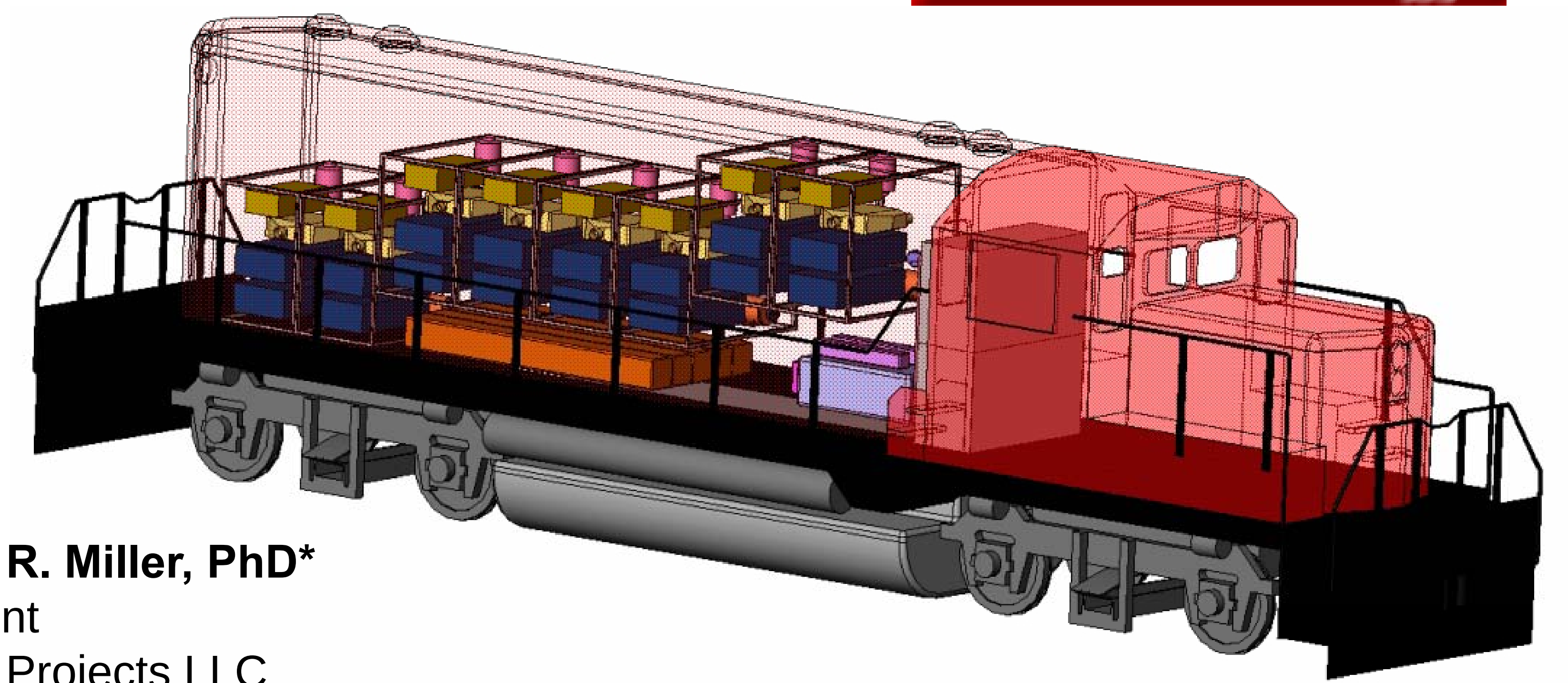
COMPARISON OF PRACTICAL HYDROGEN-STORAGE VOLUMETRIC DENSITIES



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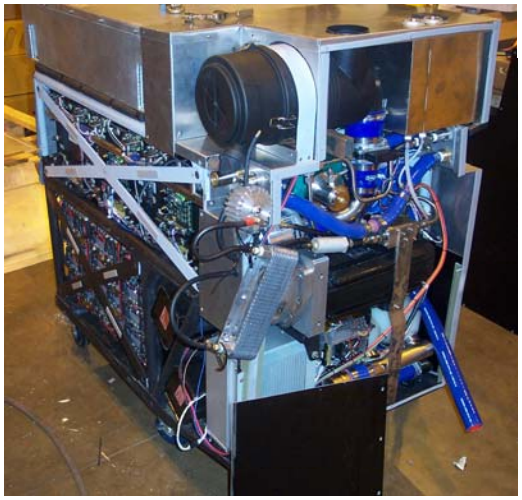
HIGH-POWER FUELCELL VEHICLE DEVELOPMENT

Vehicle Projects LLC has a unique history of leading large fuelcell vehicle projects from design through implementation.

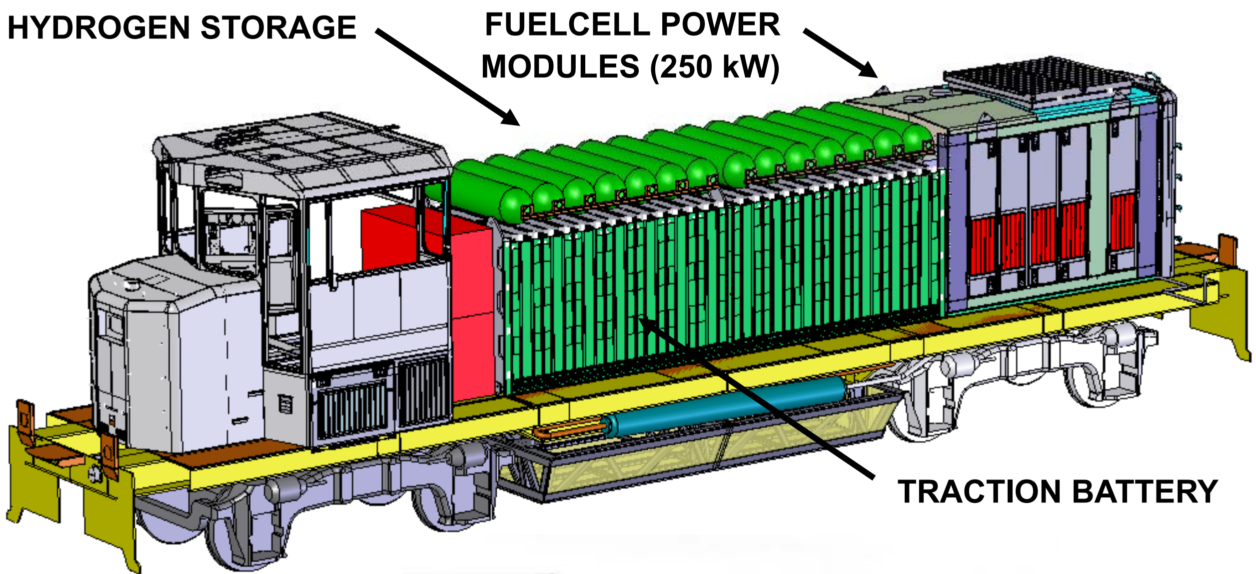


METAL-HYDRIDE STORAGE

Primarily for safety, both the mine locomotive and mine loader use reversible metal-hydride storage. Photo shows half of the hydride storage system being lowered into the loader. The vehicle stores 14 kg of hydrogen and can be refueled in 10-15 minutes.

DESIGN TO IMPLEMENTATION – HYBRID SWITCHER

The switcher locomotive is a fuelcell-battery hybrid whose prime mover provides 250 kW of continuous net power for traction or power-to-grid. An auxiliary lead-acid traction battery allows transient power in excess of 1 MW. Carbon-fiber composite tanks store 70 kg of hydrogen at 350 bar.



Project start to demo in LA railyard - 20 months

LIMITS OF HYDROGEN VOLUMETRIC DENSITIES

Fuel Occupying 1.0 L[a]	Conditions of Storage	H_2 Mass[b]
Gaseous H_2	350 bar (5,100 psi)	25 g
Liquid H_2	ρ = .070 g/mL (P = 1 bar, T = bp)	70 g
Methanol[c]	ρ = .79 g/mL, (T = 25 C)	99 g
Liquid Ammonia	ρ = 0.62 g/mL, (P = 7.2 bar, T = 15 C)	110 g
Reversible Metal Hydride	AB_5 alloy ($LaNi_5$), ρ = 8.3 g/mL, wt % = 1.5, 10 bar	125 g

[a] Fuel only – container and processor excluded

[b] Henceforth, density will use the units kg/m^3. Note that n kg/m^3 = n g/L.

[c] Reforming to hydrogen requires water also: $CH_3OH + H_2O \rightarrow 3H_2 + CO_2$. In principle, water can be obtained from the fuelcell.

THEORETICAL vs PRACTICAL STORAGE VOLUMES

For 100 kg Hydrogen Storage:

Fuel System	Theoretical (Limit) Volume,[a] m^3	Practical System Volume (PSV), m^3
Compressed hydrogen [b]	**4.0**	**10.**
Liquid hydrogen [c]	**1.4**	**3.9**
Methanol Reformer [d, e]	**1.0**	**4.3**
Ammonia Dissociator [d, f]	**0.90**	**2.3**
Reversible Metal Hydride [g]	**0.80**	**5.0**

[a] Def: 100 kg storage / Theoretical H_2 mass in 1.0 m^3 of fuel (previous slide); e.g., 100 kg / 25 kg/m^3 = 4.0 m^3

[b] Practical System Volume (PSV) (prismatic) based on Dynetek™ W205H350G8N carbon-fiber composite tanks, plus ancillaries

[c] PSV based on BMW Hydrogen 7™ automotive system

[d] PSV assumes 17 kg/h H_2 consumption rate, corresponding to 300 kW gross from Ballard™ P5 fuelcell powerplant

[e] PSV based on volume of six Intelligent Energy Hestia™ reformers, 50 kW each. Includes volume of reactant water

[f] PSV based on volume of scaled Intelligent Energy MesoChannel™ ammonia dissociator

[g] PSV based on measured volume of Vehicle Projects LLC mine loader storage system

PRACTICAL STORAGE DENSITIES: RESULTS

Fuel System	Practical Density,[a] kg H_2 / m^3	Storage Efficiency[b]
Compressed H_2	**10**	**40%**
Reversible Metal Hydride (AB_5)	**20**	**16%**
Methanol Reformer	**23**	**23%**
Liquid H_2	**26**	**37%**
Ammonia Dissociator	**44**	**40%**

[a] Def: 100 kg / Practical System Volume; e.g., for liquid H_2: 100 kg / 3.9 m^3 = 26 kg/m^3 = 26 g/L

[b] Def: Practical Density / Theoretical Density x 100%; e.g., for liquid H2: 26 kg/m^3 / 70 g/L x 100% = 26 kg/m^3 / 70 kg/m^3 x 100% = 37%. “Storage Efficiency” is a measure of how closely a storage system approaches its volumetric density limit.

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CONCLUSIONS

With today's technology:

- **Highest practical hydrogen volumetric density: Liquid ammonia (44 kg/m^3)**
- **Lowest practical hydrogen volumetric density: Compressed hydrogen (10 kg/m^3)**
- **Highest storage efficiency: Compressed hydrogen or liquid ammonia (40% each)**
- **Lowest storage efficiency: Reversible metal hydride (16%)**

FINANCIAL SUPPORT

US Department of Energy, Hydrogen Program

US Department of Energy, Office of Industrial Technologies

Government of Canada, Action Plan 2000 on Climate Change

Natural Resources Canada, Emerging Technologies Program

US Department of Defense, US Army National Automotive Center

Government of Japan, Railway Technical Research Institute

Fuelcell Propulsion Institute

BNSF Railway Company

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