Pressurized Testing of Solid Oxide Fuel Cells

16th Annual Solid Oxide Fuel Cell (SOFC) Workshop

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Naval Undersea Warfare Center
Division Newport

Mission Statement

The Naval Undersea Warfare Center is the United States Navy's full-spectrum research, development, test and evaluation, engineering, and fleet support center for submarines, autonomous underwater systems, and offensive and defensive weapon systems associated with Undersea Warfare. (SECNAVINST)

A Navy Core Equity – A National Asset

Outline

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- Unmanned Undersea Vehicles (UUVs)
- Why Pressurized Operation?
- Test Facilities
  - Pressure Vessel (PV)
  - SOFC Test Stand
- Stack Test Results
  - Ambient
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- Summary

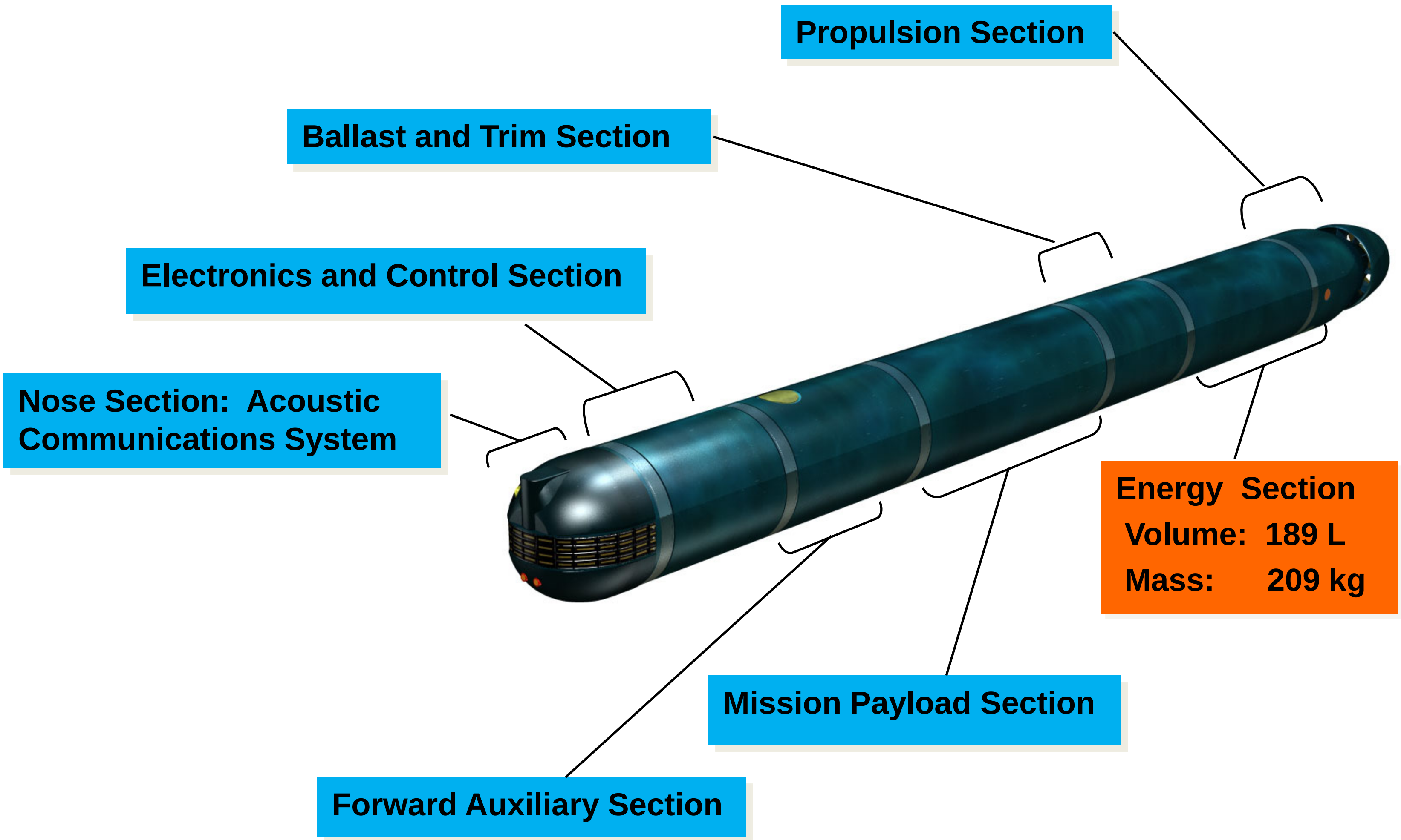
Introduction

- The Navy has a need for air-independent advanced electric power sources with high energy storage that will replace batteries in unmanned undersea vehicles (UUV) applications
- A typical UUV power source will consist of a planar SOFC stack(s), fuel processor, carbon dioxide scrubber, BoP components and fuel / oxidant storage vessels.
- SOFCs offer several distinct advantages over battery technology
  - Greater specific energy
  - Ability to utilize energy-dense fuels
  - Self-sustaining operation
  - “Gas and go” capability allows UUV to be quickly re-deployed
- Although planar SOFC stacks have demonstrated the highest efficiency and power density, concerns remain regarding their robustness, gas leakage, and long-term seal durability
- Pressurized operation should help mitigate these issues

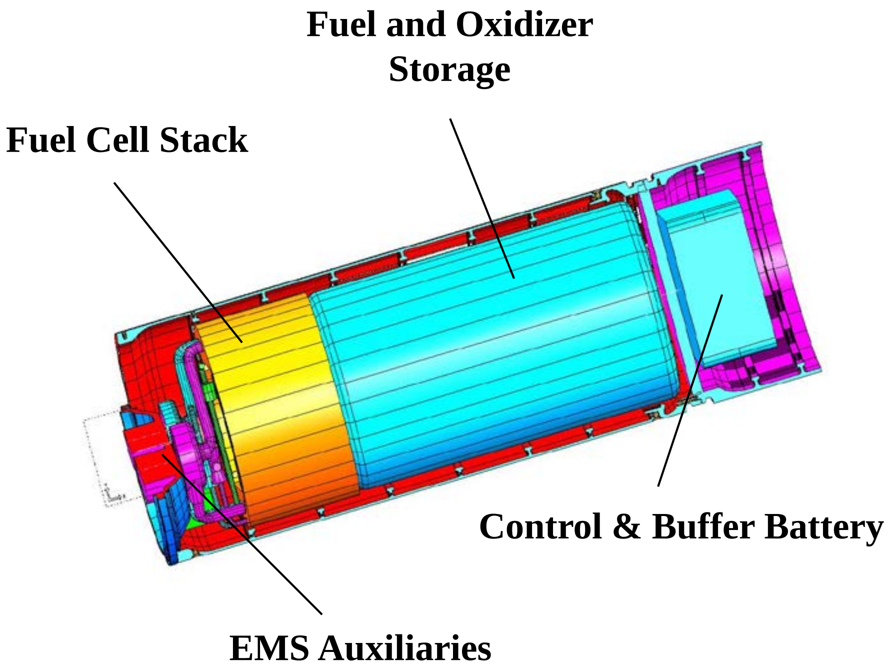
Autonomous Undersea Vehicles

Distribution Statement A - Approved for public release; distribution is unlimited

Conceptual 21-inch Diameter UUV



UUV Energy Section with Fuel Cell



Potential Benefits:

- **Longer UUV missions as a result of higher energy density**
- **Reduced down time between missions**
- **Decreased cost and increased safety versus lithium batteries**
- **Use of hydrocarbon fuels or even biodiesel**

Fuel / Oxidizer Choices

Fuel

- Hydrogen
  - compressed gas
  - cryogenic liquid
- Hydrocarbons
  - light (C_1 - C_4)
  - liquid (JP-8, diesel)
- Hydrogen-containing cpds
  - $LiAlH_4$
  - $NaBH_4$
  - Mg_2Ni (intermetallic)

Oxidizer*

- Oxygen
  - compressed gas
  - cryogenic liquid
- Hydrogen peroxide (H_2O_2)
- Oxygen-containing cpds
  - $KClO_4$
  - MnO_2

* Air-independent operation

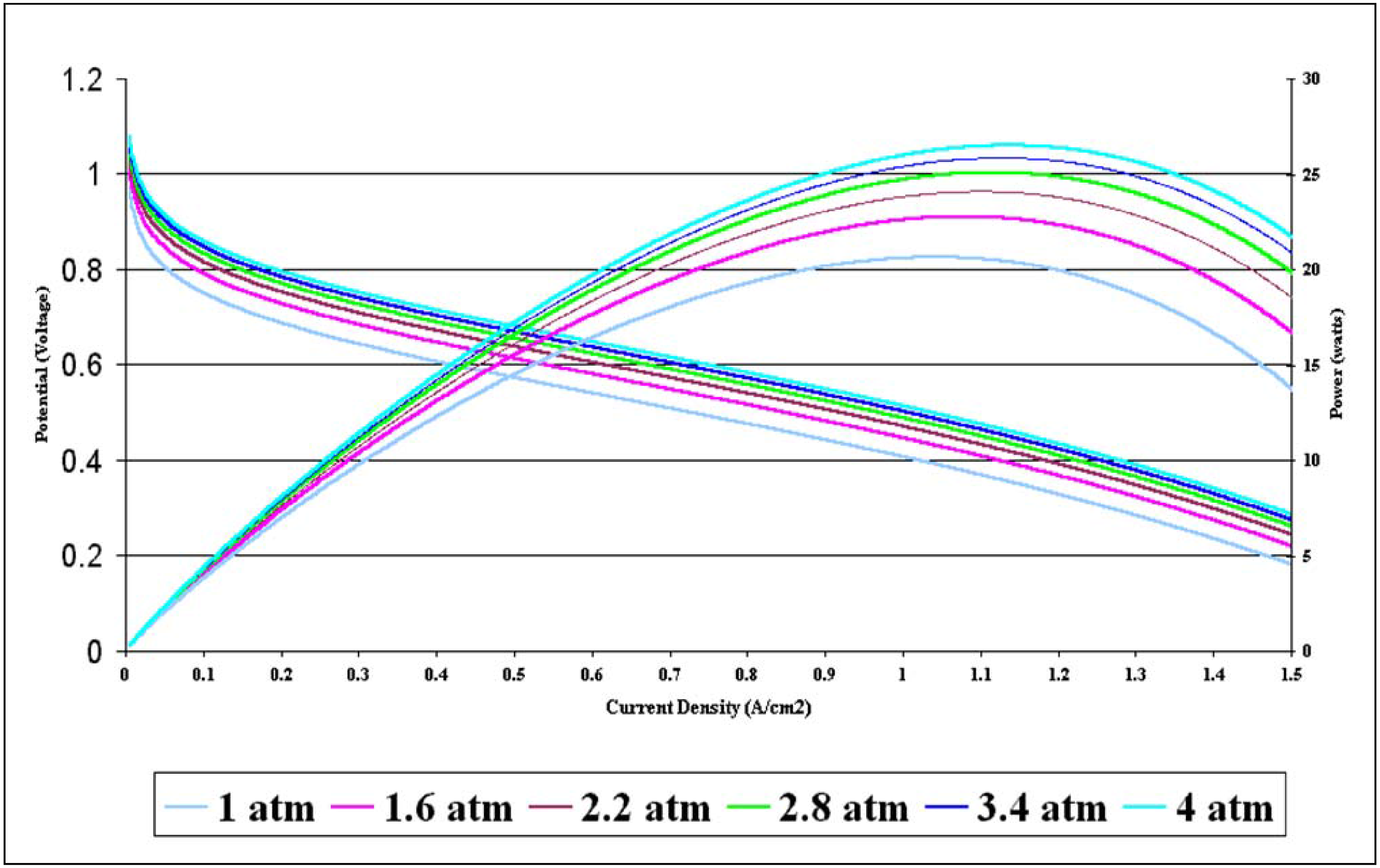
Why Pressurization?

Increase system performance, reduce SOFC losses

- ***SOFC voltage increases*** at higher pressures $$E = E_0 + \frac{RT}{nF} ln\left(\frac{p_{H2}\, {p_{O2}}^{1/2}}{p_{H2O}}\right)$$
- ***Stack efficiency*** enhanced by ~ 3%, due primarily to Nernstian and kinetic effects
- ***System efficiency*** associated with system level energy storage improves an estimated 7%
  - Lower parasitic power losses for recycling fuel and oxidant streams
  - Carbon dioxide sequestration is facilitated
  - Reduced plumbing requirements (e.g. circulation pump for anode recycle)
- ***Seal integrity*** maintained
  - High differential pressures between anode and cathode or process gas and atmosphere can cause seal between cells to fail.
  - Balance external stack pressure with process gas pressure to minimize driving force for gas leakage.

Enhanced efficiency increases system reliability and mission duration

Increased Performance



Elevated Pressure Operation

Goals

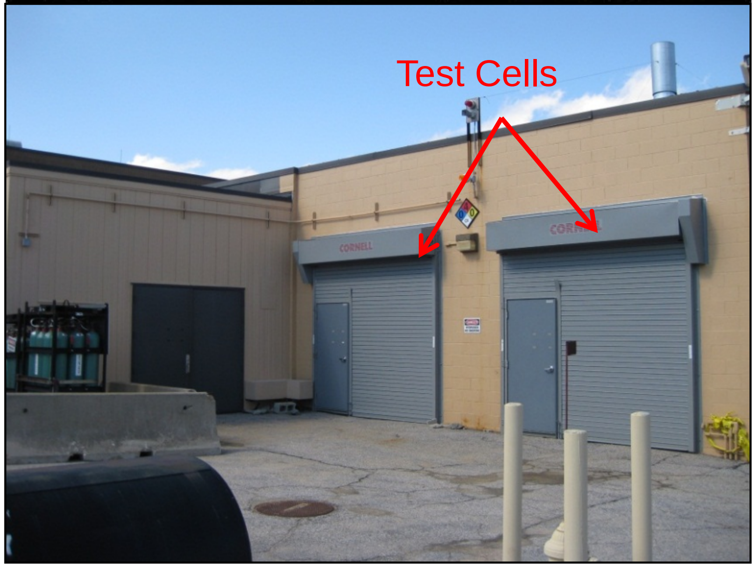
- Evaluate SECA-sponsored SOFC stacks at elevated pressure
- Construct test stand for pressurized testing of planar stacks
- Operate at elevated pressure to increase system performance and stack reliability
  - Implement algorithms for automated regulation of temperature and pressure set point tracking
  - Control three zones (anode, cathode and ambient (pressure vessel) in order to minimize pressure differentials across stack components

Test Objectives

- Establish performance of SOFC stack at ambient pressure
- Demonstrate enhanced performance at elevated pressure with air
  - Examine effects of pressure (up to 45 psia) on voltage and efficiency
  - Monitor any gas leakage as a function of operating pressure
- Extend pressurized testing to include oxygen as the oxidant

Test Facility

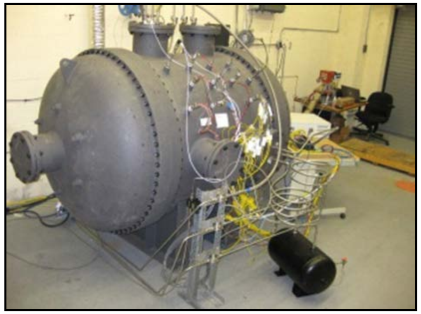
- Air Independent Propulsion (AIP) test facility at NUWCDIVNPT for long duration testing of electrical energy sections for UUVs
  - High and low temperature fuel cells
  - Pressurized fuel cell testing
  - Motors/Power electronics
  - Engines/Power systems (Stirling)
  - Reactant delivery systems



Remote operation from central control room

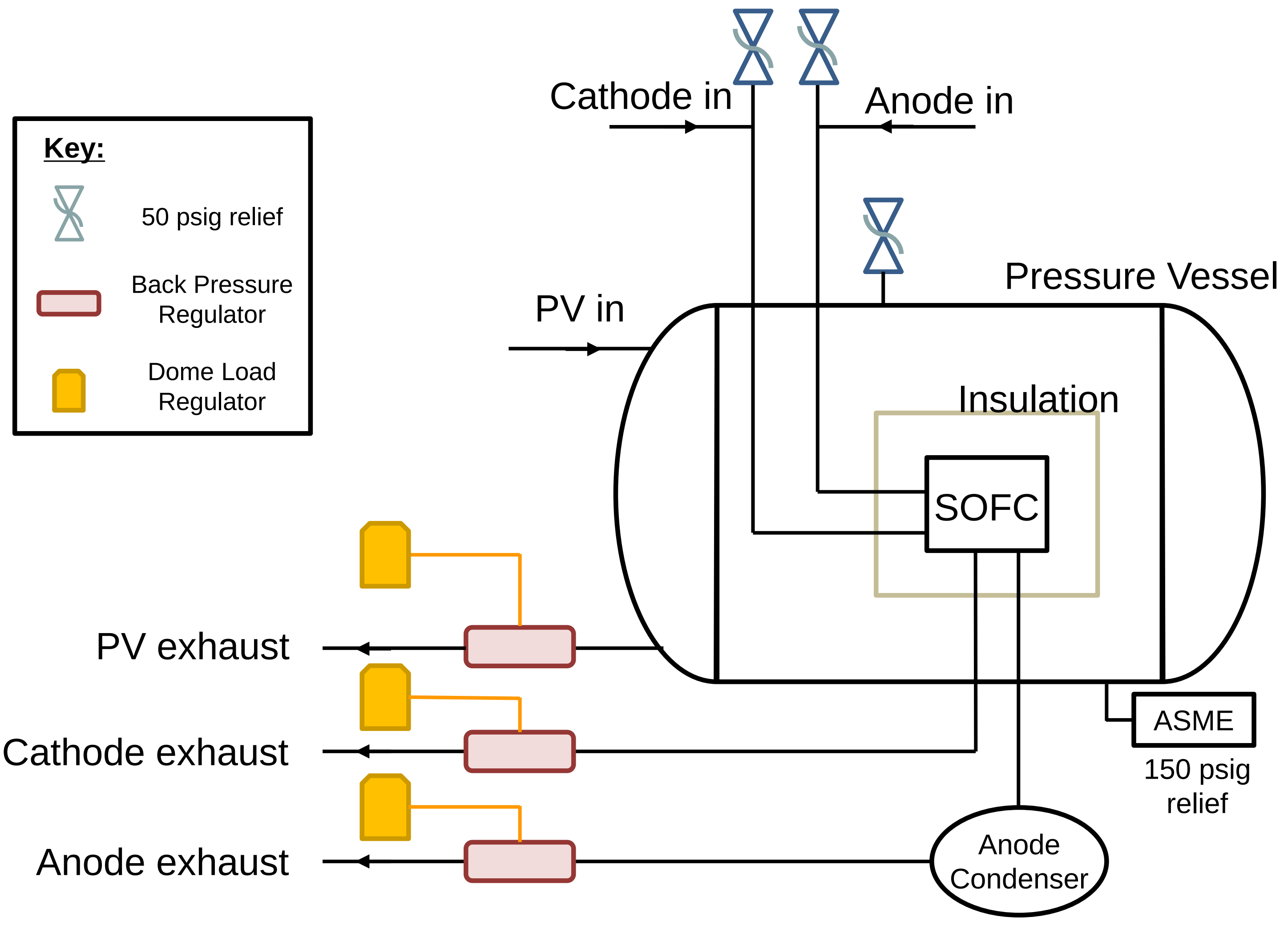
Pressure Vessel

- Carbon steel pressure vessel (50-in ID) rated to 150 psig at 250°C
- ASME-rated relief valve (0.5-in ID)
  - Protects integrity of the pressure vessel (PV)
  - Will not re-close once it has opened

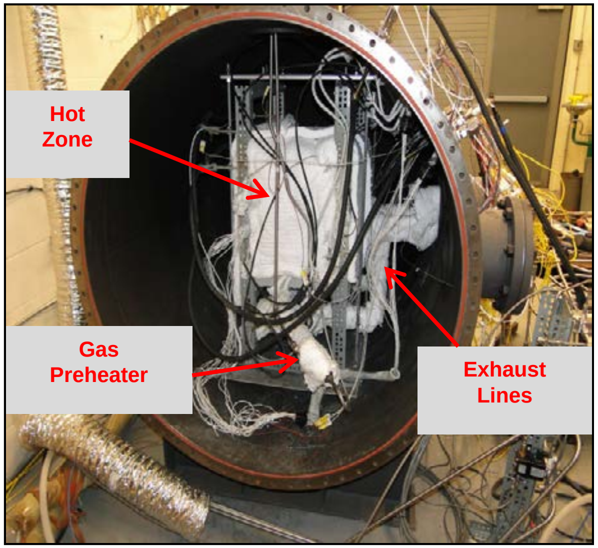


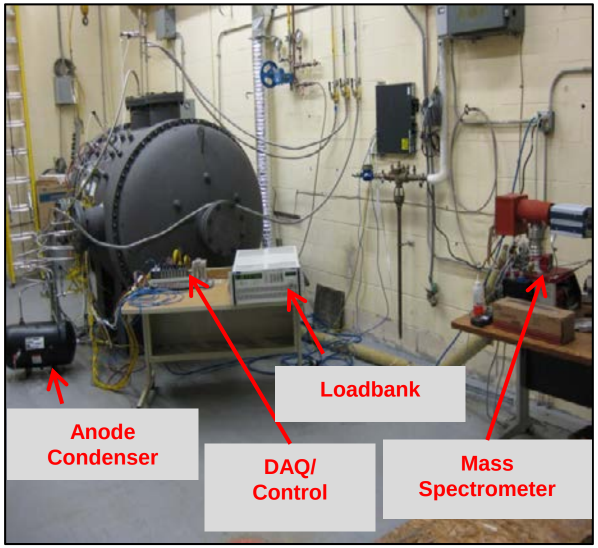
- Supplemental relief valves (0.25-in ID)
  - Installed on anode inlet, cathode inlet and PV
  - Pre-set for each specific test to prevent over-pressurization
- Equilibar® back pressure regulators
  - Installed on the exhaust of each pressurized zone (anode, cathode and PV)
  - Automatically open in case of abort condition or power loss
- Gas flow
  - Capacity up to 700 SLPM total flow in
  - Gas composition sampled via mass spectrometer (MS)
- Temperature monitored in process lines and pressure vessel

Pressure Vessel Schematic



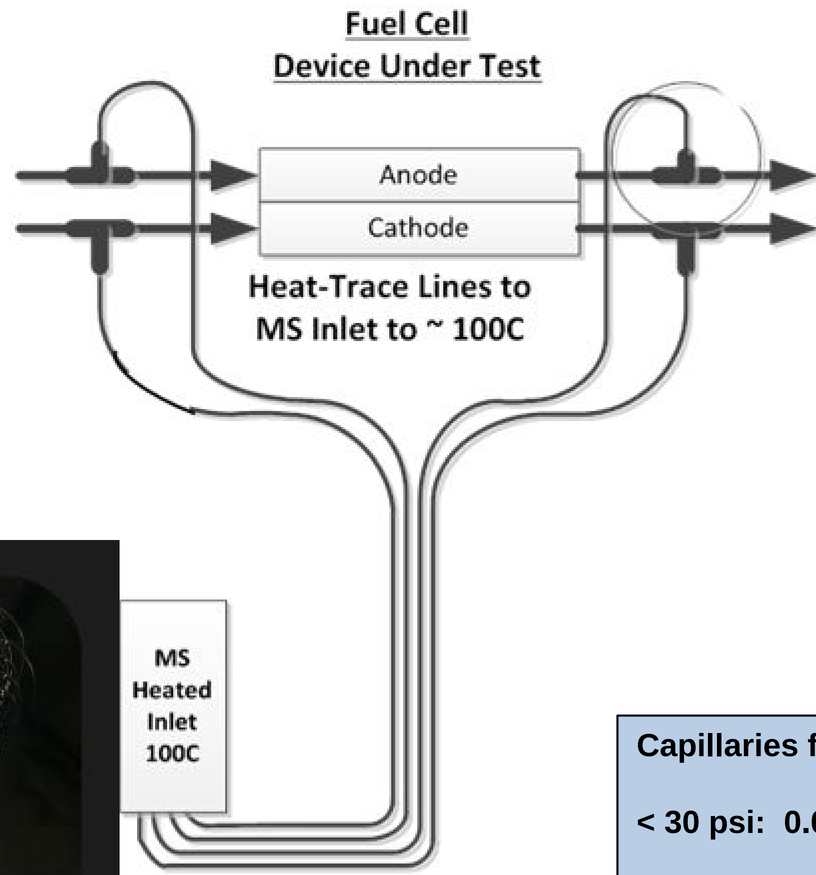
Pressurized SOFC Test Stand

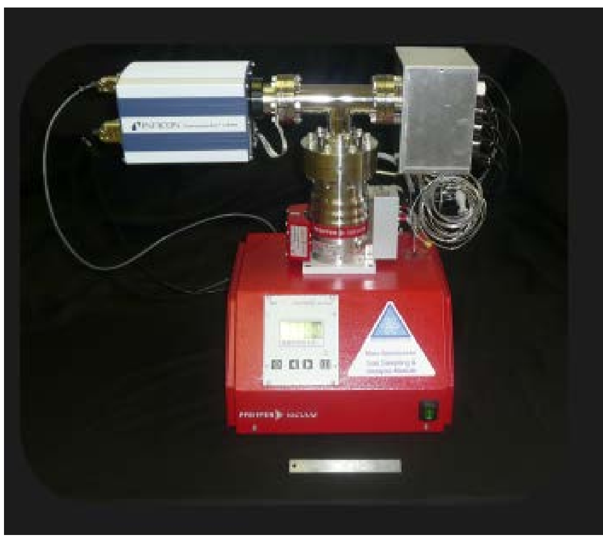




- 50” ID carbon steel pressure vessel rated to 150 psig at 250ºC
- Hot box consisting of four heating elements constructed around stack
- Inline heaters for preheating anode and cathode reactant gases
- Gas sampling at 7 locations via mass spectrometer
- Voltage monitoring of individual cells

Mass Spectrometer Sampling





Capillary sampling lines:
- anode in
- anode out
- cathode in
- cathode out
- pressure vessel

Gas sampling of up to 7 locations is possible

Capillaries for processes:

< 30 psi: 0.010” ID x 1/16” OD

30 psi < P < 50 psi: 0.007” ID x 1/16” OD

Delphi Gen IV Stack

- **Number of cells: 10**
- **Individual cell area: 403 cm^2**
- **Stack Assembly**
  - **Laser-welded cassette**
  - **Glass ceramic seals**
  - **Stainless steel manifold**
  - **Co-flow gas design**

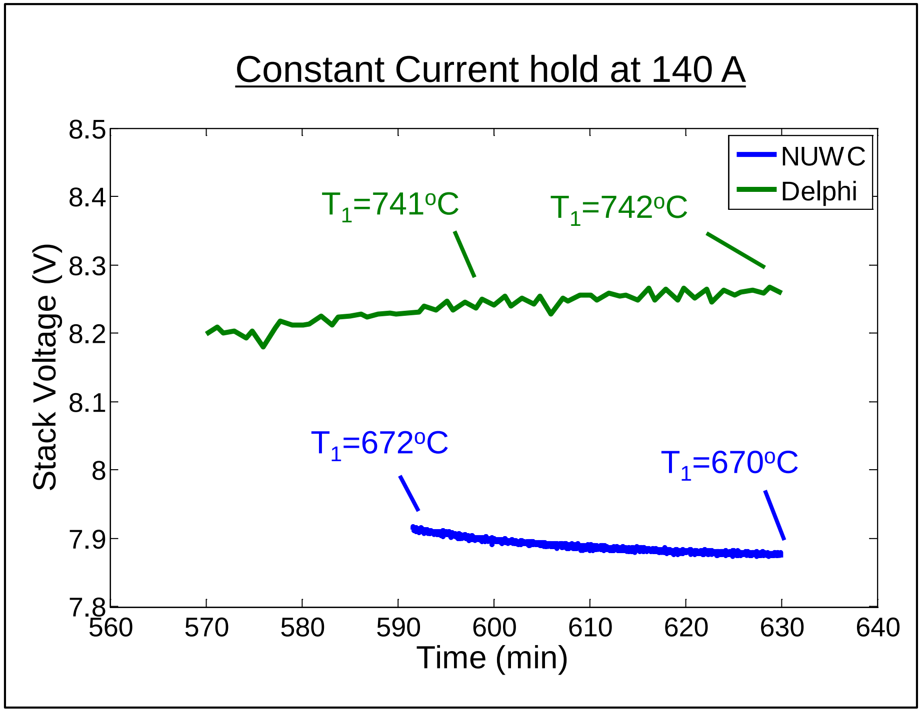
- **Test conditions**
  - **Gases:**

    Anode $x_{H_2} = 0.5$, $x_{N_2} = 0.5$ **(dry)**

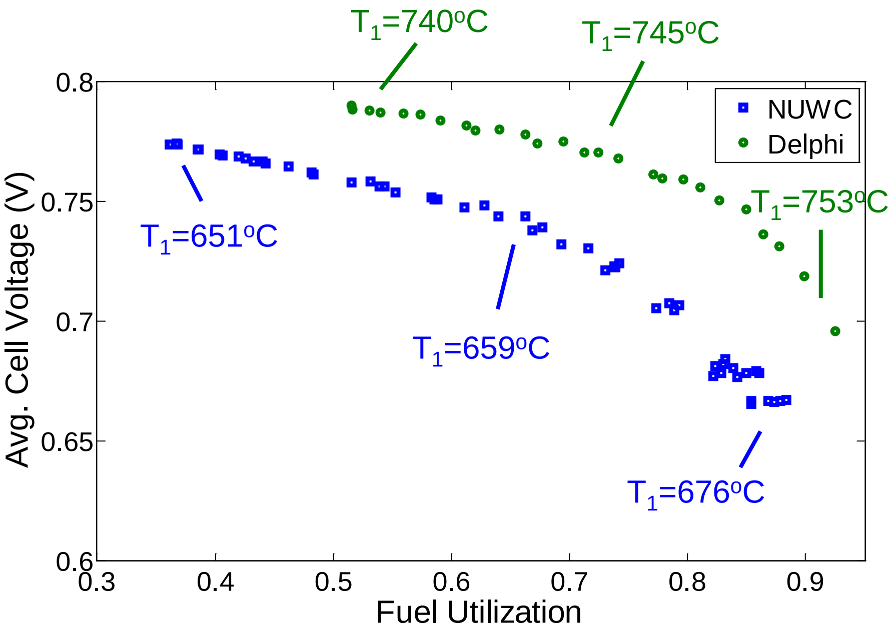
    Cathode **air / oxygen**
  - **Pressure: 1 to 3 atm**
- **Power output : 1.75 kW (240 A, 7.3 V) at 50% fuel utilization at 700°C with all zones at 45 psia**

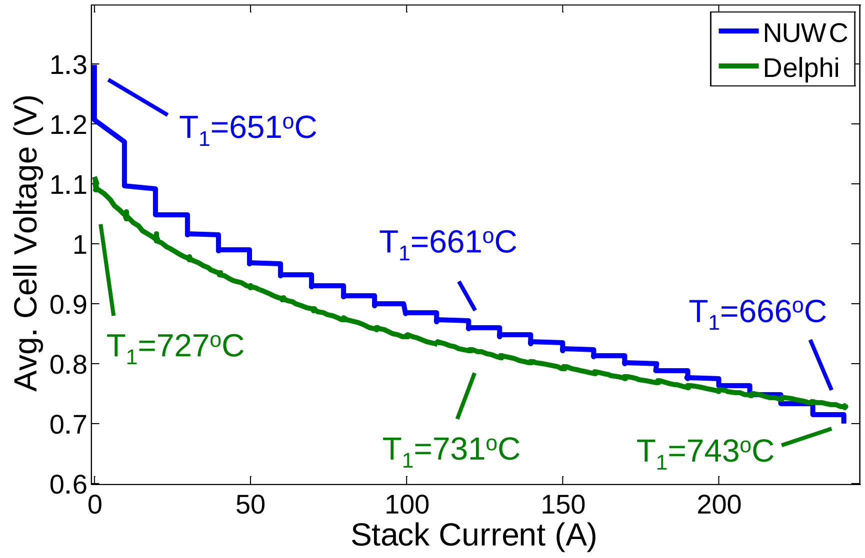
Ambient Test Results

- Tests performed by Delphi prior to stack delivery and data provided to NUWC
  - Constant Current hold
  - Fuel utilization sweep
  - Polarization curve
- NUWC started operations by ramping current to 240 A, reaching an operating power level of 1.7 kW
- Current lowered and held at 140 A
- Stack temperature limited by inlet gas preheating
  - Lower air flows used to keep higher inlet gas temperatures
  - Lower stack temperature while under a load resulted in lower voltage
  - Stack temperature largely dependent on internal heat generation from load



Ambient Test Results

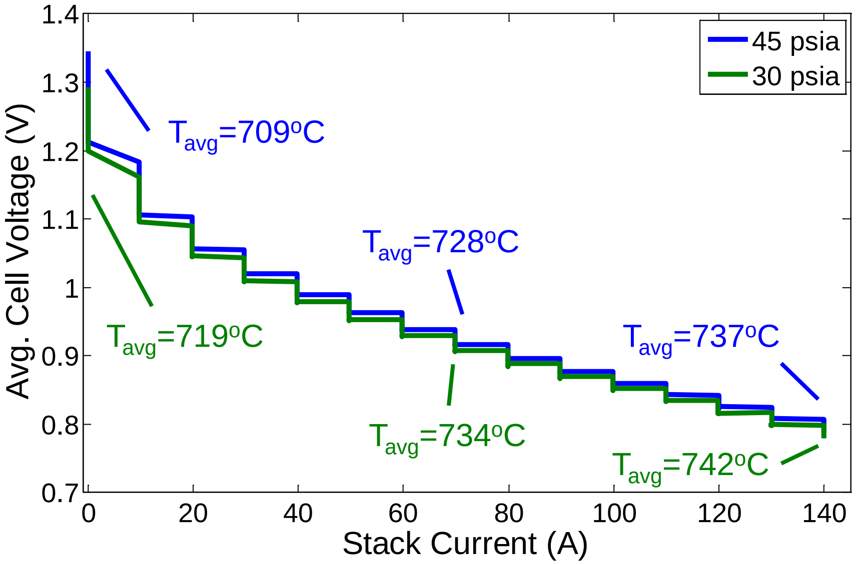




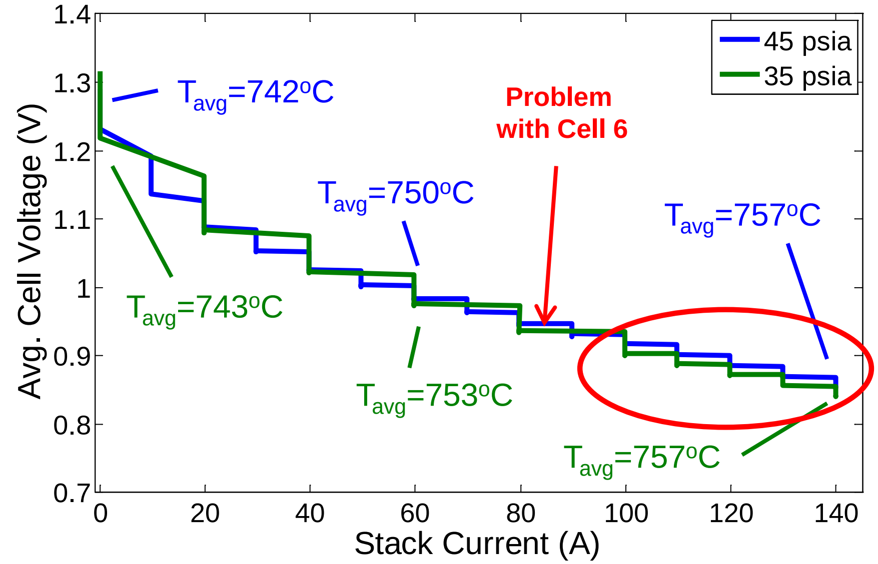
- **50% H_2: 50% N_2 flow lowered under constant 180 A load and constant air flow**
  - **Results were comparable with offset due to lower operating temperature**
  - **Lower flow resulted in increase fuel utilization and stack heating**
- **Polarization curve collected from 240 A decreasing 10 A per 30 sec**
  - **Temperature change is inherent in SOFC polarization, but larger changes than expected were due to lower inlet temperature and flows**

Pressurized Test Results

Air

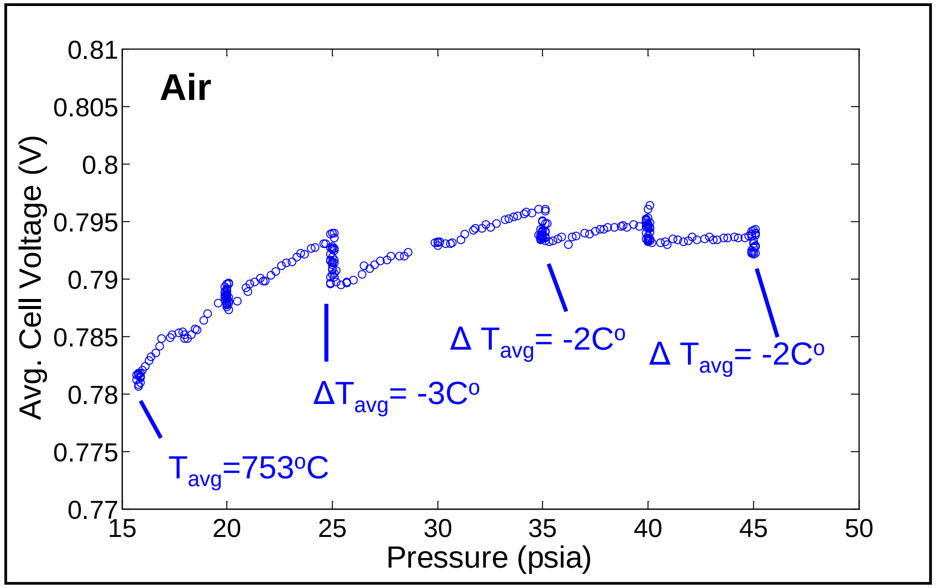


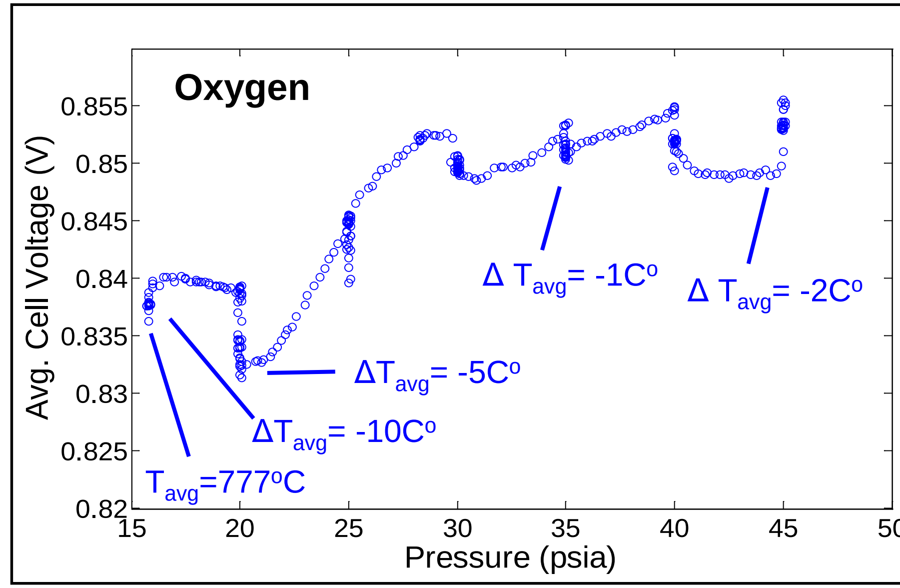
Oxygen



- **Pressurized polarization curves collected after pressurization to 45 psia while held at 140 A and constant fuel and oxidant flows**
- **Higher pressure resulted in higher voltage (efficiency), even with a lower stack temperatures**
- **Temperature decreased with increase in pressure due to increase in gas density and specific heat, resulting in an increased cooling effect from the reactant gases**

Pressurized Test Results





P (psia)	15-20	20-25	25-30	30-35	35-40	40-45	Total
Δε (%)	0.64	0.48	0.16	0.16	0.16	0.08	1.68

P (psia)	15-20	20-25	25-30	30-35	35-40	40-45	Total
Δε (%)	0.136	0.984	0.328	0.336	0.32	0.288	2.392

- **Constant current steady state operation**
  - **140 A load, constant gas flows**
  - **Pressurized at 0.5 psi / min**
- **Increase in voltage even with continuous decrease in stack temperature as pressure was increased (pre-heating of reactant gases insufficient)**
- **30 minute hold every 5 psi resulted in further cooling and decrease in voltage**
- **Largest efficiency gains over first 10 psi increase, higher gain for oxygen**

Summary

- Delphi Gen IV 10-cell stack was tested at pressures up to 45 psia with both air and pure oxygen
- Efficiency gain of 2.4% and 1.7% demonstrated at 45 psia for oxygen and air, respectively
- Combined efficiency gain of almost 6% was observed for oxygen at 45 psia vs. air at 15 psia
- Limitations reaching and maintaining stack temperature due to insufficient capacity of inline gas heaters
- Fuel cell technology has the potential to greatly increase endurance of UUV missions over current battery technologies
- A minimum of 10-15 thermal cycles will make SOFCs economically competitive with Li-based battery systems

Acknowledgements

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Delphi Corporation

Dr. A. Alan Burke (Chemours)

Efficiency Calculation

Efficiency = f (i, T, P, utilizations, reactant feeds, stack materials; significant increase in performance occurs at 3 to 4 atm

<u>Relative Efficiency Gain</u>

- **Calculated by comparing operating voltage at elevated pressure vs. ambient pressure**
- **Difficult to make comparisons of stacks with different designs and operating conditions**

<u>Absolute Efficiency Gain</u>

- **Voltage gain vs. total fuel value entering the system**
- **Equate voltage to Lower Heating Value (LHV) of hydrogen (-241.8 kJ/mol)**

$$E_{LHV} = -\Delta H_{LHV} / nF = 1.25\ V$$

- **Gross SOFC efficiency (ε) with reference to LHV (H_2)**

$$\varepsilon = V_{cell} / 1.25V * 100\%$$

- **Absolute efficiency gain ($\Delta\varepsilon$)**

$$\Delta\varepsilon = \Delta V_{cell} / 1.25\ V * 100\%$$

where ΔV_{cell} is the pressure-induced voltage change