and mixed with water on-site:
  - Water does not need to be of high-purity
  - Tests underway to determine applicability of various water sources
- Sustainability: well suited to long mission duration

Transportation: Commercial Vehicle Demonstrations

Hydrogen On Demand™ Systems

Chrysler Town & Country Natrium®

- Fuel cell electric hybrid minivan
- Debut at 2001 EVAA, tour 2002-03
- 300 mile range for system
- 2002 Popular Science "Best of What's New" award winner

Peugeot-Citroën H_2O Vehicle

- Fuel cell electric hybrid vehicle, fire rescue vehicle concept car
- Debut at 2002 Paris Auto Show
- FC is ~5 kW range extender
- >250 km range for system

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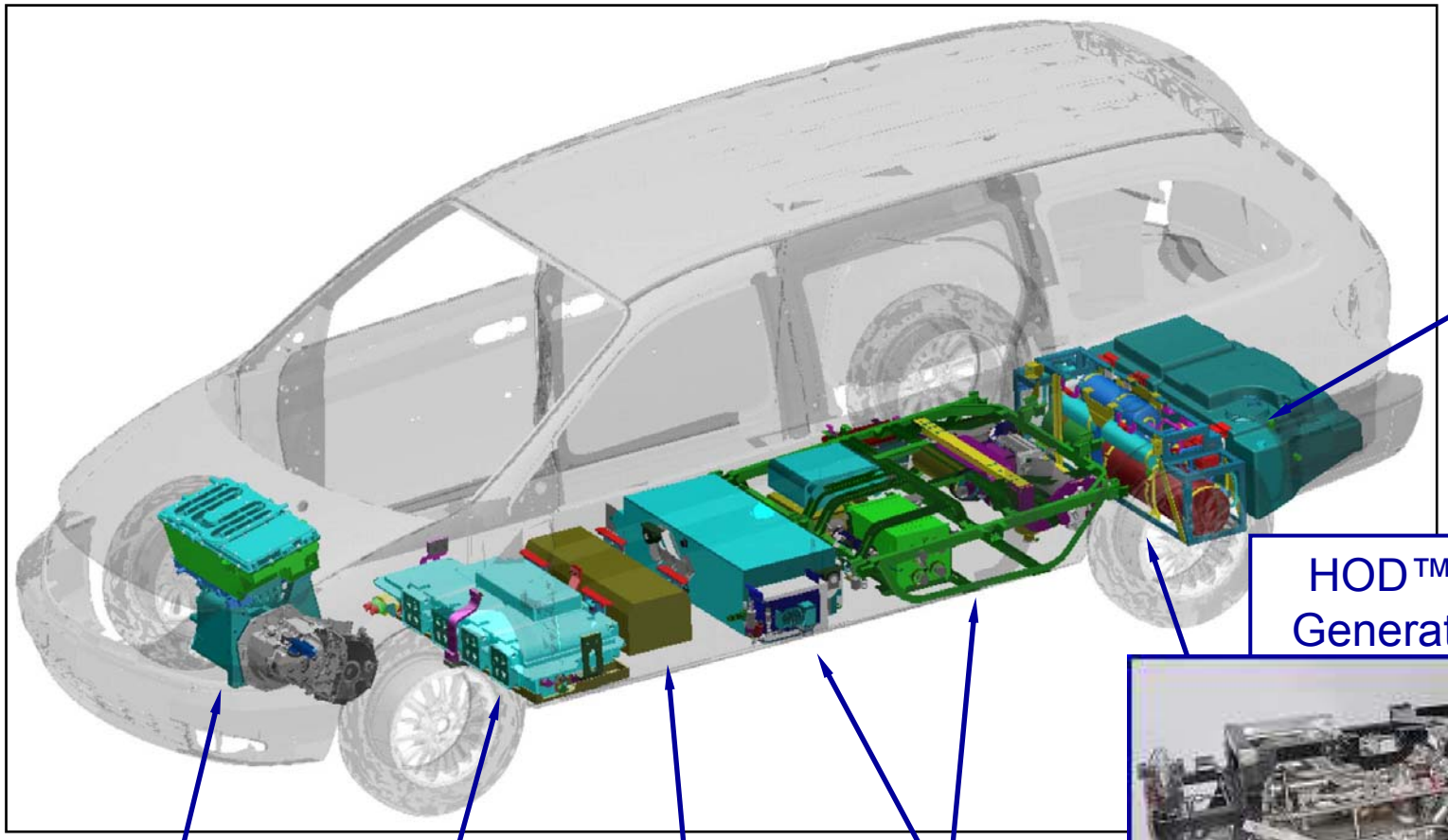
Chrysler Town & Country Natrium®

Powered by the Hydrogen on Demand™ system



Sodium Borohydride Fuel/Borate Tank

HOD™ Hydrogen Generation System

Electric Drive Motor

Lithium Ion Battery Pack

DC/DC Converter

Ballard Fuel Cell Engine

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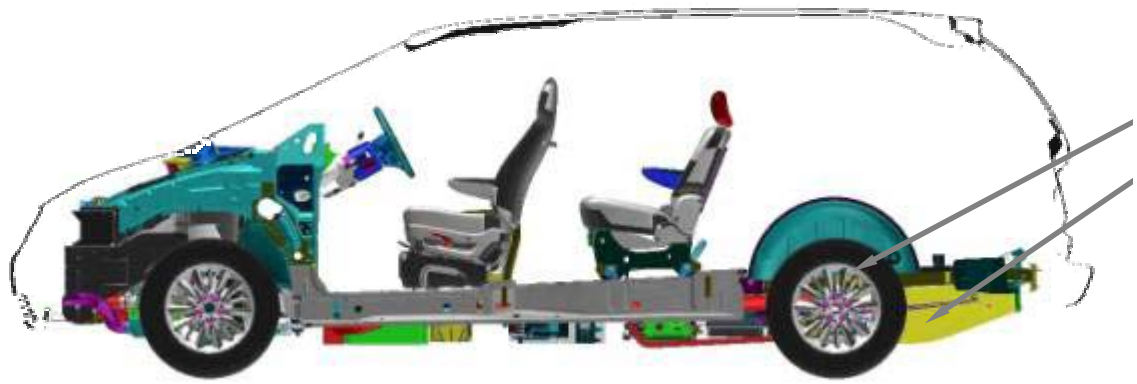
Volumetric Efficiency of Hydrogen Storage/Generation

Increased Packaging Flexibility

Compressed H_2 cylinders
(3 tanks @ 5,000 psi)



Hydrogen On Demand™
H_2 generation system,
fuel and borate tanks

(Equals energy storage of
about 5 compressed tanks)

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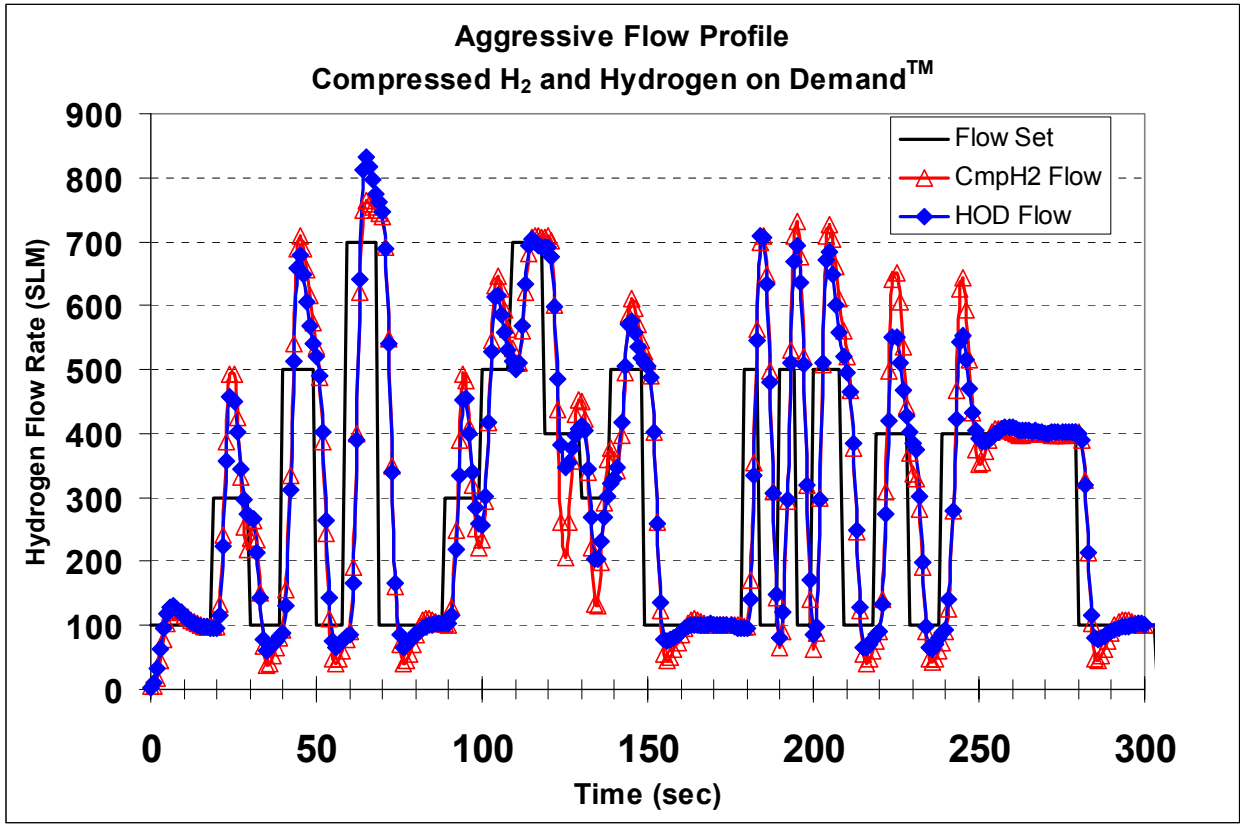
Hydrogen on Demand™ System Performance

Hydrogen Flow Profile Comparison Against Compressed H_2



Compressed hydrogen (in **red**) shown vs. Hydrogen on Demand™ (in **blue**)

Hydrogen flow profile shown is similar to flows experienced in a typical driving cycle

Up to ~65 kW power demand shown in this test run.

HOD™ has the ability to "load follow", even with aggressive transients.

MCEL has demonstrated HOD technology scaled from <2 W to ~100 kW.

Source: R. Mohring, *et al*, SAE World Congress 2002, Paper No. 2002-01-0098.

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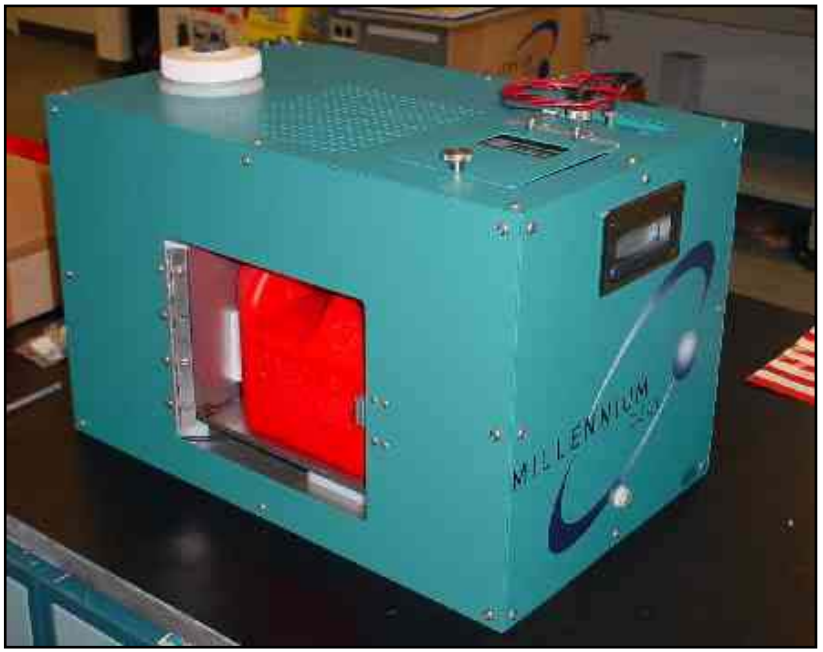
Hydrogen on Demand™ Standby/Auxiliary Power Unit

DS –1 Prototype 1.2 kW System



Hydrogen on Demand™ (3 hour runtime @ max load)
1.2 kW hydrogen generation system

- Small systems typically run at < 40 psig system pressure
- Rated at 18 SLM H_2, max flows of up to ~45 SLM (~3 kW)
- One-button operation – works as a “black box” hydrogen source that looks like a low pressure hydrogen cylinder

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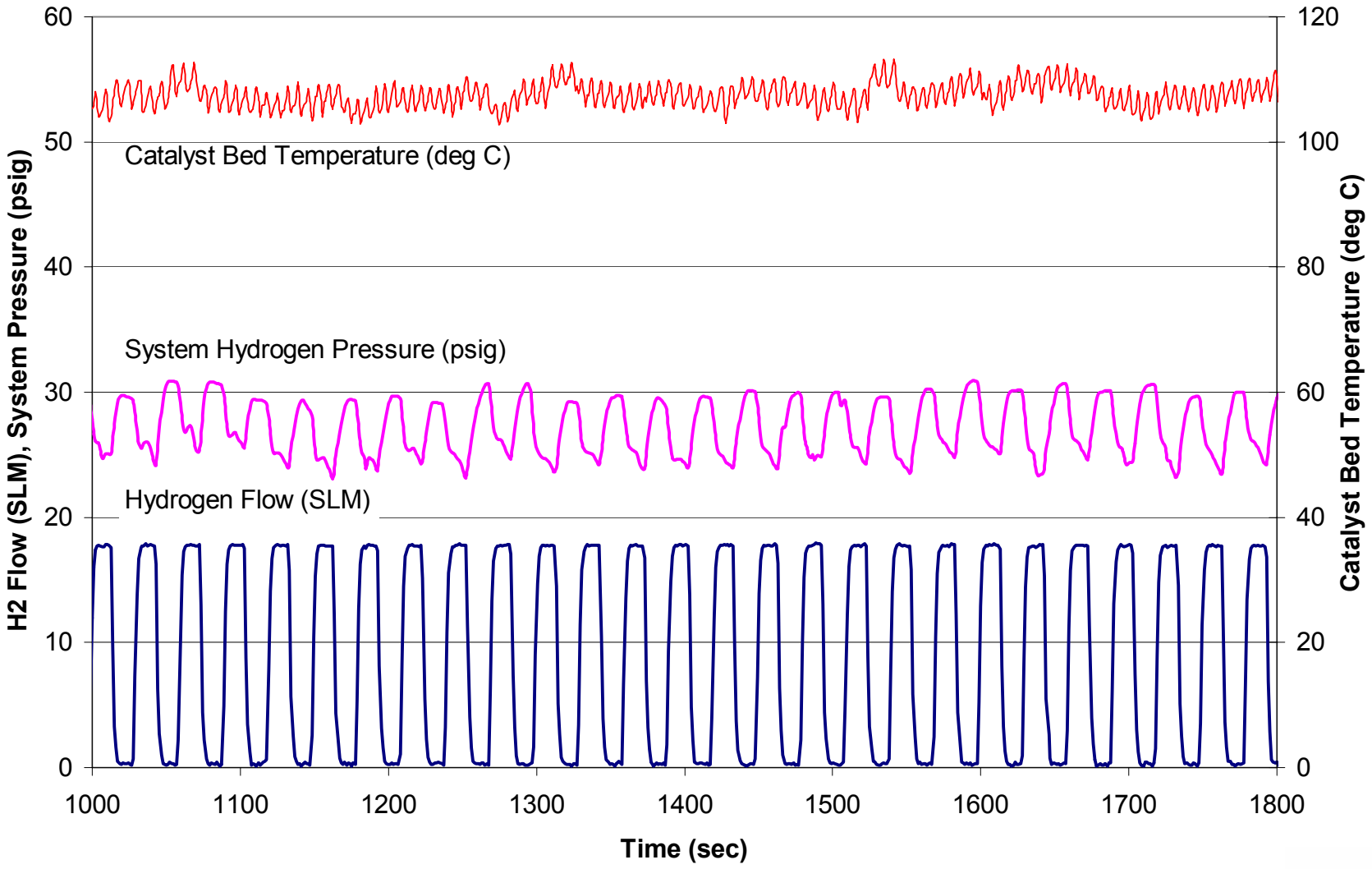
DS-1 HOD™ System, Load-following Testing

15 sec Interval Flow Testing, 0 – 18 SLM H_2 (~ 0 – 1.4 kW), P_0 = 28 psig



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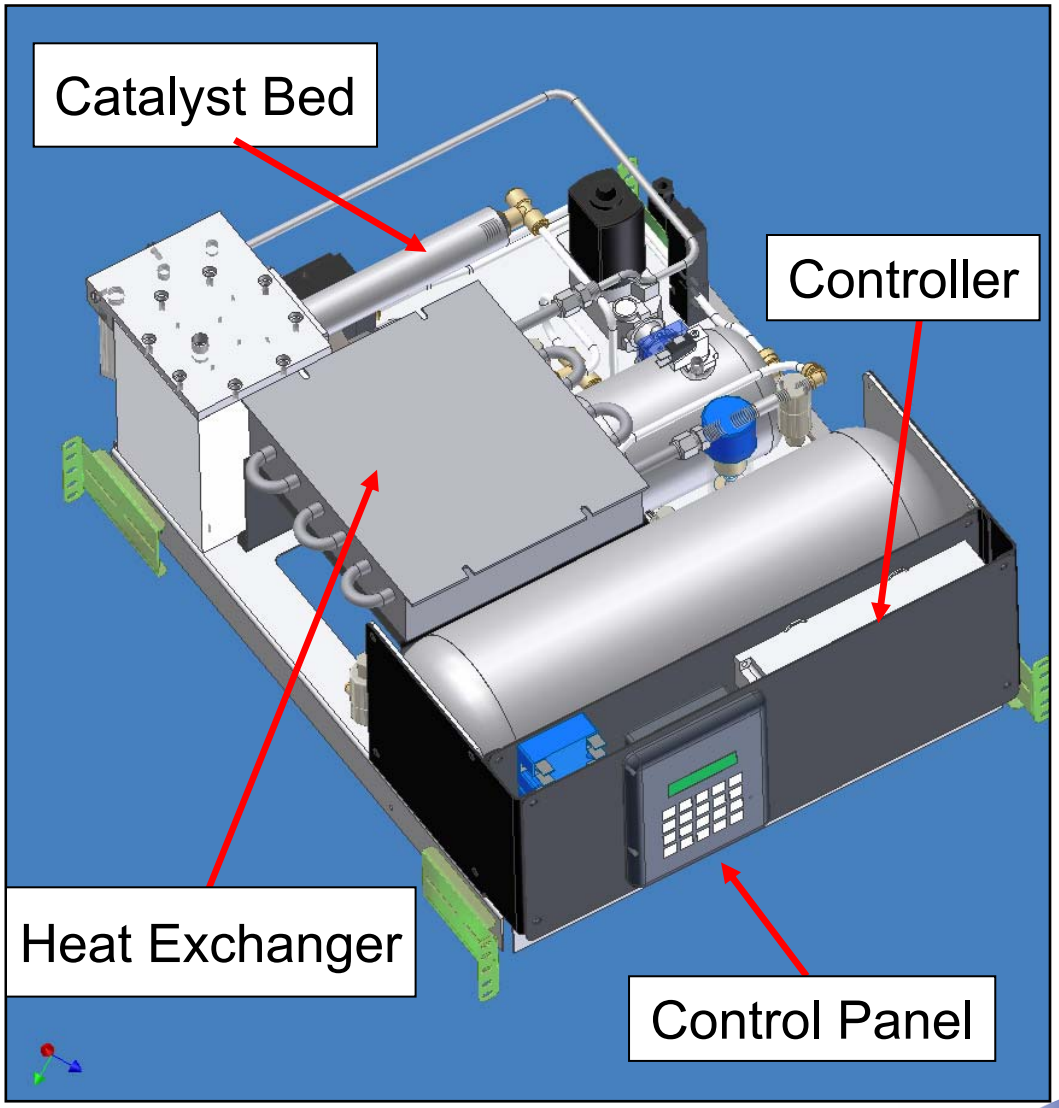
1.5 kW Rack-mount HOD™ System

Hydrogen generation module

- Fits standard 19” telecom rack
- H_2 output: 0-20 SLM @ >99.9% purity
- Delivery pressure: 20-30 psig
- Load-following
- Modular PLC controls
  - Easy integration with fuel cell control logic



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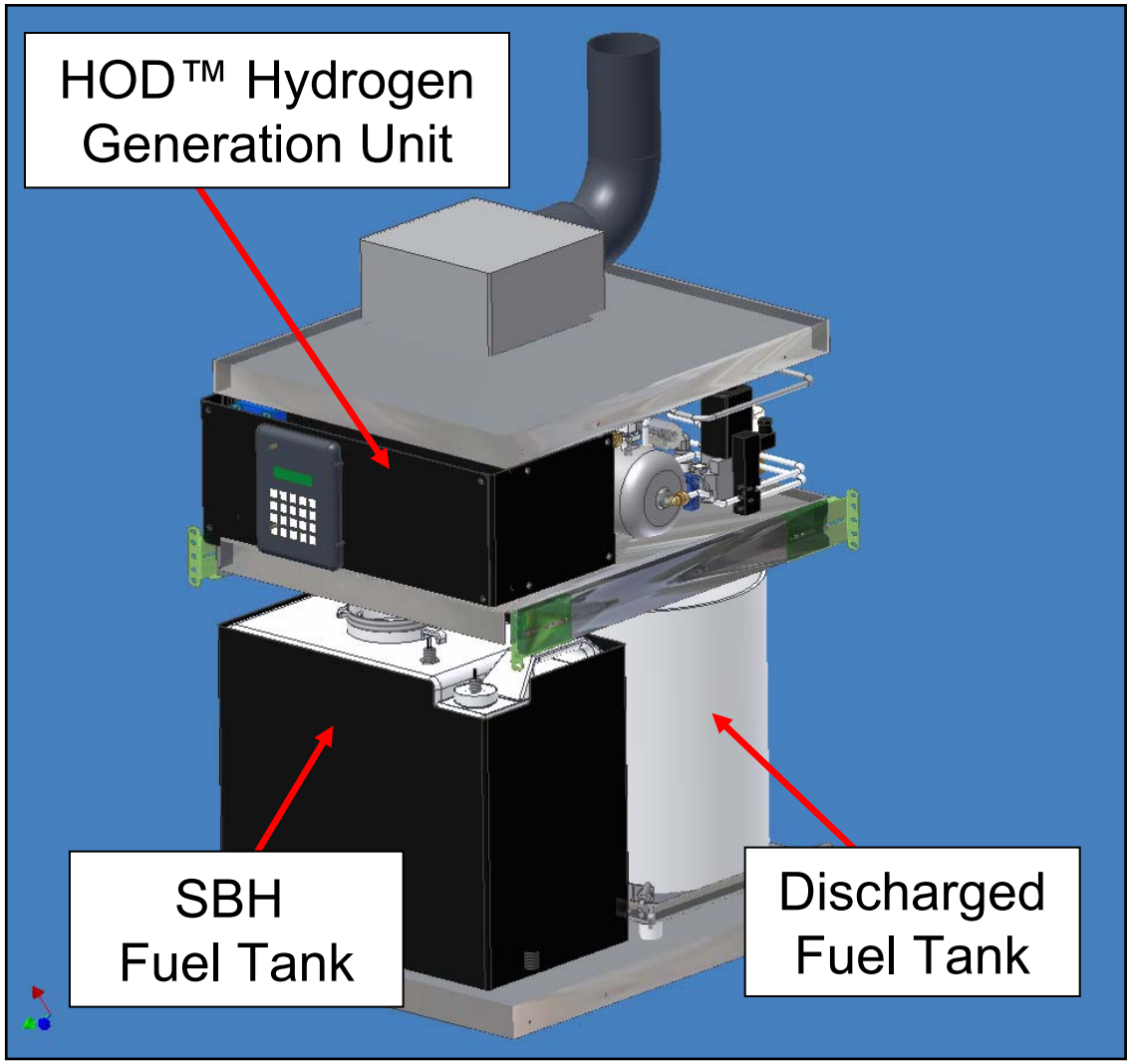
1.5 kW Rack-mount HOD™ System

Shown with fuel/borate storage module



- Stored hydrogen:
  - ~10,000 SL
- Generator module approx. dimensions:
  - 17” W x 6.5” H x 21” D
- Fuel storage module:
  - 17” W x 14” H x 21” D
- Dry weight (w/o rack): approximately 50 lbs.
- **Performance testing currently underway**

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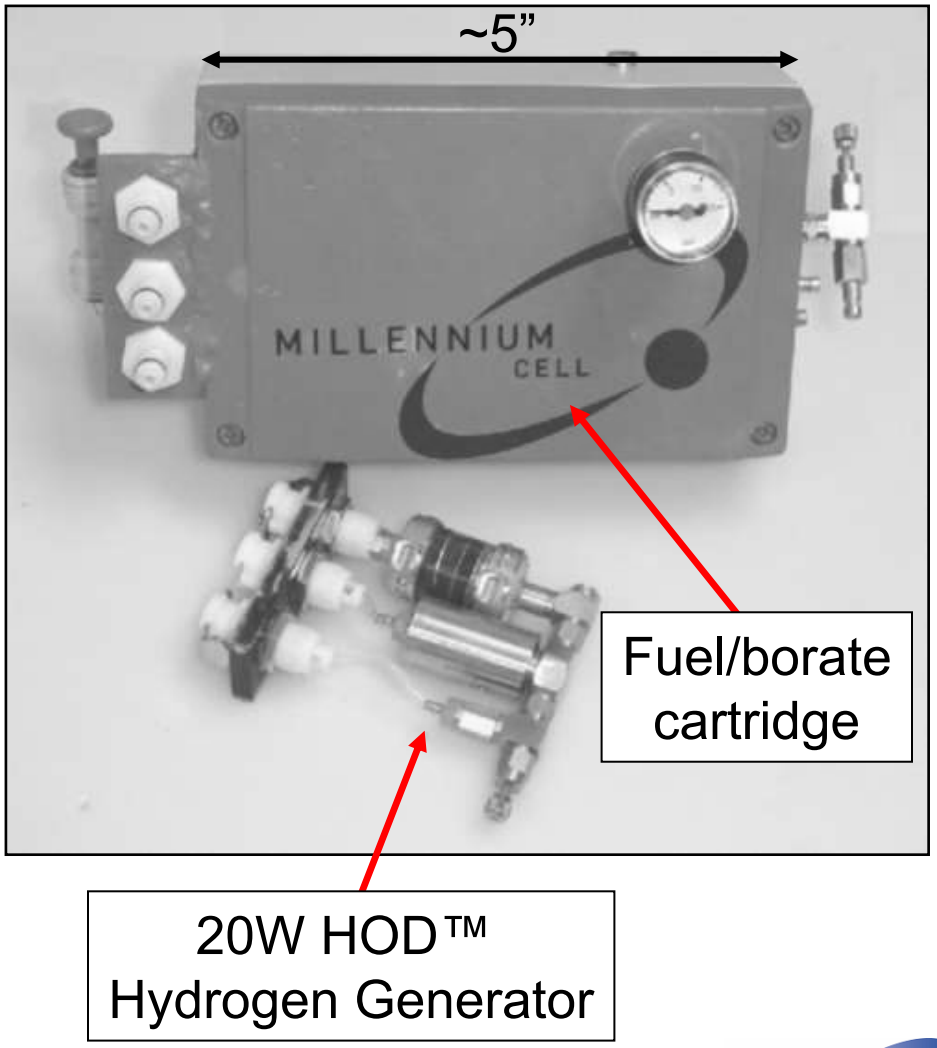
Prototype Man-portable HOD™ System

- Second-generation proof-of-concept prototype
  - Currently in CAD design turn
- Supports 20W (40W peak) operation
- Exchangeable fuel/borate cartridge
- Hydrogen supply at 5-10 psig
- Zero parasitic load
- Orientation independent



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Military Battery Replacement

- Long mission life favors a fuel cell + hydrogen storage solution over primary batteries (such as BA5590)
- Dry SBH fuel cartridges can be mixed on-site as needed
- Targeting development for a 72 hour mission at 30W
- Estimated total energy density of a complete system (HOD™ + 50% efficient FC):
  - BA5590: ~ 170 Wh/kg
  - Today's technology: >700 Wh/kg (~400 Wh/kg if water is carried)
  - Short-term technology development: >1,100 Wh/kg (>450 Wh/kg if water is carried)

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Summary

- Millennium Cell is pursuing the use of sodium borohydride ($NaBH_4$, SBH) as a hydrogen storage medium
- Hydrogen on Demand™ hydrogen generation technology has been successfully demonstrated in multiple applications
- The energy density and properties of SBH offer unique features and benefits for military applications:
  - Non-combustible liquid fuel, ability to mix on-site, long shelf-life…
- Development opportunities:
  - The fuel cell creates water…Optimization of HOD + PEMFC system can allow for use of high concentration SBH fuels
  - Systems design and engineering to access higher energy densities
  - Continued improvements in $NaBO_2$-to-$NaBH_4$ regeneration chemistry and catalyst technologies

Thank you!

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