Technical Issues and Opportunities for Fuel Cell Development for Autonomous Underwater Vehicles

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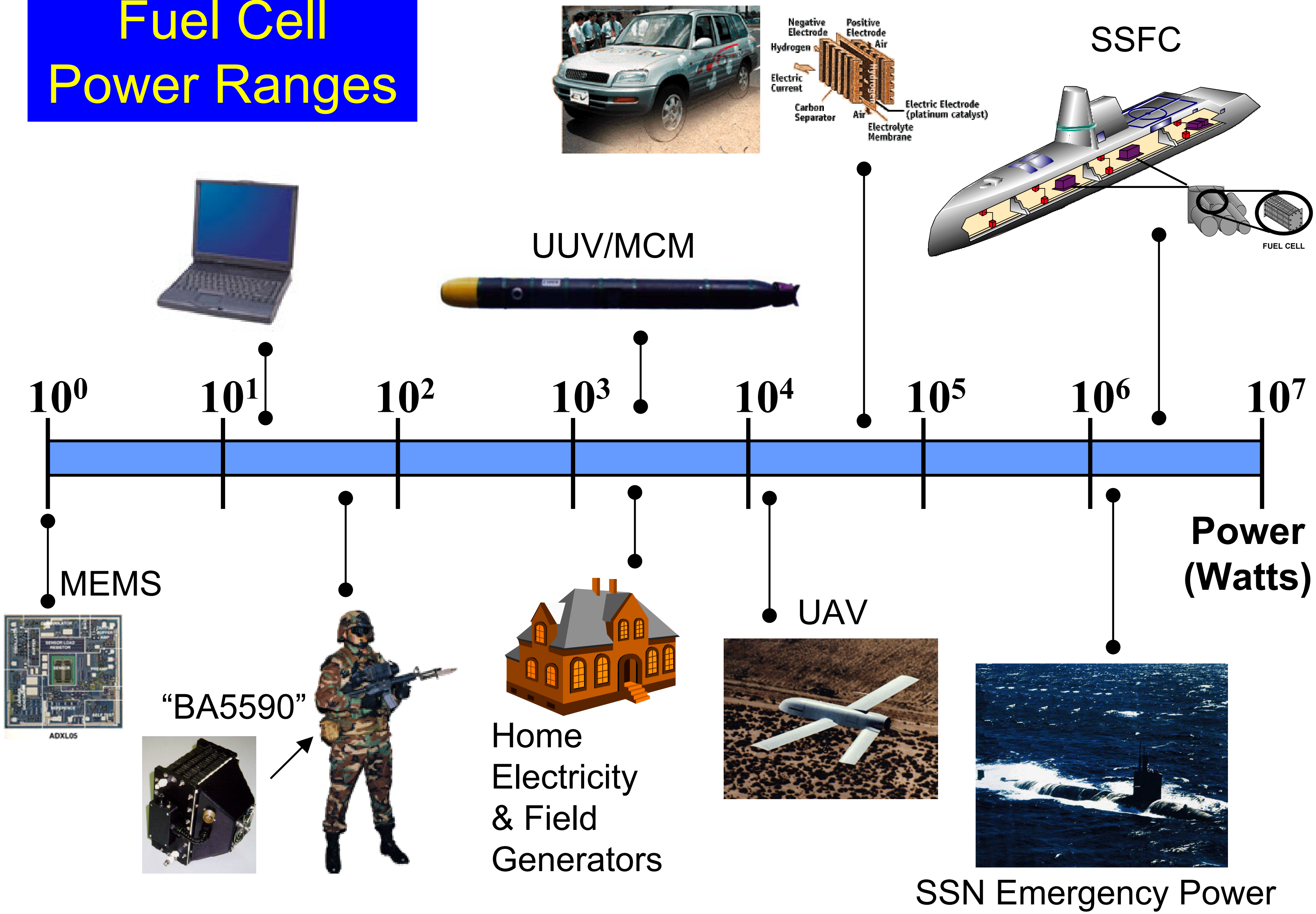
Fuel Cell Power Ranges



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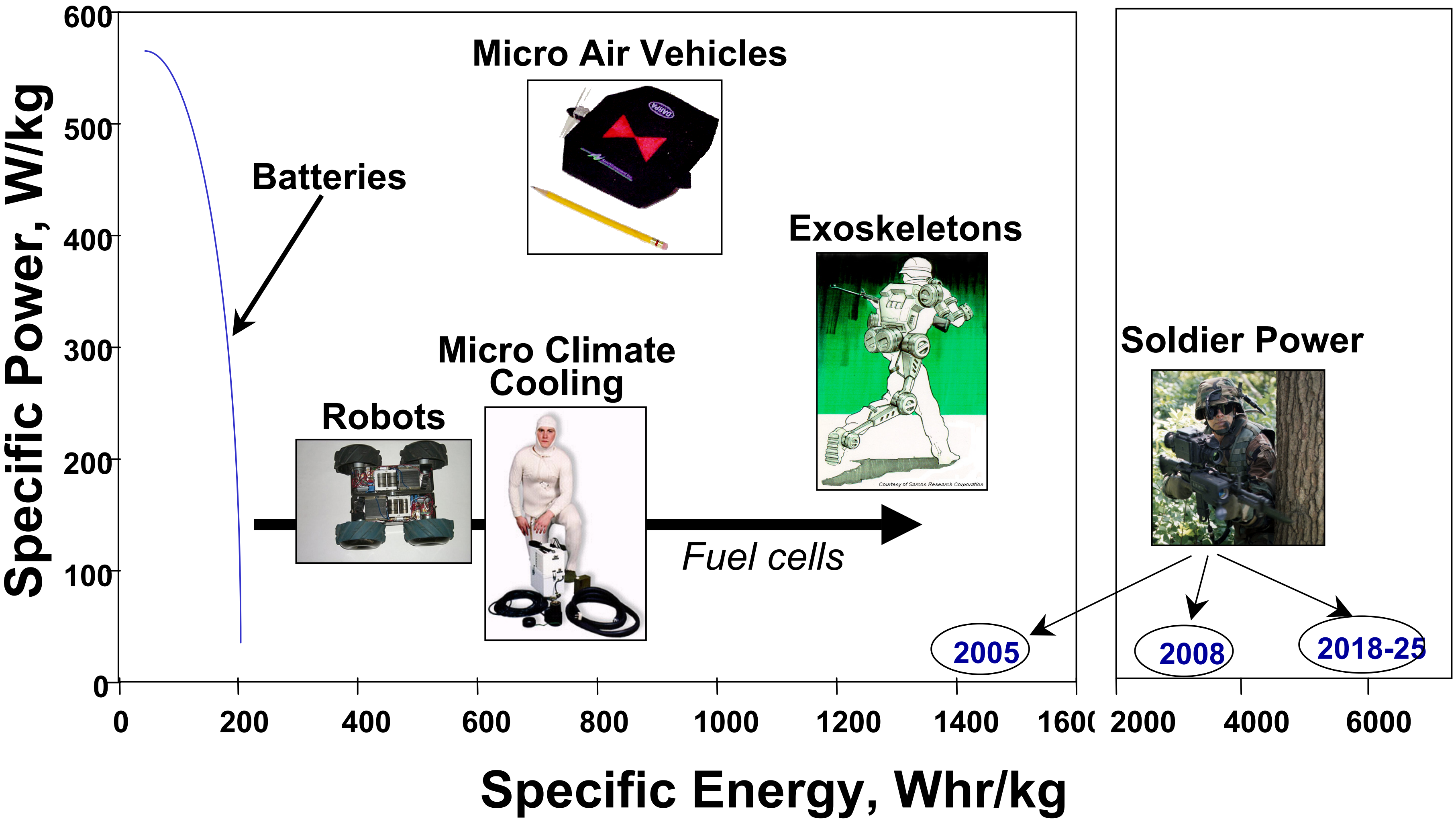
Performance Shortfall of Today's Portable Power Sources for DoD Applications



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Fuel Cells for the Navy & Marine Corps

Fuel efficient, quiet power sources

Fuel cells under development for many DoD applications

- Applications
  - Shipboard power
  - Autonomous vehicles
  - Person-portable power
  - Field generators
  - Ground and sea combat vehicles
- Major Challenges for AUVs
  - Operation in confined space
  - Compact, lightweight, rugged
  - Oxygen storage
  - Storage and/or refining of fuel

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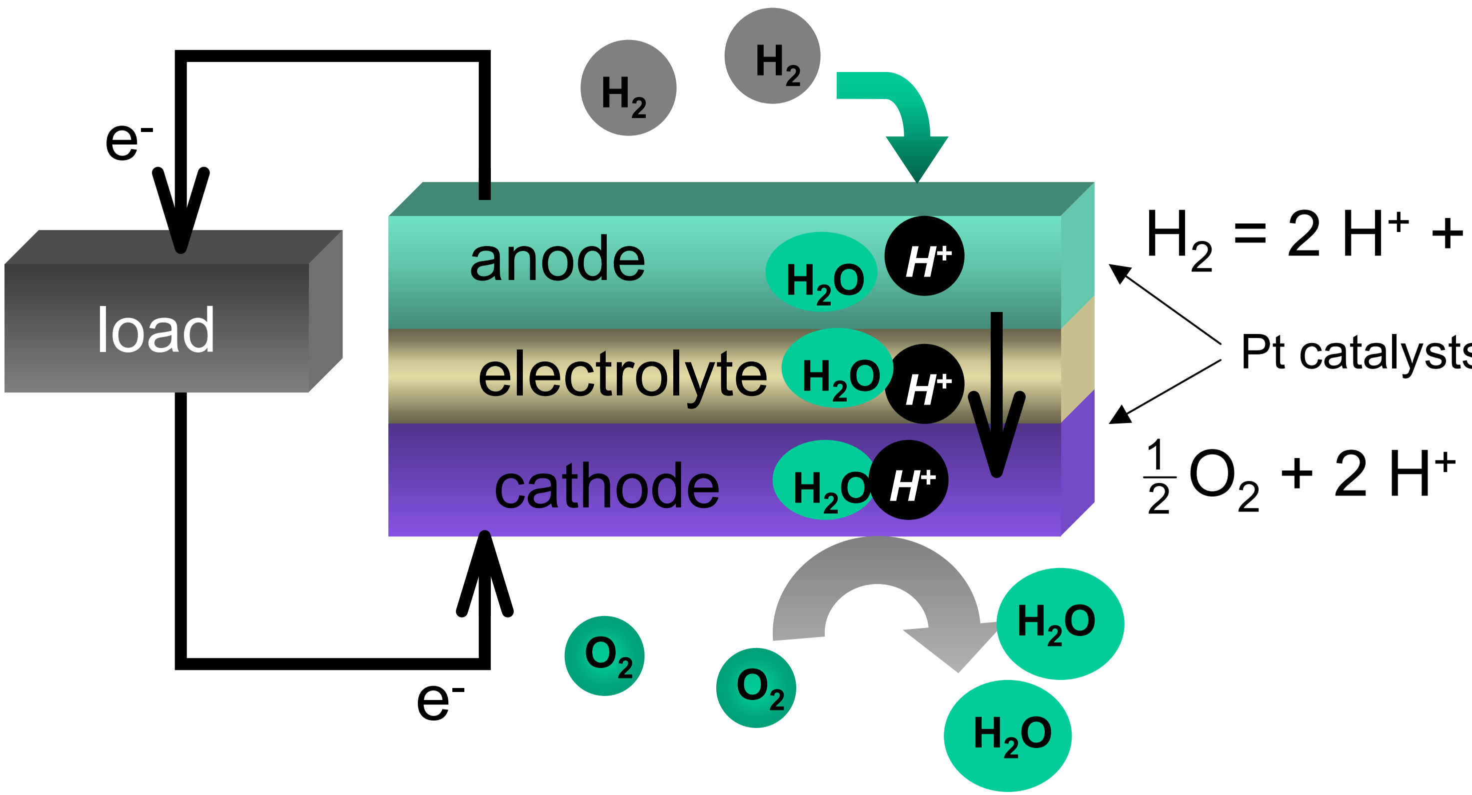
Electricity from electrochemistry

- Electrochemical conversion process
- Oxygen and hydrogen combined on catalysts to produce water, electricity and heat



$$H_2 = 2\,H^+ + 2\,e^-$$

$$\tfrac{1}{2}\,O_2 + 2\,H^+ + 2\,e^- = H_2O$$

Proton exchange membrane fuel cell
Perfluorosulfonic acid (Nafion® polymer) membrane

Comparison of Fuel Cell Technologies

Different fuel cell chemistries - electrolytes and catalysts

Fuel cell type	Operating temp (¡C)	Efficiency Air/CH_4	Efficiency O_2/H_2
Proton exchange membrane	70-90	30-35%	66-73%
Phosphoric acid	190-215	35-40%	--
Molten carbonate	600-650	45-50%	--
Solid oxide	700 - 1000	50-55%	70%

$$\text{Efficiency} = \frac{\text{Electrical work out}}{\text{Energy of reaction}}$$

Reported efficiencies vary depending on size of fuel cell and whether penalty for hydrogen production is included

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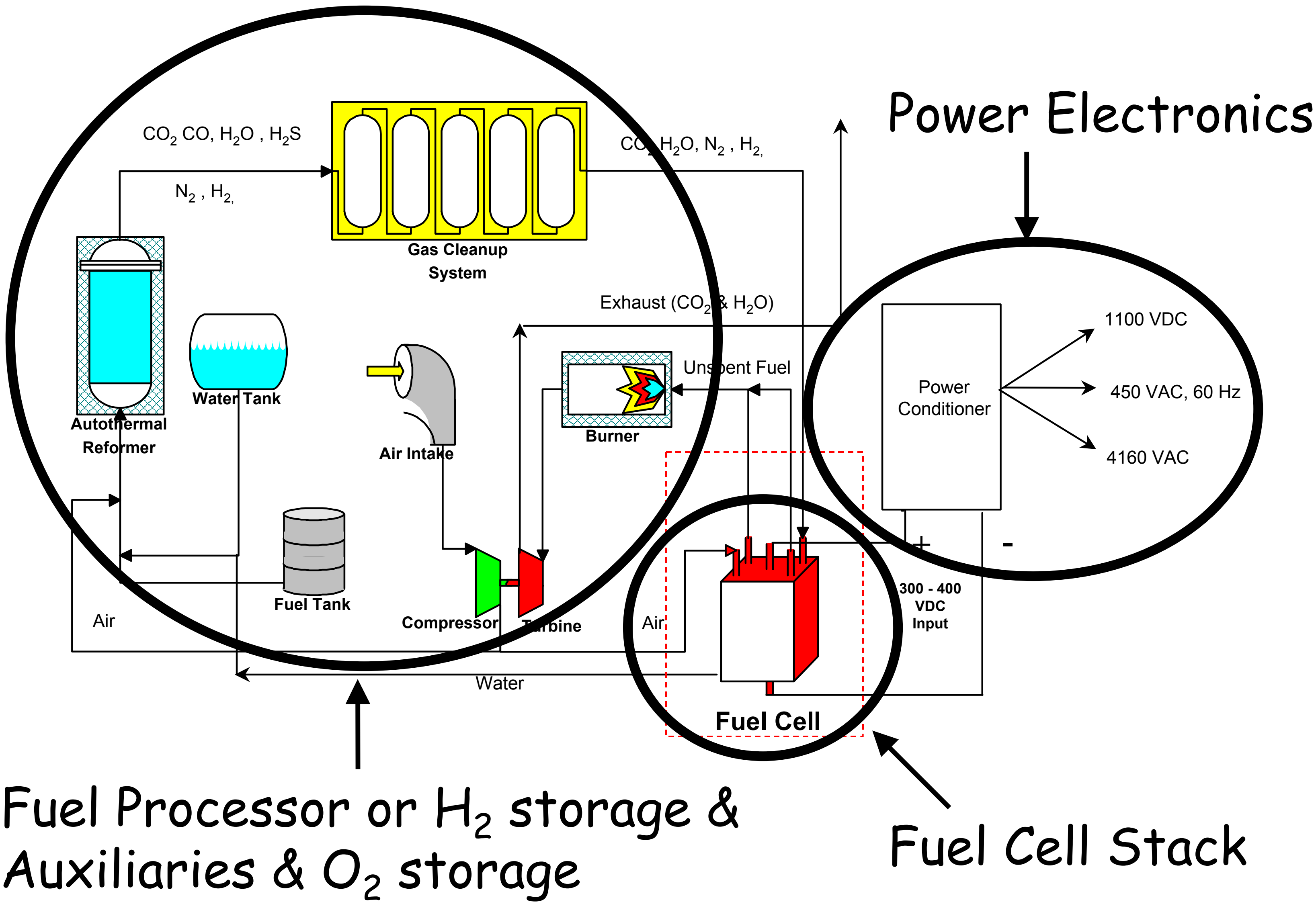
Components of a Fuel Cell System



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System and Balance of Plant

Must meet or beat batteries on multiple criteria

- Safety
- Efficiency
- Reliability
- Durability
    - ➲ standby operation
    - ➲ storage
    - ➲ changes to orientation
    - ➲ high shock loads

Function in confined spaces

- Handle any leaking hydrogen and oxygen
- Maintain buoyancy
- Avoid changes in weight distribution

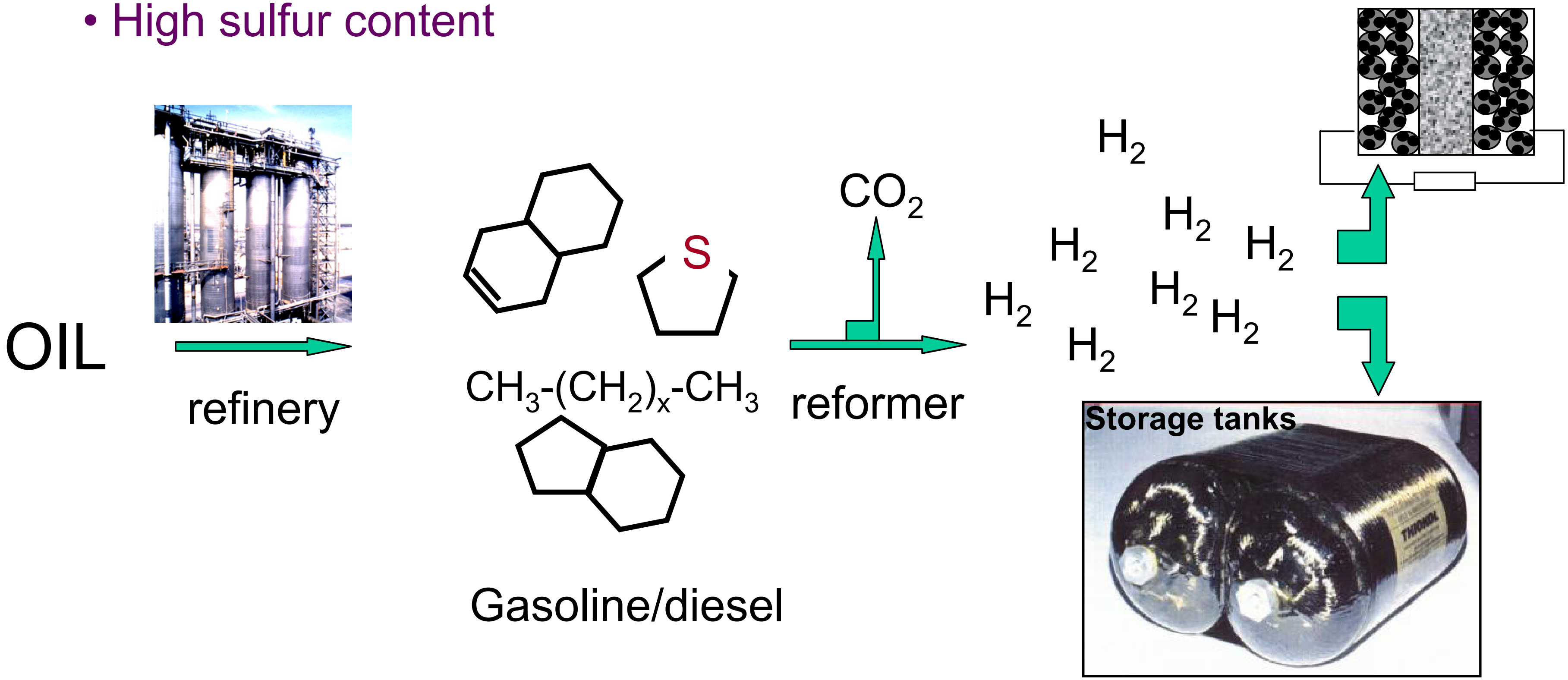
Fuel choices - hydrocarbon or hydrogen?

Logistics fuel

- Richest source of hydrogen
- Must be reformed to hydrogen
- High sulfur content

Hydrogen

- Must be stored effectively
- Efficiency penalty for reforming



Hydrogen must be stored if reformer is not with fuel cell

Hydrogen storage options

4500 psi H_2
289 Wh/kg, 1.7% Storage

NH_3 + $LiAlH_4$
1000 Wh/kg, 6% Storage

High pressure storage

- Weight percent is typically low (2 to 4%)
- Composite tanks may be able to store 11% H_2 at 5000 psi
- Ballast must be added to offset light weight of tanks

Metal hydrides

- 1- 8 % H_2 intercalated into $LaNi_5$, FeTi, Mg_2Ni and ZrV_2
- Provides ballast
- May need heat to release hydrogen
- High pressure packaging needed

Chemical sources

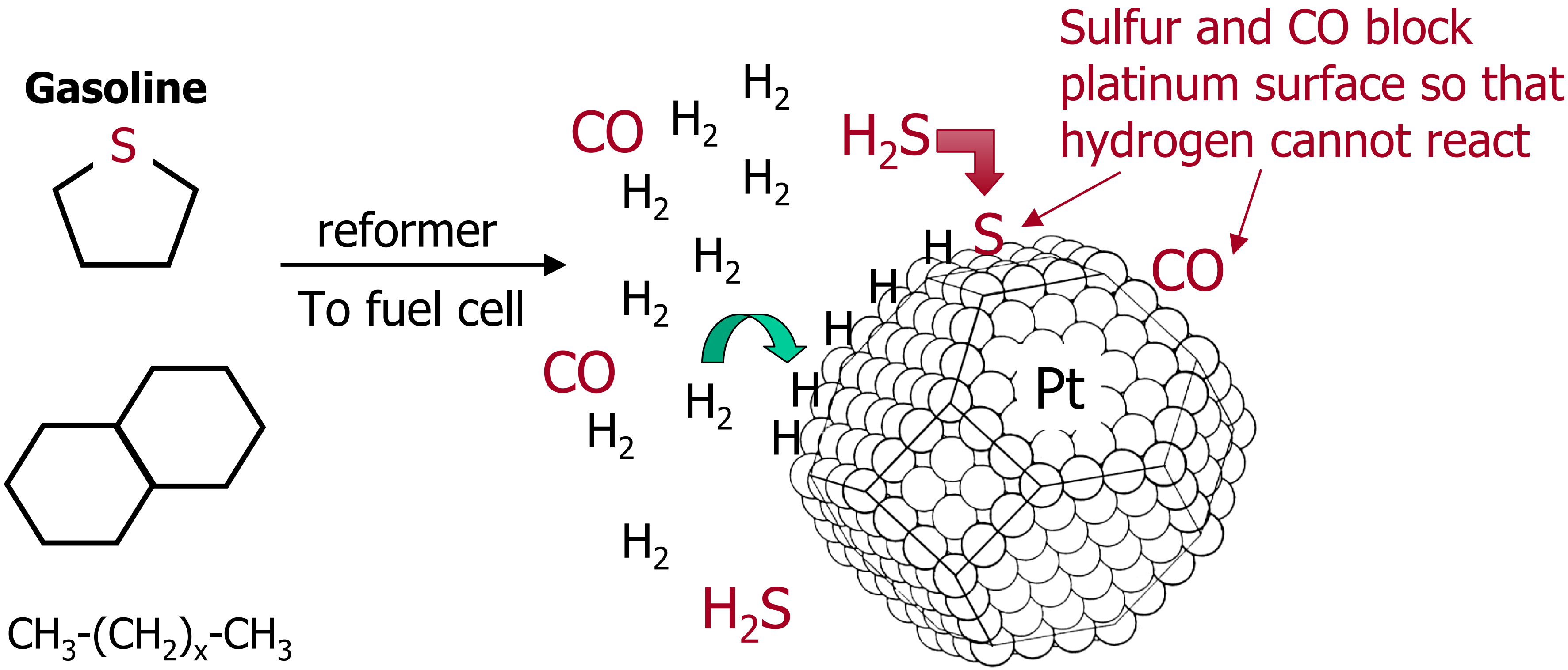
- Ammonia (NH_3), Sodium borohydride ($NaBH_4$), Aluminum hydrides (e.g., $LiAlH_4$)
- High weight % of hydrogen
- Impurities in hydrogen stream
- Additional system needed for catalytic decomposition & elevated temperatures
- Storage of waste gases to maintain AUV weight

Cryogenic hydrogen

- Hydrogen is in a supercritical
- No issues with weight distribution

“Poisons” decrease fuel cell performance

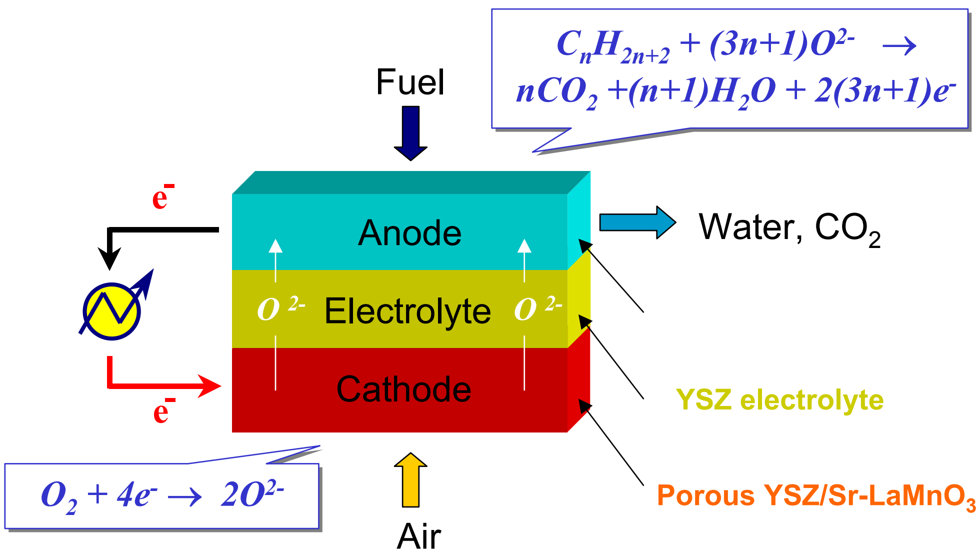
- Sulfur is a natural product in liquid hydrocarbons
- CO is a by-product in reformed hydrocarbons



- CO poisoning not significant over 150 °C
- Sulfur poisoning is an issue for all fuel cells

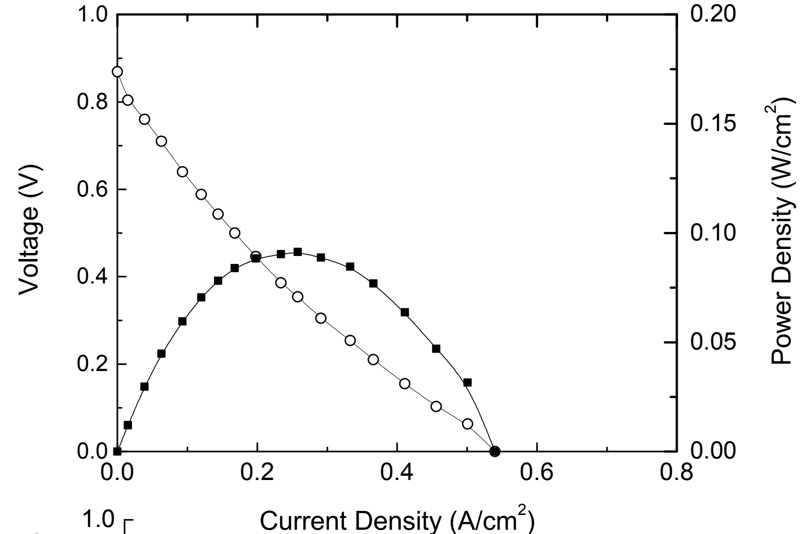
Direct Oxidation/Reforming at Anode

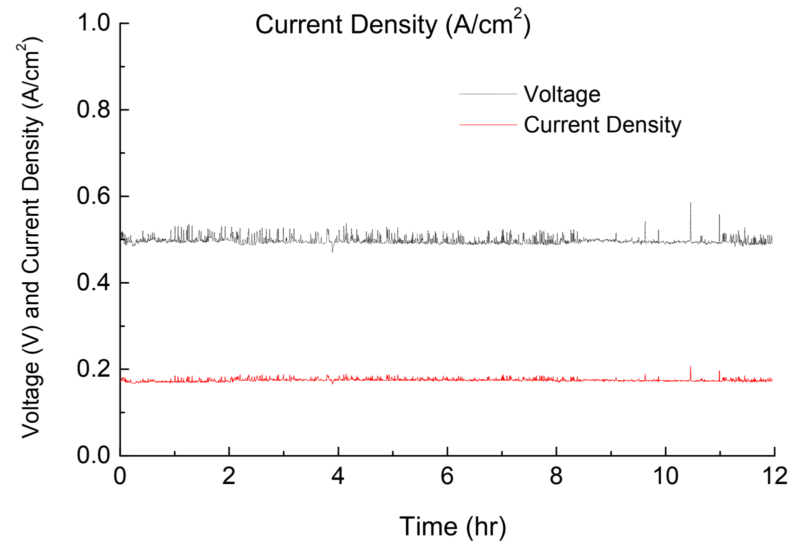
Diesel Fuel ☑ Electricity



New materials for direct electrochemical oxidation (DECO) at anode - no reformer and no water needed!

I-V for Diesel Fuel at 700°C





Diesel – Performance vs. Time

Penn Engineering™

Oxygen storage options

Chemical storage

Hydrogen peroxide (H_2O_2), $LiClO_4$, $NaClO_3$ (oxygen candles), other oxyhalides, and peroxides/superoxides

- High volumetric oxygen density
- Reformer needed for conversion to O_2 gas
- Method needed for reactant product storage

Cryogenic liquid oxygen (LOX)

- Pure sources of oxygen
- Safety during handling/storage

➲ On demand oxygen re-supply on host platform

The oxygen content of water (150 µmole O_2/L at depths of 600 m) is too low for oxygen harvesting through a gill system

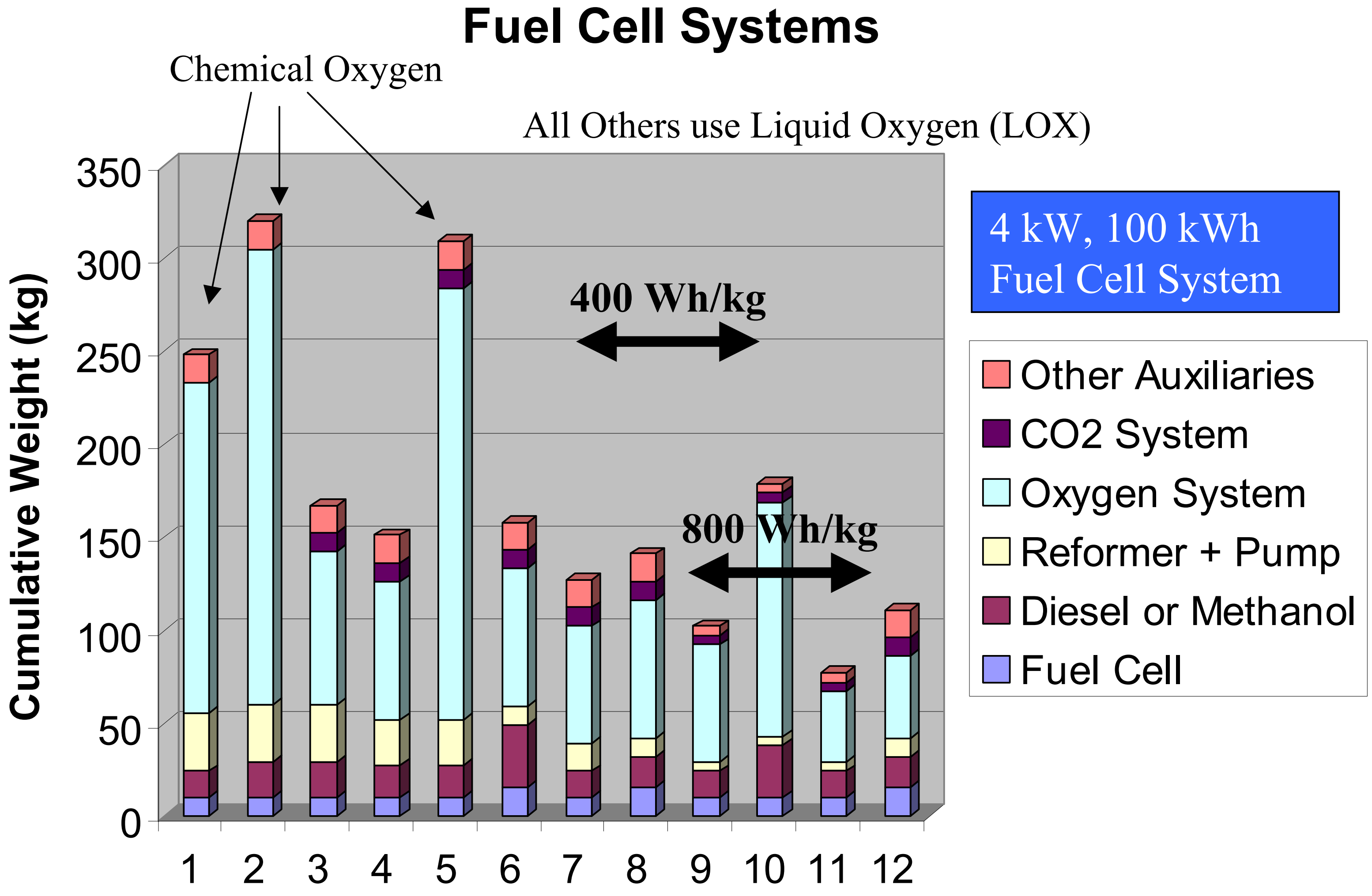
AUV PEM Fuel Cell Operating on Diesel

PEM Fuel Cell System for 4 kW and 100 kWh

Components	Weight (kg)
PEM Fuel Cell	10
Fuel System	
Diesel Fuel	14
Reformer + Pump	31
O_2-storage/generator system	178 ←
Other Auxiliaries	15
Totals	248
Add 10% for Structure	273
Specific Energy (w-hr/kg)	**350**

- **O_2 and CO_2/S-Absorbers = >65% Total System Weight**
- **Relatively Low Specific Energy ⇒ 400 Wh/kg Goal**

Comparison of UAV Fuel Cell Approaches



1 & 2. PEM
Logistic + Chemical O

3 & 4. PEM
Logistic and LOX

5. PEM
Logistic and H_2O_2

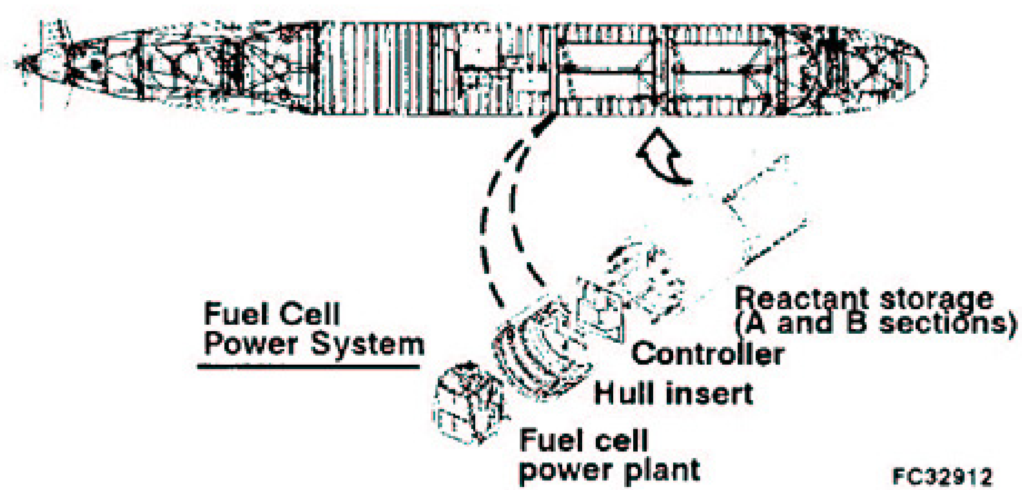
6. PEM/DMFC
Methanol and LOX

7. SOFC
Logistics + LOX

8-12. SOFC
Logistics/DECO + LOX

DARPA UUV Program - Power systems

- Semi fuel cell - Loral
- PEMFC - International Fuel Cells (IFC)



IFC design for 44-inch UUV

- 15-kW power plant
- Four fuel cell stacks and an accessory section.
- No circulation of gases for thermal and water management.
- In 1994, operated successfully for over 500 hrs

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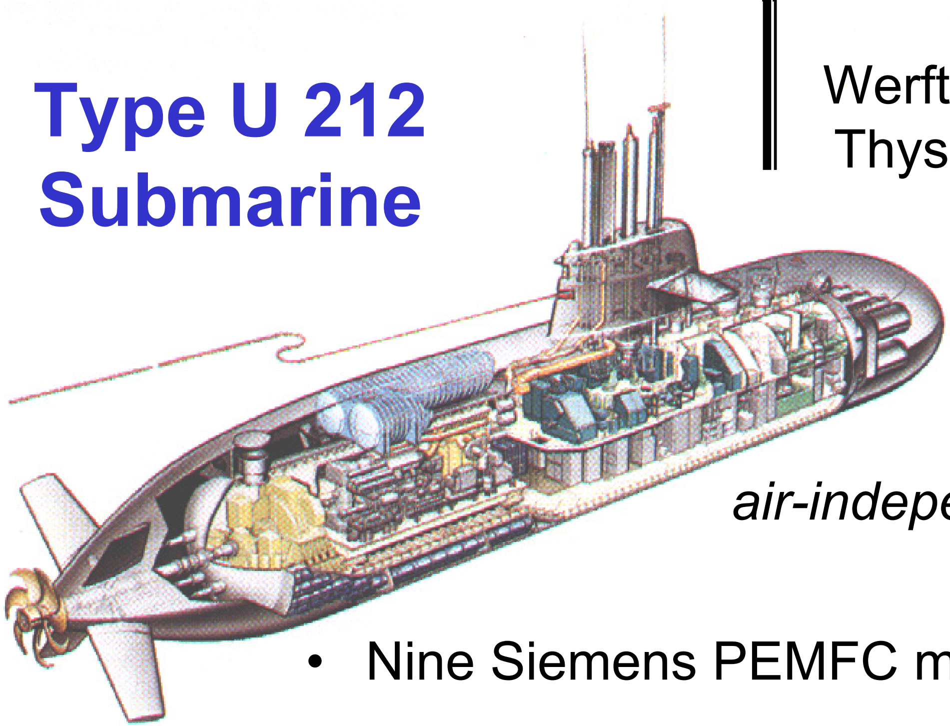
Type U 212 Submarine



Howaldtswerke-Deutsche Werft GmbH (HDW) of Kiel and Thyssen Nordseewerke GmbH (TNSW) of Enden.

Fuel cell based air-independent propulsion (AIP)

- Nine Siemens PEMFC modules providing 30-50 kW each
- Hydrogen (metal-hydride) fuel and LOX oxidizer
- Hull is extended for fuel cell system
- Capacity for 3000 miles AIP
- Germany: Four hulls contracted: first to be commissioned in 2004, sea trials in 2002
- Italy: Two hulls contracted: first to be commissioned in 2005, launch 2002

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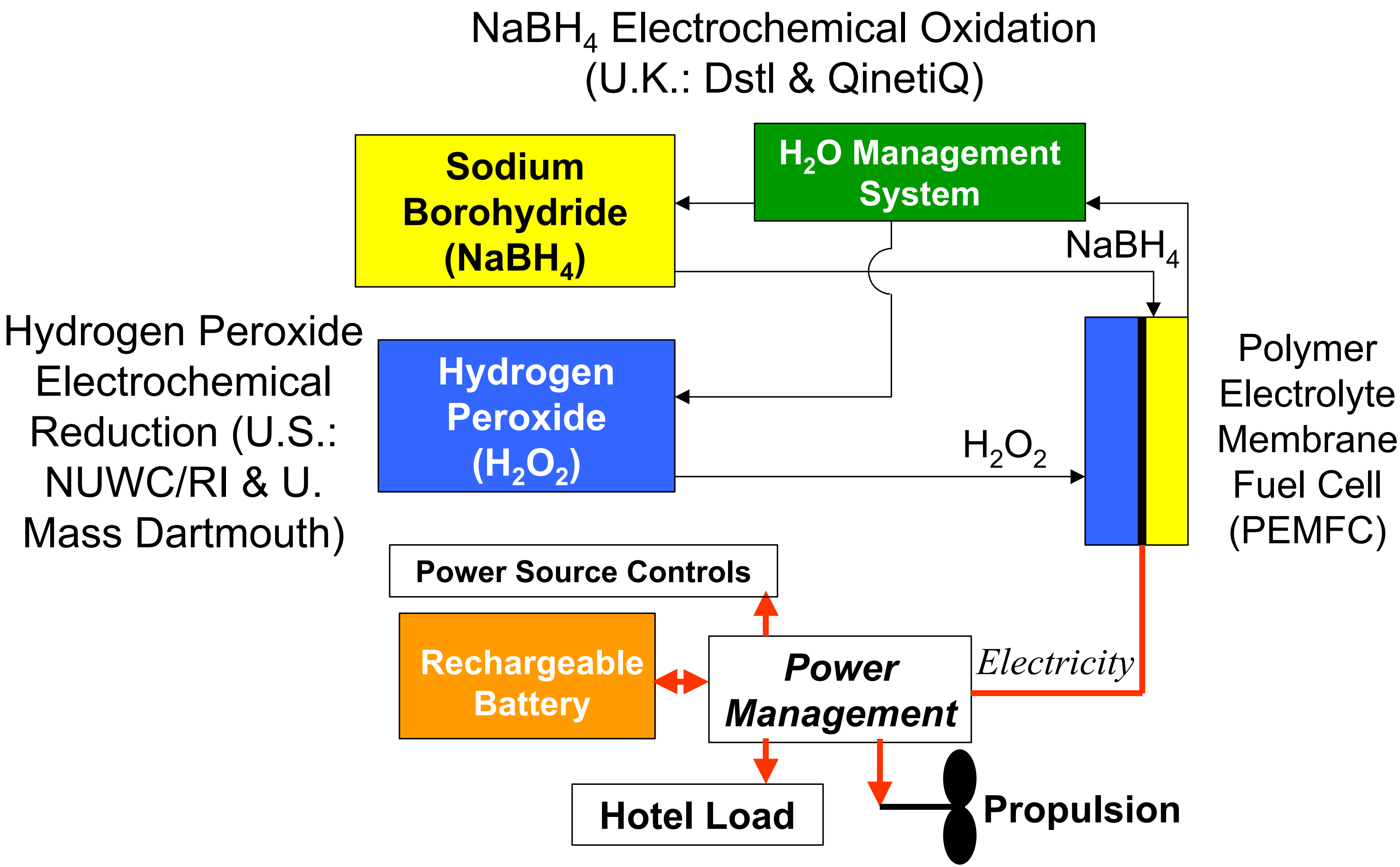
Autonomous Undersea Vehicles (AUVs) of the Future

Need high energy for long missions
➲ cannot be met with battery technology

U.S./U.K Joint Fuel Cell Program



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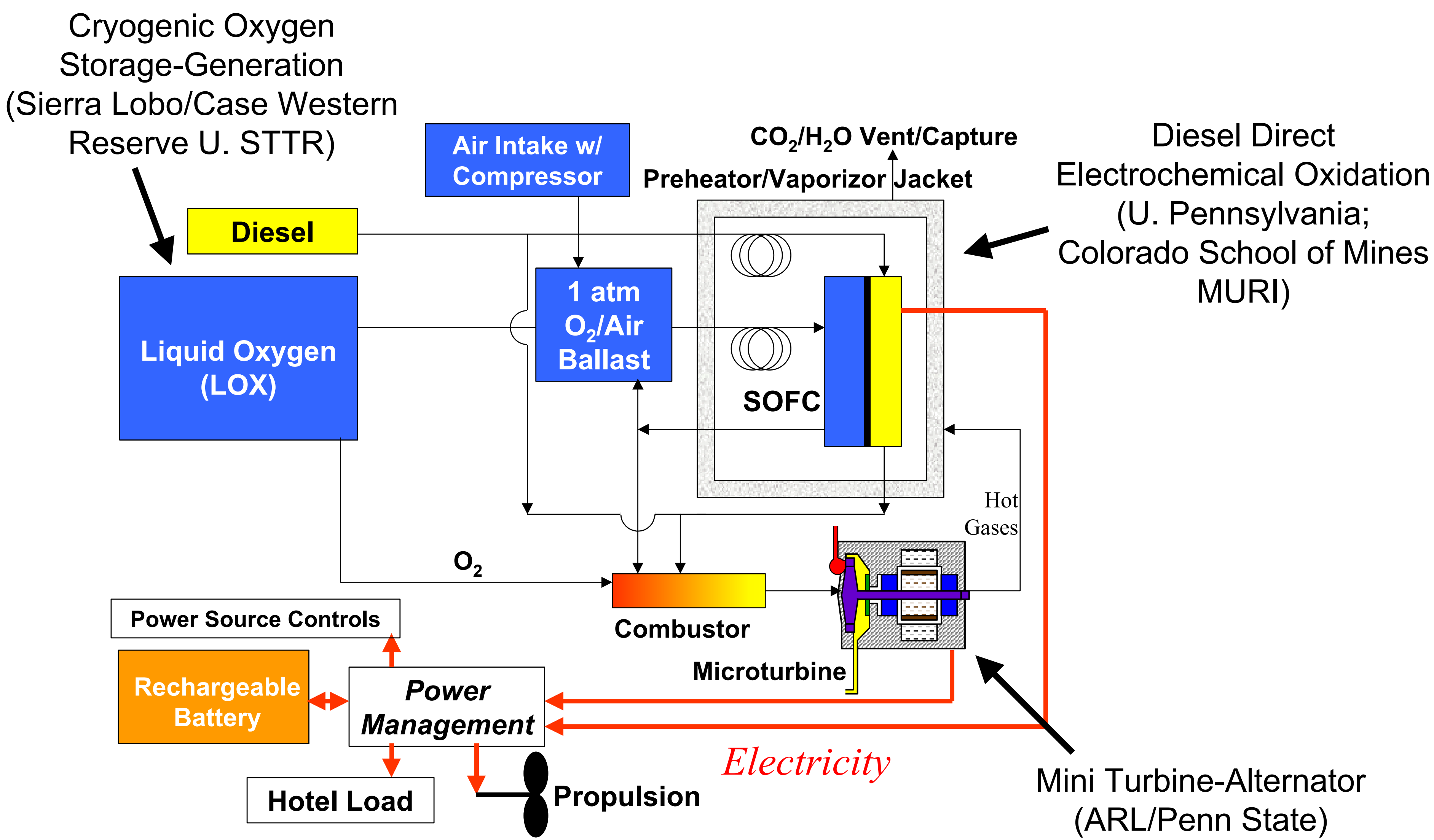
Solid Oxide Fuel Cell (SOFC) in Conceptual UUV Integrated Power System



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Grand Challenge

Electric Power Sources for the Navy and Marine Corps

Develop new, safe, efficient, environmentally friendly, non-petroleum based sources of power and power generation concepts that would support portable long-lived power sources for all future Marine-carried equipment and electric power sources required for all-electric ships and other Naval warfighting platforms

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Fuel Cells for AUVs

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Advantages

- Higher specific energy/energy density than batteries
- Potential to operate directly on logistics fuels
- Rechargeable

Challenges

- Full system integration to high energy system
- Efficient oxygen and fuel (hydrogen) storage
- Buoyancy of stored gases
- Maintaining center of mass

Near Future Opportunities

- Proton Exchange Membrane Fuel Cells with advanced oxygen and hydrogen storage capabilities

Navy-After-Next Opportunities

- Solid Oxide Fuel Cells operating on logistics fuels by direct oxidation/reforming at anode (no reformer needed)