Solid Oxide Fuel Cells in Undersea Vehicle Applications

NAVSEA WARFARE CENTERS NEWPORT

ONR Revolutionary Research . . . Relevant Results

U.S. DEPARTMENT OF ENERGY

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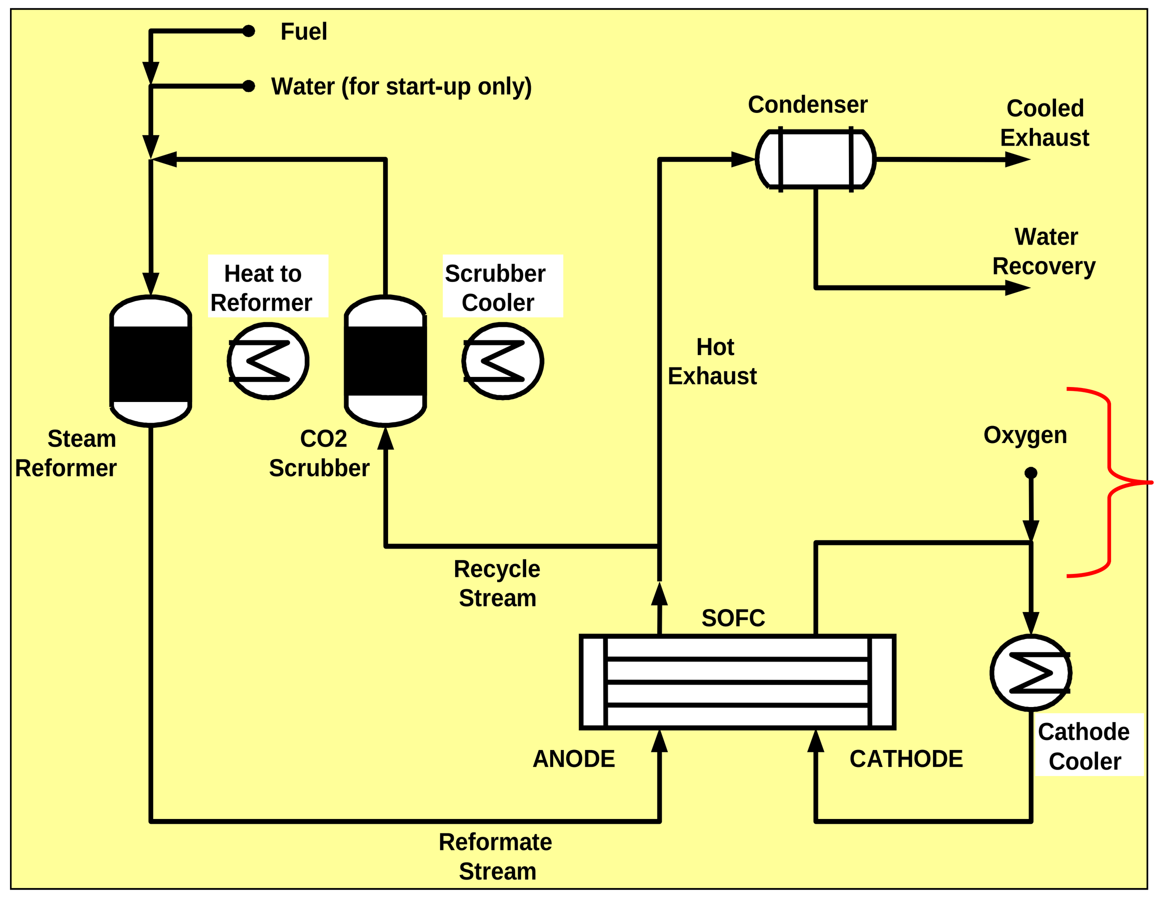
INTRODUCTION

- The U.S. Navy is currently investigating SECA solid oxide fuel cells for the propulsion of Unmanned Undersea Vehicles (UUVs).
- Key goal is to operate a SOFC power source on logistic (military) fuels in an air-independent environment.
- A typical UUV power source will consist of a SOFC stack(s), fuel processor, carbon dioxide scrubber, balance of plant components and fuel / oxidant storage.



- SOFCs offer several distinct advantages over rechargeable battery technology:
  - potential for achieving specific energy greater than 300 Wh/kg.
  - capable of utilizing energy-dense fuel (extended mission time)
  - "gas and go"--allowing a UUV to be re-launched at short notice.
  - self-sustaining while supplying heat to reforming processes.

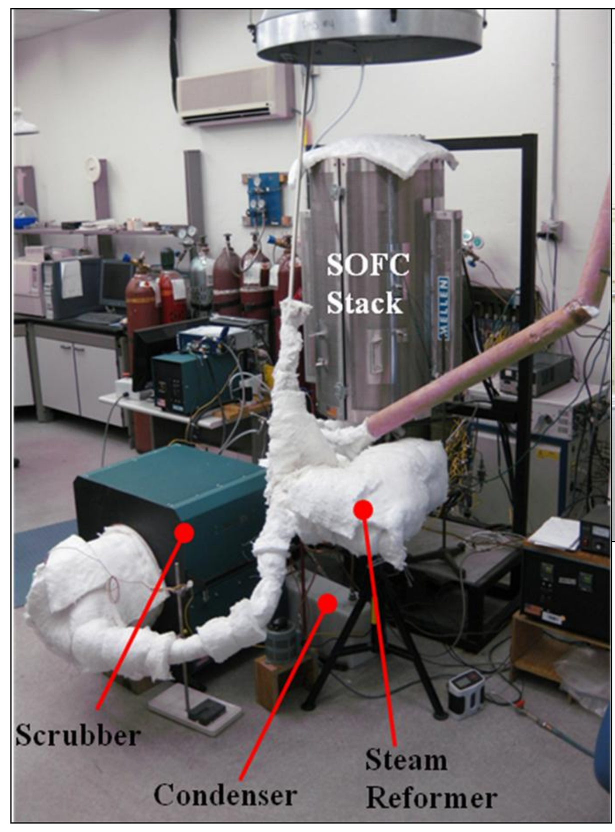
APPROACH

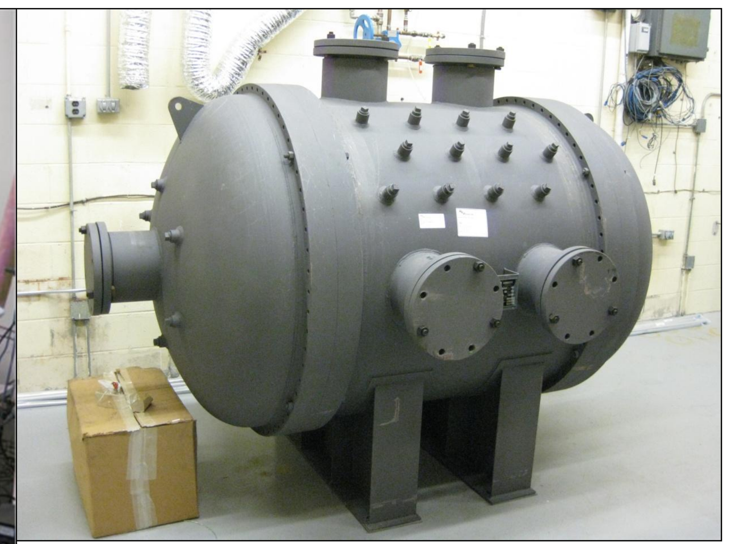
- Evaluate pressurization of planar SOFC stacks
- Test SECA SOFC stacks under pure oxygen and methane feeds
- Operate SOFC stacks and components under simulated UUV operating conditions, which is also similar to oxygen-blown coal gasifier plants with hot anode-gas recycle and CO_2 sequestration.

Why Methane ??

- Global Commodity, Secure Domestic Supply, Cost-effective
- Lower CO_2 emissions than logistics fuels, and highest demonstrated efficiency for SOFC systems (> 60% gross)
- Gaseous feed facilitates fuel reforming, start up, thermal management, and response to power or flow transients
- Liquid Methane (LM) has competitive energy metrics while offering enhanced reliability and efficiency

FACILITIES





50-inch ID vessel for pressurized SOFC stack and system demonstrations

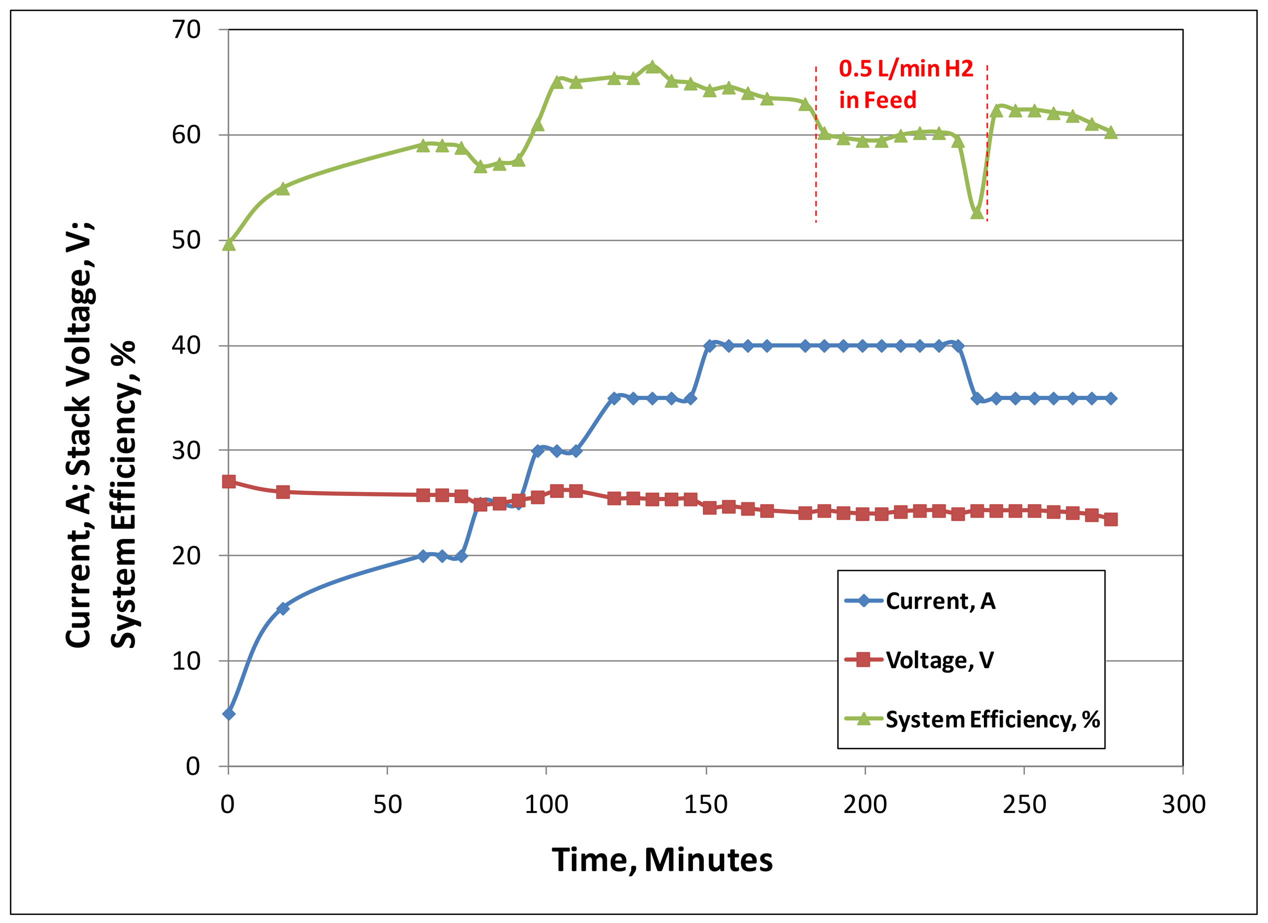
Experimental Facilities at NUWCDIVNPT

<u>30-cell Delphi Corporation SOFC Stack</u>

The Delphi stack tested was a Gen 3 design with 105 cm² cells. This stack design uses welded cassettes and glass-based seal, and it does not require external compression.

RESULTS

- Achieved continuous power output of 800 W (35 A at 24 V) with ~80% methane utilization, > 85% oxygen utilization, and > 60% gross system efficiency



Performance of the system demonstration in July 2011. Stack current, voltage, and system efficiency are plotted versus time. Supplemental hydrogen flow was added for a brief period to stabilize cell voltages, which were decreasing over time.

FUEL SELECTION

Reactants	Specific Energy, W-hr/kg	Energy Density, W-hr/L	Predicted Energy Metrics with Efficiency Noted
SOFC, LM/LOX with CO_2 sorbent and water storage	1100	705	315 W-hr/L @ 45%
SOFC, Methanol/ LOX, with CO_2 Sorbent	970	770	305 W-hr/L @ 40%
SOFC, S-8/LOX with CO_2 sorbent	1050	825	290 W-hr/L @ 35%
SOFC, JP-10/LOX with CO_2 sorbent	1000	800	280 W-hr/L @ 35%
PEM, Cryo-Compressed H_2 (7.5 wt.%)/ LOX with water storage	1370	540	270 W-hr/L @ 50%

Energy Metrics Include Reactants, Cryogenic Tanks, and Storage of Product Water and CO_2 for LDUUV. Packaging of fuel cell and related subsystems is <u>*not*</u> considered. System efficiency varied in relation to ease of reforming.

Fuel Type	Pros	Cons	Cost, $/kW-hr
S-8, JP-10	low flammability, high energy density	Expensive, complex reforming, shelf life	0.8
Methane	Cheap, Non-toxic, Non-corrosive	Cryo (<110 K)	0.0166
Methanol	Liquid at Room Temp., flammability < gasoline	Toxic, Corrosive, Hygroscopic	0.0184
Liquid H_2	No carbon emissions	Cryo (~ 20 K), Electrolysis for renewable	0.45

Why Pressurization ??

- ***<u>Stack efficiency</u>*** can be increased by ~ 3%, and this is primarily due to Nernstian and kinetic effects
- An estimated *7% <u>system level efficiency</u>* gain is associated with the *system-level energy storage.*
  - Reduced plumbing and parasitic power losses for recycling fuel and oxidant streams
  - Carbon dioxide sequestering is facilitated

All these system efficiency enhancements directly increase mission duration and system reliability.

<u>Gas Leakage</u>

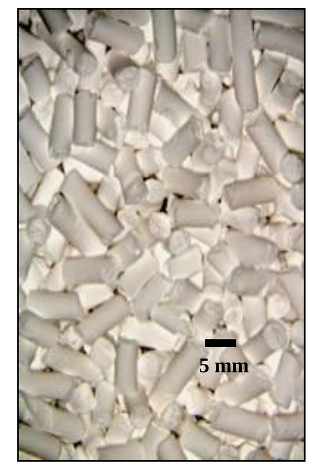
Stack performance was limited due to cathode cross-over of oxygen into the anode flow stream. Occurred near the stack exhaust manifold and affected performance because of the high anode recycle rates used in this study. Such cross-over is not acceptable for an anode-recycle system, and this decreases efficiency, power output, and lifetime.

CO_2 SEQUESTRATION

CO_2 removed from exhaust gas of SOFC via an active sorbent, calcium oxide-based, which is chemically converted to calcium carbonate at high temperature.

Over 50% mass gain demonstrated

$CaO + CO_2 \rightarrow CaCO_3$ + HEAT (178 kJ/mol)



<u>Manufactured by TDA Research, Inc.</u>

Pelletized CO_2 Sorbent

Large Displacement Unmanned Undersea Vehicle (LDUUV)

Full Specs available from ONR BAA 11-028

	Threshold	Objective
Nominal Power Density (Watts/liter)	0.4	0.6
Energy Section Length	304.8 cm (120'')	304.8 cm (120'')
Energy System Volume (liter) (see Figure 1)	3454(1) liters	3454(1) liters
Energy System Mass (kg)	3540(2,3)	3540 kg(2,3)
Energy System Buoyancy (kg)	0(3)	0(3)
Energy (kWh)	817(4)	1800(4)
Duration (hrs)	46 Days (1104 Hrs)	70 Days (1680 Hrs)

Note 1. Flooded volume with ambient seawater per the 42" X 42" X 120" inner hull geometry (reference Figure 1)
Note 2. Includes the fuel + oxidizer + tankage + BOP + Power converter + pressure vessel (if required) + ballast/syntactic-foam (if required) +seawater with a tolerance of +/- 50kg.
Note 3. Ambient seawater Specific Gravity of 1.025
Note 4. Includes an additional 10% of reserve energy beyond that required for power profiles in Figures 2 & 3.

Table 1: Threshold and Objective Metrics

CONCLUSIONS

- SOFC technology has the potential to greatly increase UUV mission time compared with current rechargeable battery technology.
- Methane shows promise for SOFC – powered UUVs, especially larger LDUUV
  - o Non-toxic
  - o Strategic resource
  - o Low CO_2 emissions per BTU
  - o High efficiency conversion
- SOFC stacks require further ruggedness and reliability for UUV application.
- Testing in 2013 will evaluate planar SOFCs at elevated pressure, matching external pressure to anode and cathode pressure to minimize gas leakage and enhance cell performance.