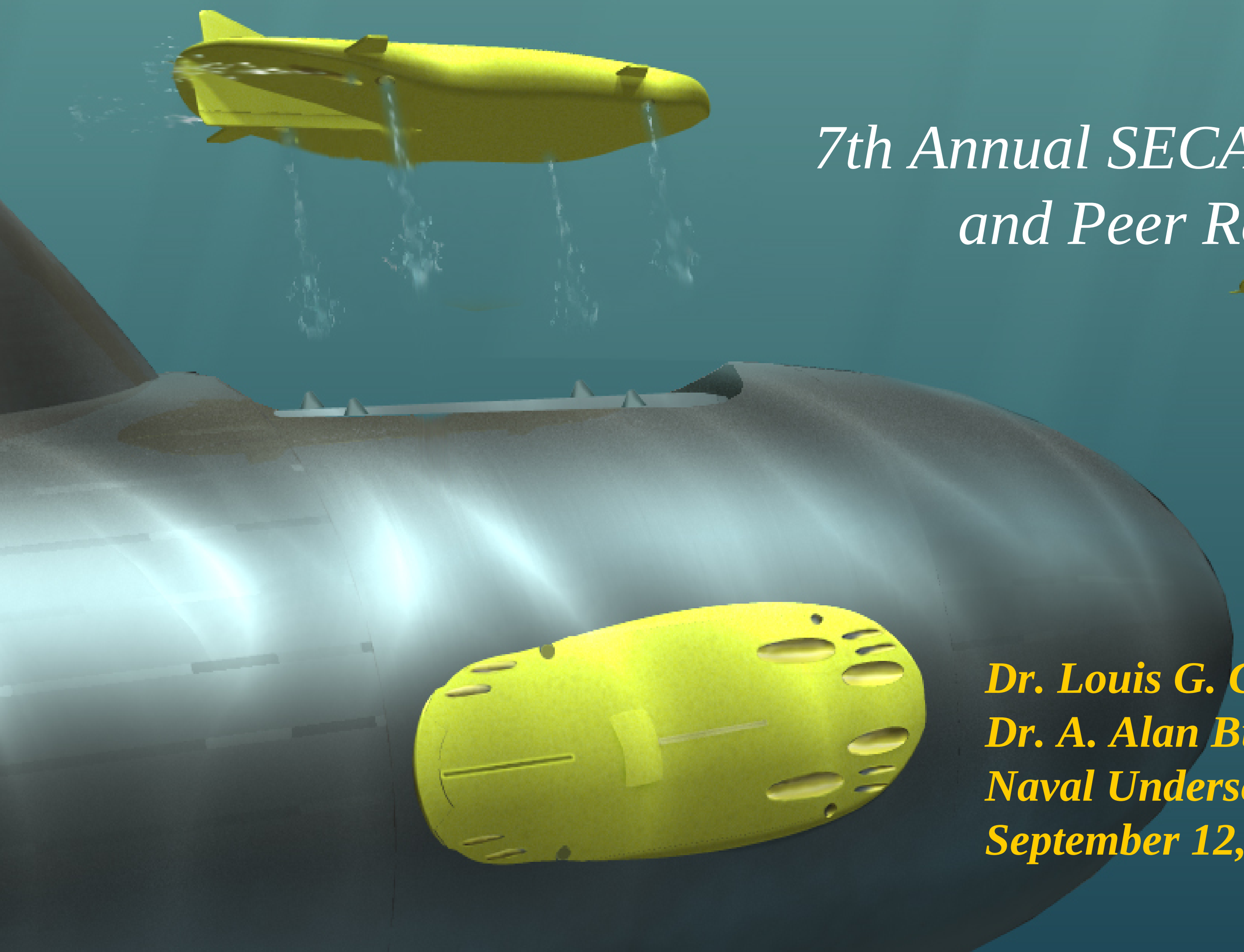
# Unmanned Underwater Vehicles



7th Annual SECA Workshop
and Peer Review

**Dr. Louis G. Carreiro**
**Dr. A. Alan Burke**
**Naval Undersea Warfare Center**
**September 12, 2006**

# Outline

I. Introduction to NUWC

II. Background on UUVs

III. UUV Energy Requirements

IV. SOFC Stack Testing

IV. System Design

V. Related Programs / NAVSEA Fuel Cell Activities

VI. Summary


NAVSEA
NEWPORT
Undersea Warfare Center Division

# Part of the NAVSEA Team

**Commander**
**Naval Sea Systems Command**

**Naval Undersea Warfare Center**

**Naval Undersea Warfare Center Division Keyport**

- In-Service Fleet Support
- Test, Training & Evaluation
- Depot / Industrial

**Naval Undersea Warfare Center Division Newport**

- Research
- Development
- Test, Training & Evaluation
- In-Service Engineering

**Working Together to Deliver the Best Solutions Quickly**

## 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)

## Repository of USW knowledge

- **Highly trained and experienced workforce**
- **Unique disciplines enable constructive collaboration with private sector and academia**
- **State-of-the-art tools and facilities**

**A Navy Core Equity – A National Asset**

# Mission Functions

***Products:***

- USW Combat Systems
- Sonar
- Torpedoes, UUVs Targets & Countermeasures
- Launchers
- Electronic Warfare
- Ranges
- Communications
- Periscopes


***Services:***

- Warfare Analysis
- R&D
- Modeling, Simulation & Analysis
- Technical Design Authority
- Installation
- In-Service Engineering
- Systems Maintenance
- Technical Assistance

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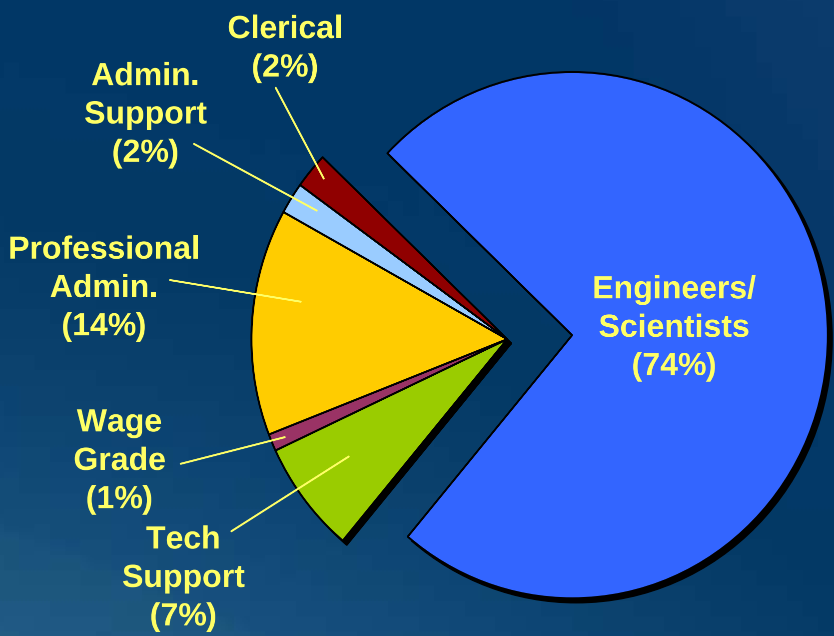
# NUWC Workforce

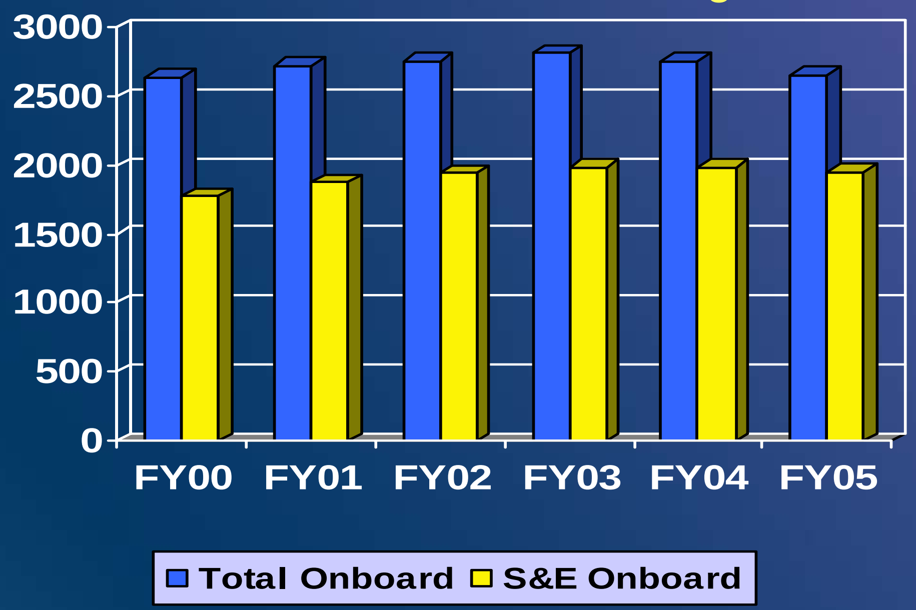



**FY06**

| | |
|---|---|
| Civilian | 2800 |
| Military | 42 |

## *Advanced Degrees*

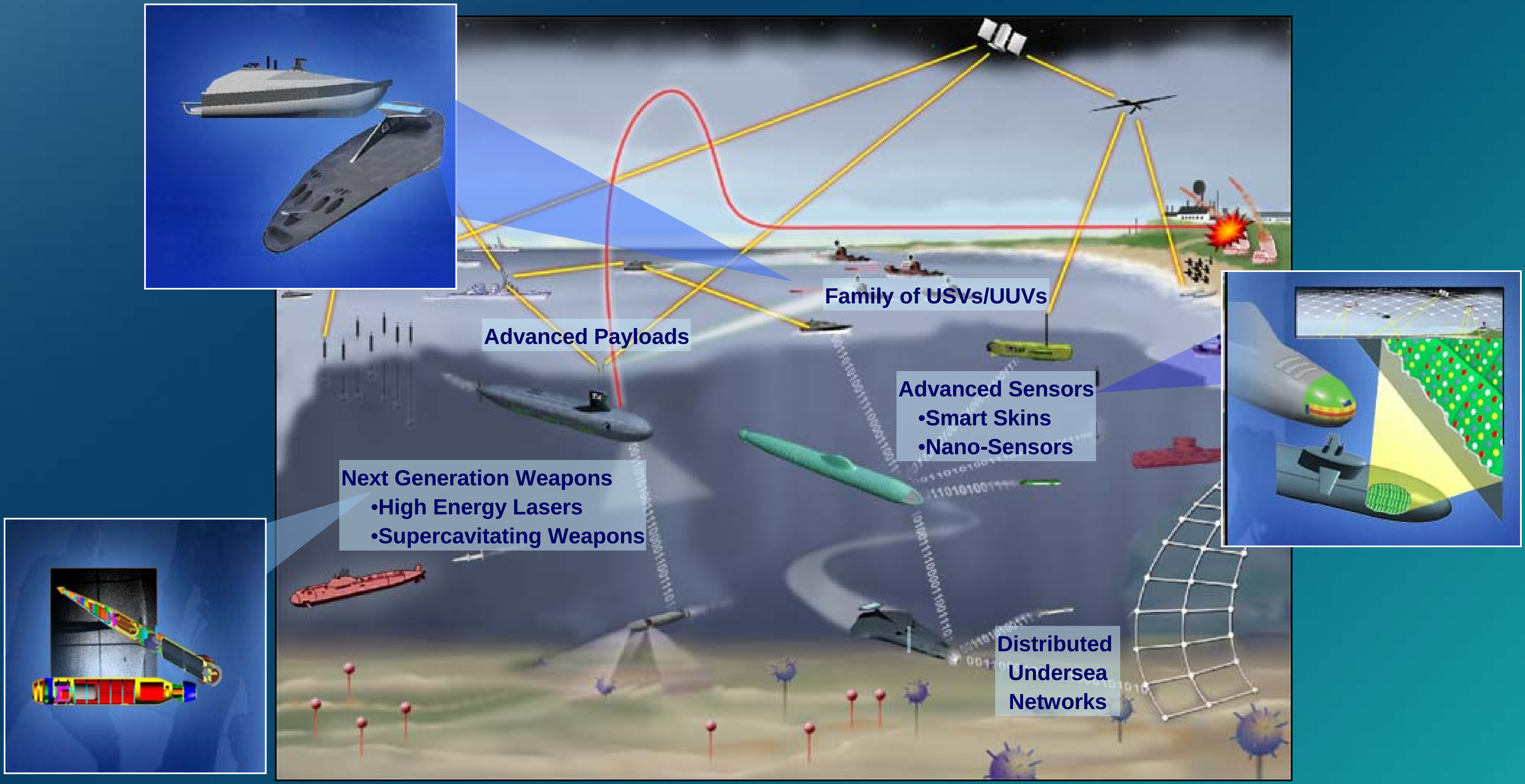
**45 % of Our Scientists and Engineering Staff Have Advanced Degrees**




***74% Of Our Workforce are Engineers and Scientists***

***Advanced Degrees - 143 PHD's (8%) And 730 Master's (37%)***

# NUWC's Contribution to the Navy After Next




**SEAPOWER 21 – Transformation for the Navy**

NAVSEA WARFARE CENTERS NEWPORT

# Nine UUVMP SeaPower 21 Sub-Pillar Capabilities

| Force Net | Sea Shield | Sea Base | Sea Strike |
|---|---|---|---|
| • ISR [1]<br>• Oceanography [5]<br>• Communication Navigation Network Nodes (CN3) [6] | • Littoral Sea Control<br>  • ASW [3]<br>  • MCM [2]<br>• HLD - AT/FP<br>  • Inspect/ID [4] | • Payload Delivery [7] | • Information Operations [8]<br>• Time Critical Strike (TCS) [9] |

| Class<br><br>Diameter | Displacement (lbs) | Endurance High hotel Load (hours) | Endurance Low hotel load (hours) | Payload ($ft^3$) |
|---|---|---|---|---|
| Man Portable 3-9” | <100 | <10 | 10-20 | <0.25 |
| LWV ~12.75” | ~500 | 10-20 | 20-40 | 1-3 |
| HWV ~21” | <3000 | 20-50 | 40-80 | 4-6 |
| Large >36” | ~20,000 | 100-300 | >>400 | 15-30 + external stores |

*In four vehicle classes…*


EMATT
MK30 MOD 2
MK30 MOD 1
REMUS
MARV
21UUV
NMRS
MRUUV FLT1
LMRS
U.S. NAVY
MRUUV FLT2
U.S. NAVY
MTV
MANTA
Autonomous Undersea Vehicles

# NUWC Demonstration UUV's


## REMUS (50-100 watts)

- Hundreds of In-Water Runs
- Oceanographic Sensors
- Chemical Sensors
- Acoustic Communications
- Hull Inspection Camera Suites

21”
Diameter

## 21UUV (2-5 kW)

- > 100 In-Water Runs
- Acquisition Program Risk Mitigation
- Vision Based Navigation, Camera Suites, Photo Mosaic's
- Side Scan Sonar Imagery
- “Electric Torpedo” Testbed and Weapon Launch from MTV
- Autonomous Controller Experiments


## MARV - Mid-sized Autonomous Research Vehicle

- Technology Demonstrations for Various S&T Programs
- Low Speed Control and Hover Payload (Thruster Based) Demonstrations
- Imaging Sensor Evaluation
- Homing and Docking Demonstrations **(800-1000 watts)**


## MTV - Manta Test Vehicle (5-10 kW)

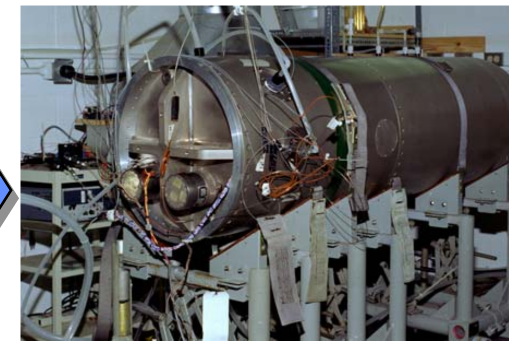
- > 90 In-Water Runs
- Multiple UUV and Weapon Launch
- Advanced ISR Suites – RADINT, SIGINT, Optics, IR
- Deployed ASW Systems
- Advanced Networked Communications

# UUV Energy Source Development

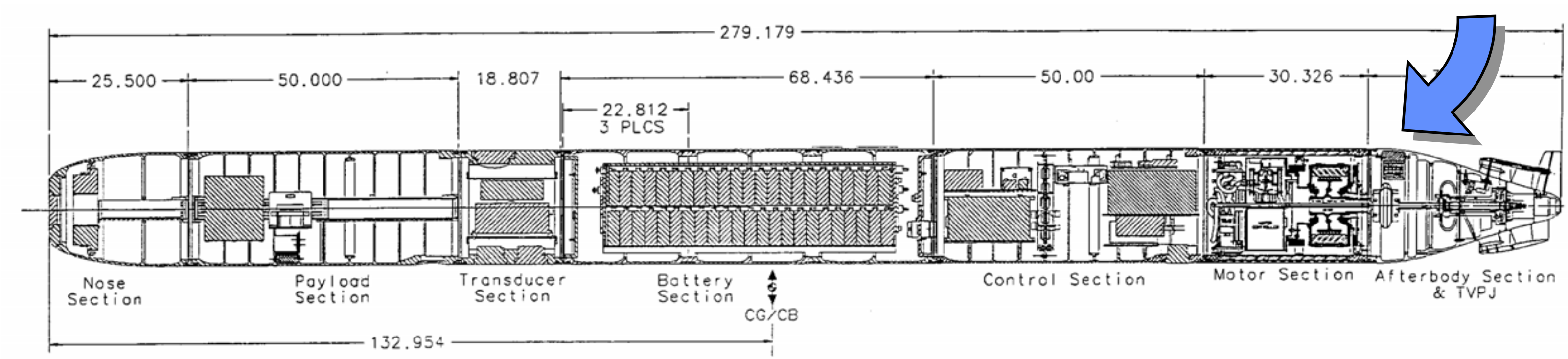
***Stack Testing***

***Component Lab Testing***


***Prototype Fab***



***Integrate & Land Based Test***

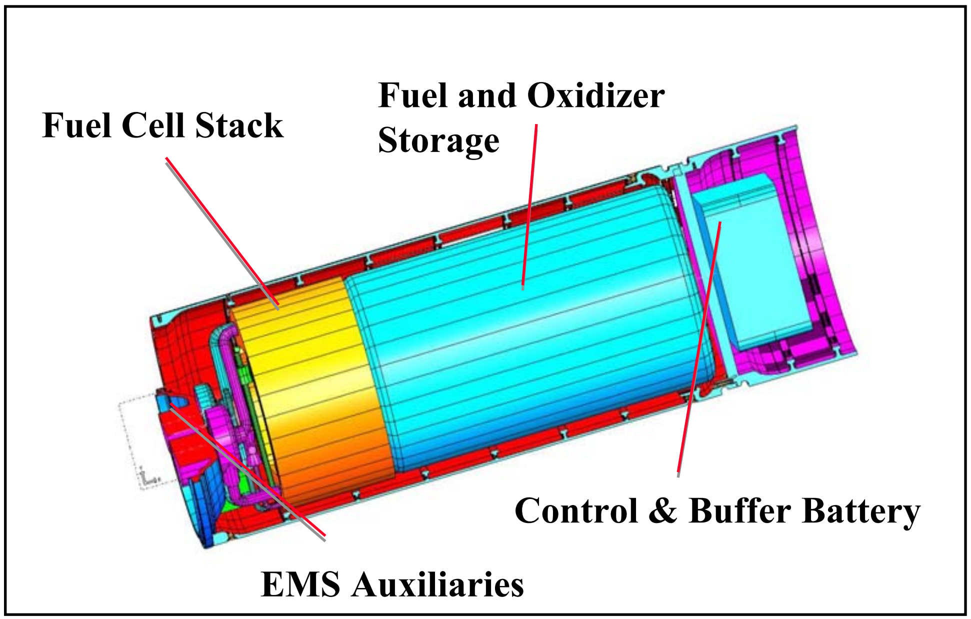



***Solid Oxide Fuel Cell High Energy Source for UUV's***

# Air-independent Fuel Cells for UUVs

## ***Objective:***

**Implement <u>air-independent</u> fuel cell technology into UUVs**




## ***Potential Benefits:***

- **Longer UUV missions as a result of higher energy density**
- **Faster turn-around time between missions (less down time)**
- **Decreased cost and increased safety versus primary lithium batteries**
- **Use of logistics fuels or even biodiesel**

**UUV Energy Section**

**For 21” UUV, available volume / mass: 189 L / 209 kg**

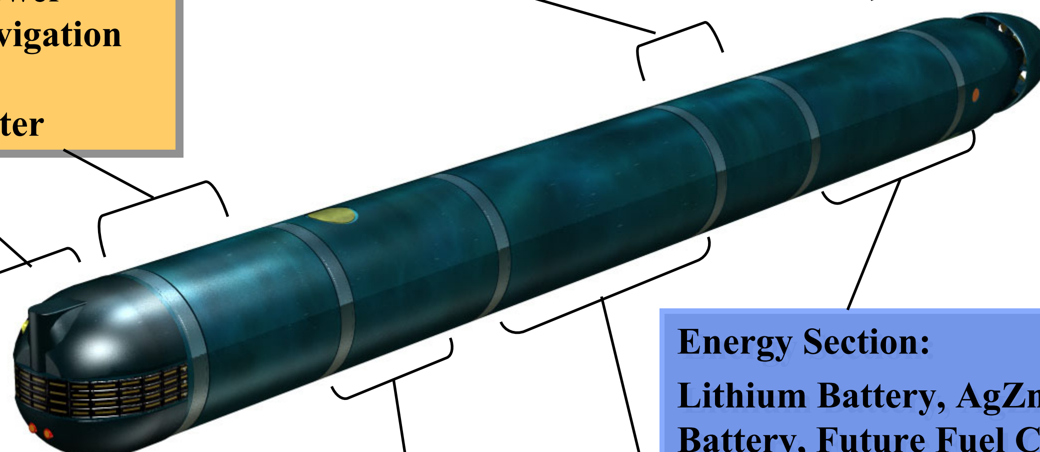
# Conceptual 21” Diameter Mission Reconfigurable UUV

**Propulsion Section:  Trust Vectored Pumpjet, Control Surfaces, Recovery and Handling System, Future Integrated Motor Propulsor**

**Ballast and Trim Section:  Pump, Valves, Aft Tank**

**Electronics and Control Section:  Power Distribution, Vehicle Computer, Navigation System, Communications System, Payload/Vehicle Integration Computer**

**Nose Section:  FLS, Acoustic Communications System**



**Energy Section:**

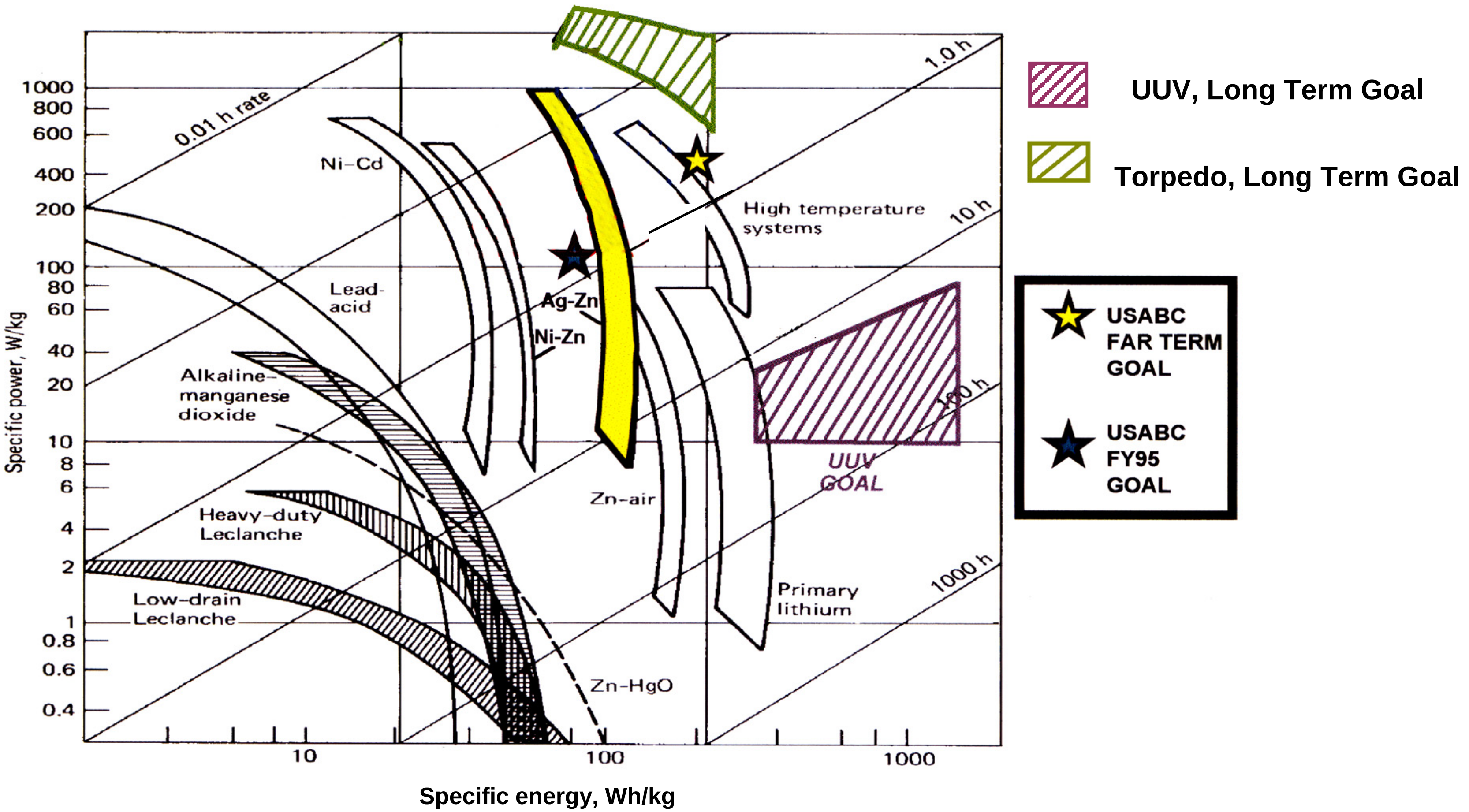
**Lithium Battery, AgZn Battery, Future Fuel Cell**

**Mission Payload Section:  5 Cubic Feet with Standard Interfaces**

**Forward Auxiliary Section:  SATCOM & GPS Antennas, Antenna Mast, Anchor, Forward Ballast Tank**

- **20.95 Inches OD, 240 Inches Long**
- **Weight = About 2800 lbs**
- **Speed = 3 to 8 knots**
- **Sortie Reliability Ps = 0.953**
- **Sortie Duration = up to 40 Hours**
- **Sortie Reach = 75 - 120 NM**
- **Full Impulse Launch Capable**

# Torpedo & UUV Power & Energy Needs




SOURCE: David Linden Handbook of Batteries, 2nd ed, 1995

**Commercial Sector and Conventional Energy sources will not meet the Navy Torpedo, UUV Future Requirements**

# UUV Requirements / Restrictions

- Start-up
- Weight / Volume
- Neutral buoyancy
- Gas evolution / Noise signature
- Safety
- Fuel and oxidizer choices
- Refueling
- Logistic Fuels / Sulfur
- Cost
- Temperature
- Endurance

NAVSEA WARFARE CENTERS NEWPORT

# Targeted SOFC Performance

**For a planar stack having net output of 2.5 kW:**

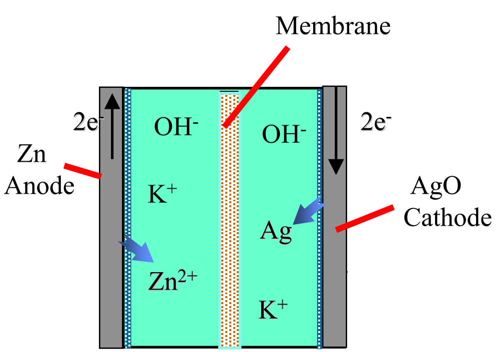
- 100 cells
- Active cell area - 11 cm x 11 cm
- 0.80 volts/cell
- 35 amps @ 80 volts (= 2.8 kW gross power)
- Operating temperature ⇒ 700 to 725°C
- ~30 thermal cycles
- Start-up time (15 to 30 minutes)

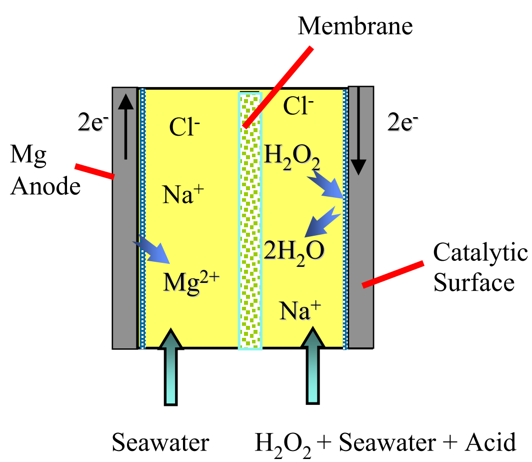
# Comparison of Energy Sources

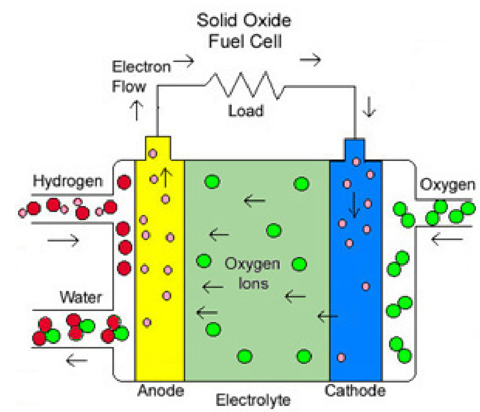
| Type of System | Specific Energy, Wh/kg | Energy Density, Wh/L | Max Mission at 2.5 kW, hr | Number of cycles |
|---|---|---|---|---|
| NiCd | 30 | 75 | 3 | 1500 |
| Lead Acid | 30 | 65-95 | 3 | > 300 |
| NiMH | 95 | 330 | 8 | 500 |
| AgO-Zn | 110 | 240 | 9 | 15 |
| Sec. Li Ion | 130 | 325 | 11 | ~2000 |
| Li Polymer*Expected | 210 | 330 | 18 | > 600 |
| $Li\text{-}SOCl_2$ | ~ 450 | 900-1000 | 35-38 | 1 |
| PEM ($NaBH_4$+LOX) | 330 | 340 | 21 | 150 |
| SOFC ($C_{12}H_{26}$+LOX) | 400-450 | 400-450 | 30-40 | 30 (??) |

# Energy Source Transition

## Battery → SFC → Fuel Cell




**Anode / Cathode consumed**

**Anode consumed**
**Catholyte refillable**

**Anode -Fuel**
**Cathode - Oxidizer**
**(both refillable)**

# Fuel / Oxidizers

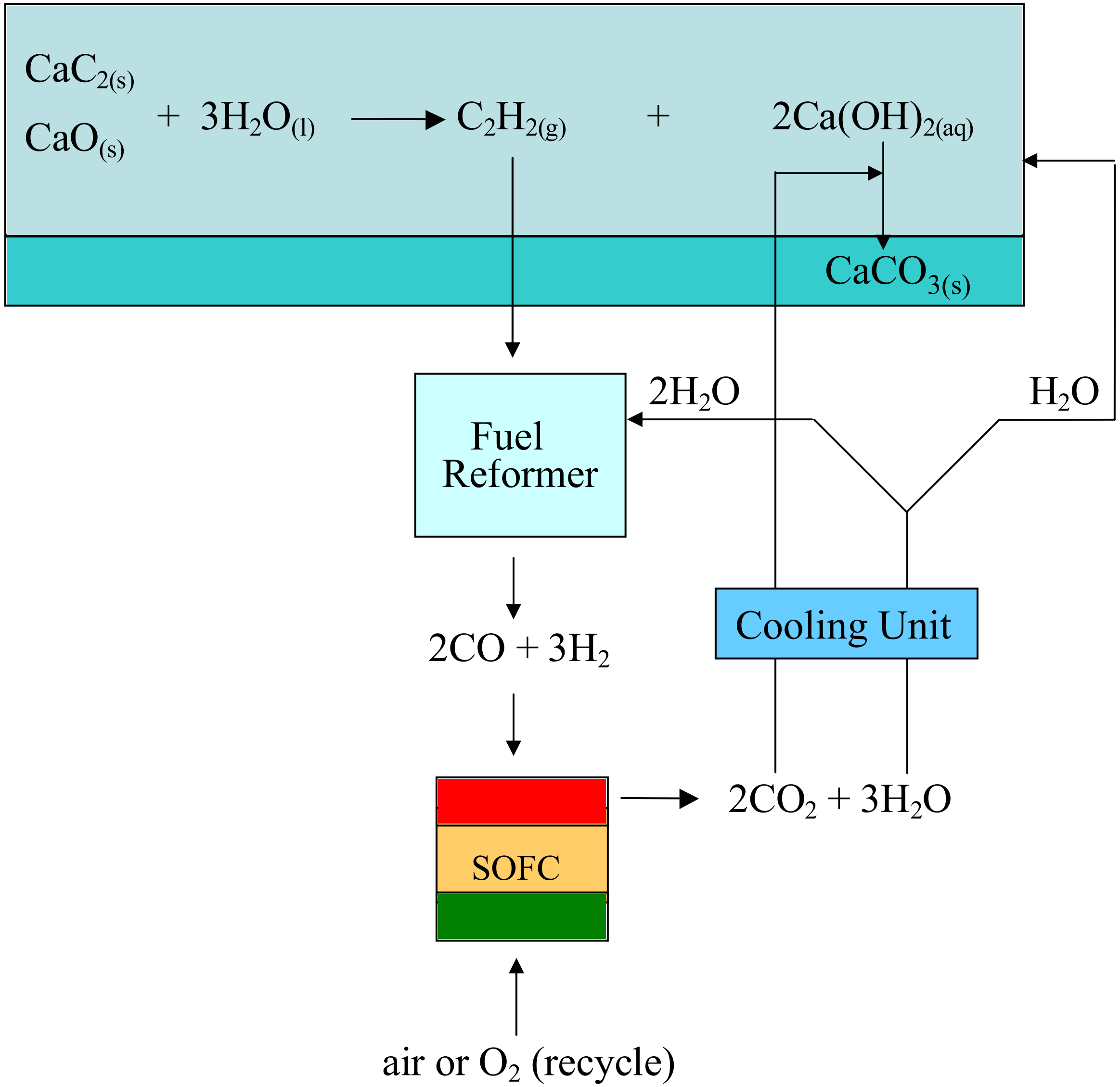
## Fuel

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

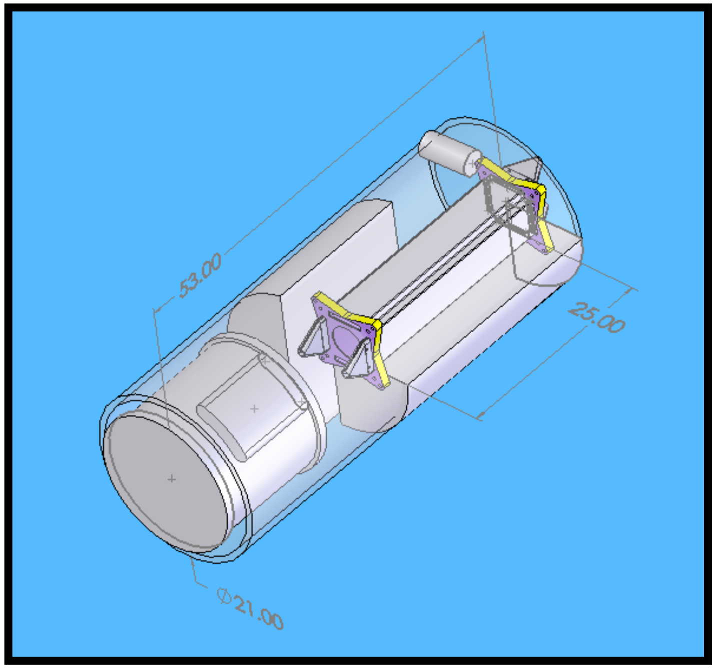
## Oxidizer

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

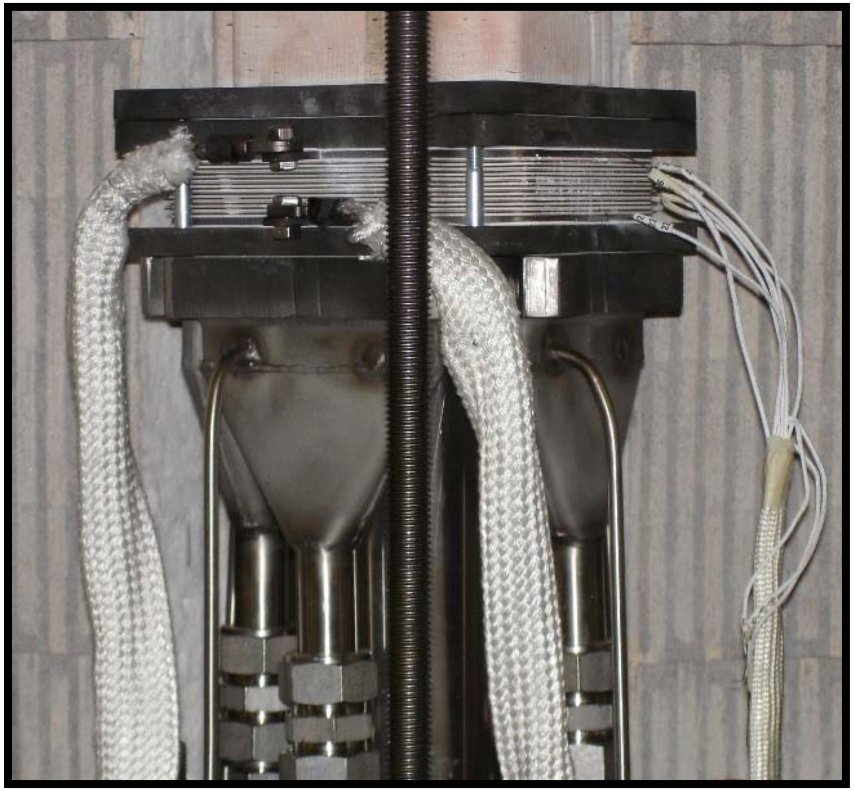
# Carbide Fuel System



# SOFC Stack Testing and System Design

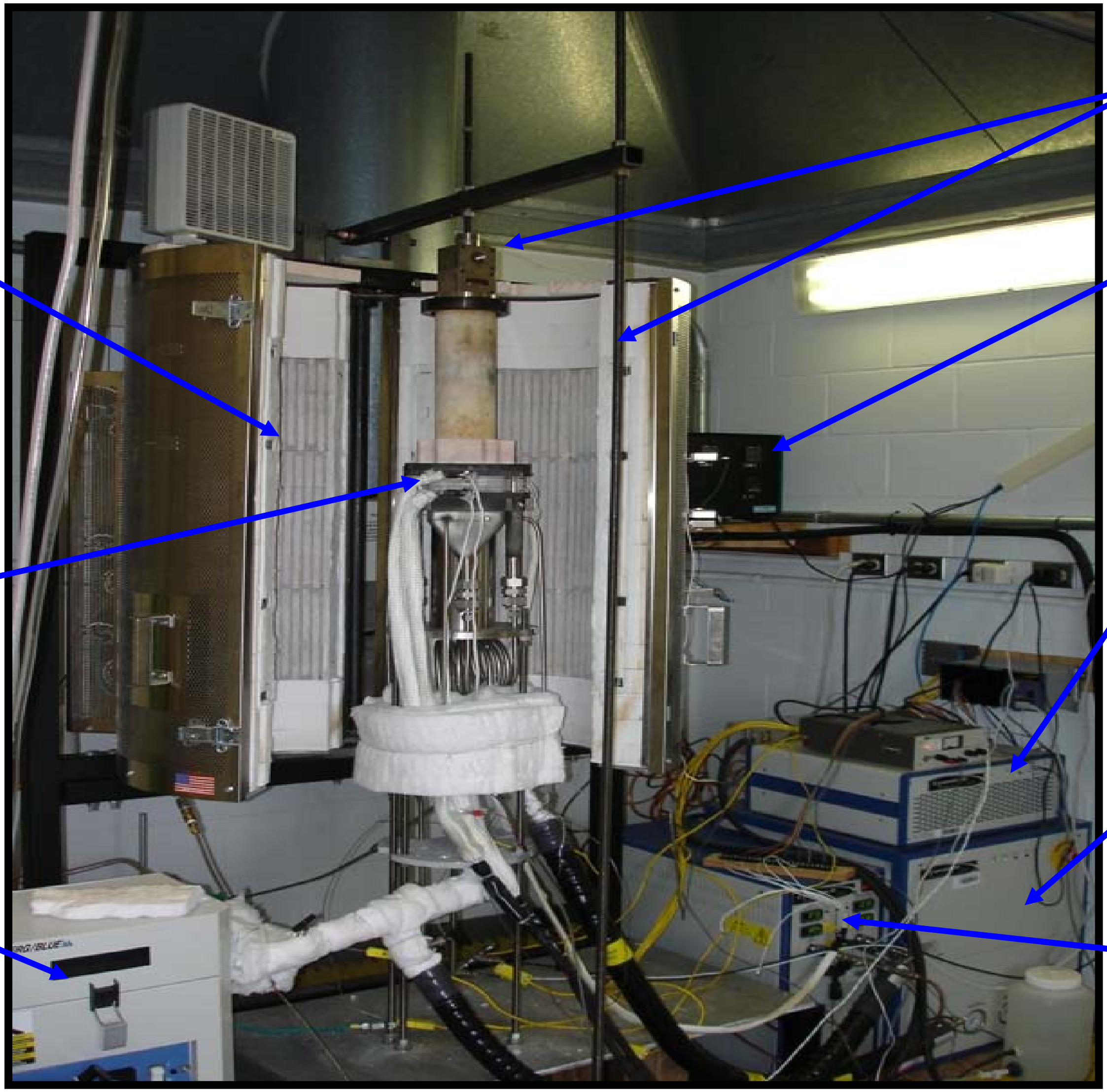



**21" UUV Energy Section**



**Versa Power Systems (VPS)**
**Solid Oxide Fuel Cell Stack**

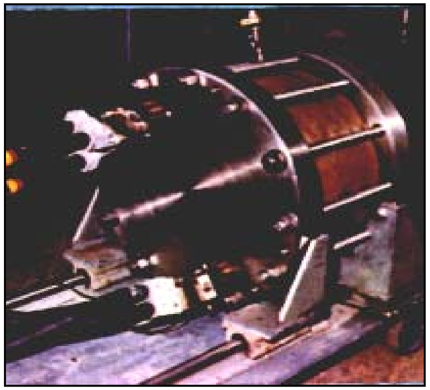
# SOFC Test Stand

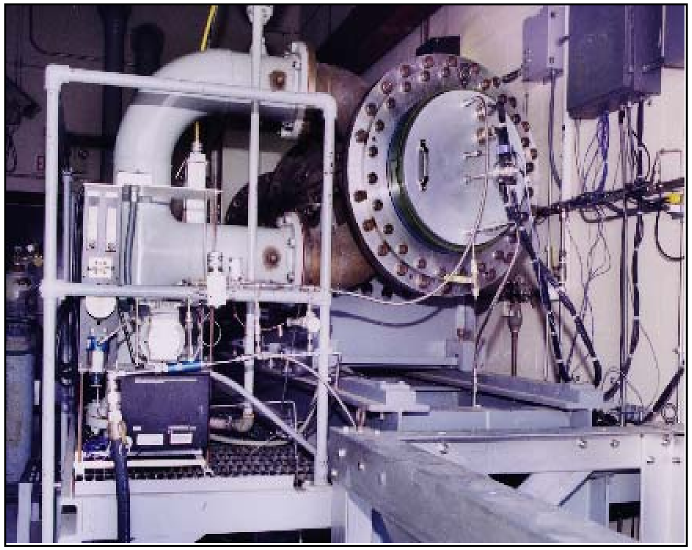


# NUWC Propulsion Test Facility (PTF) Electric Propulsion Systems Testing

### *Testing*

- Breadboard and brassboard systems
- Primary and secondary batteries
- Electrical components (motors)
- PNTF measure radiated noise in <u>zero</u> sea sate environment



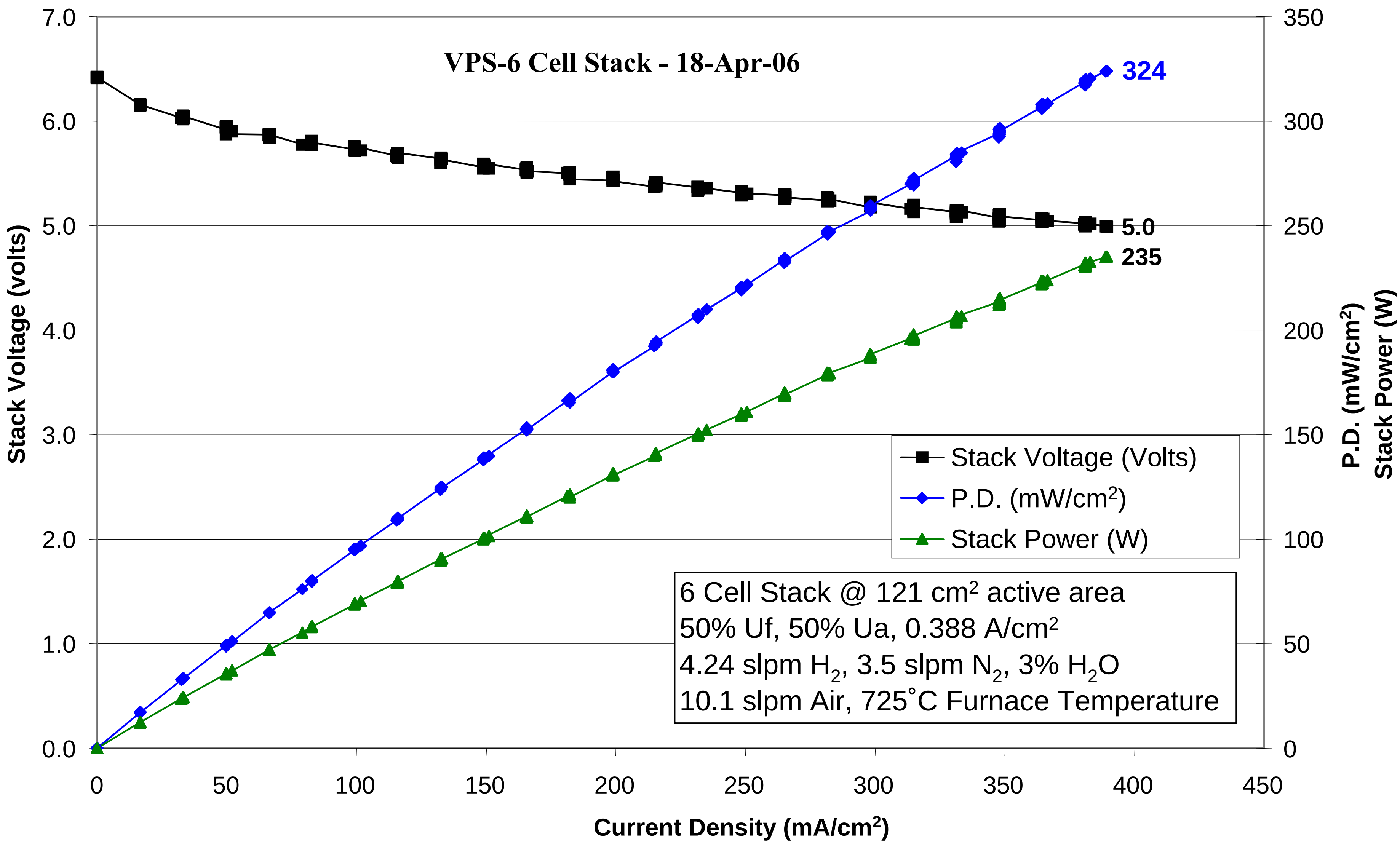


### *Specifications:*

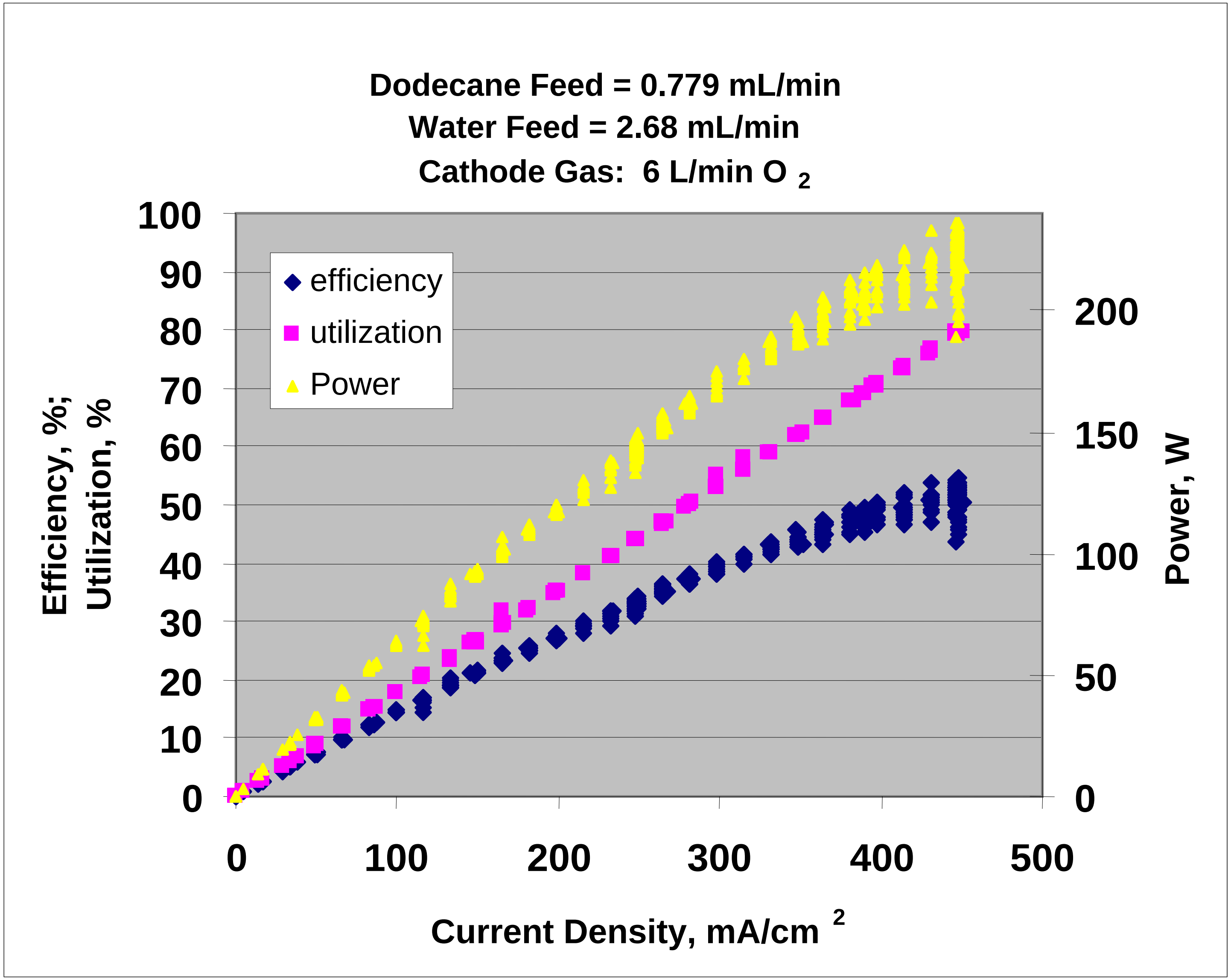
- High power (1 Mw) load bank system
- Motor testing (up to 1000 hp)
- Power supply (450 VDC at up to 2500 Amp)
- Ocean flow simulator/ 4000 gpm high-flow cooling loop
- Dedicated monitoring/control systems

***Full Power System Performance Evaluation Coupled to Seawater & Vehicle Environment (Prototype & Fleet)***

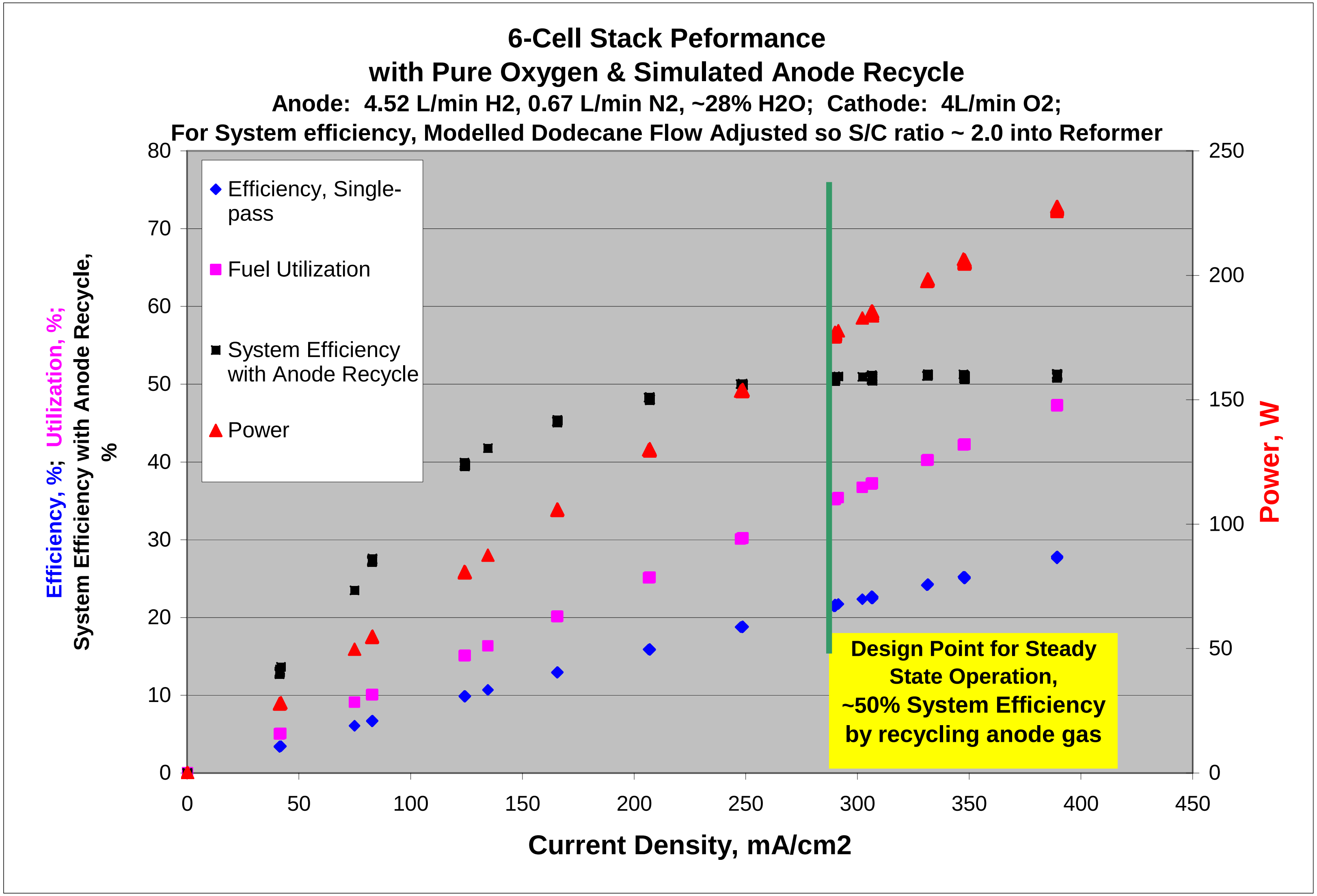
# NUWC SOFC Testing - $H_2$ Performance Testing



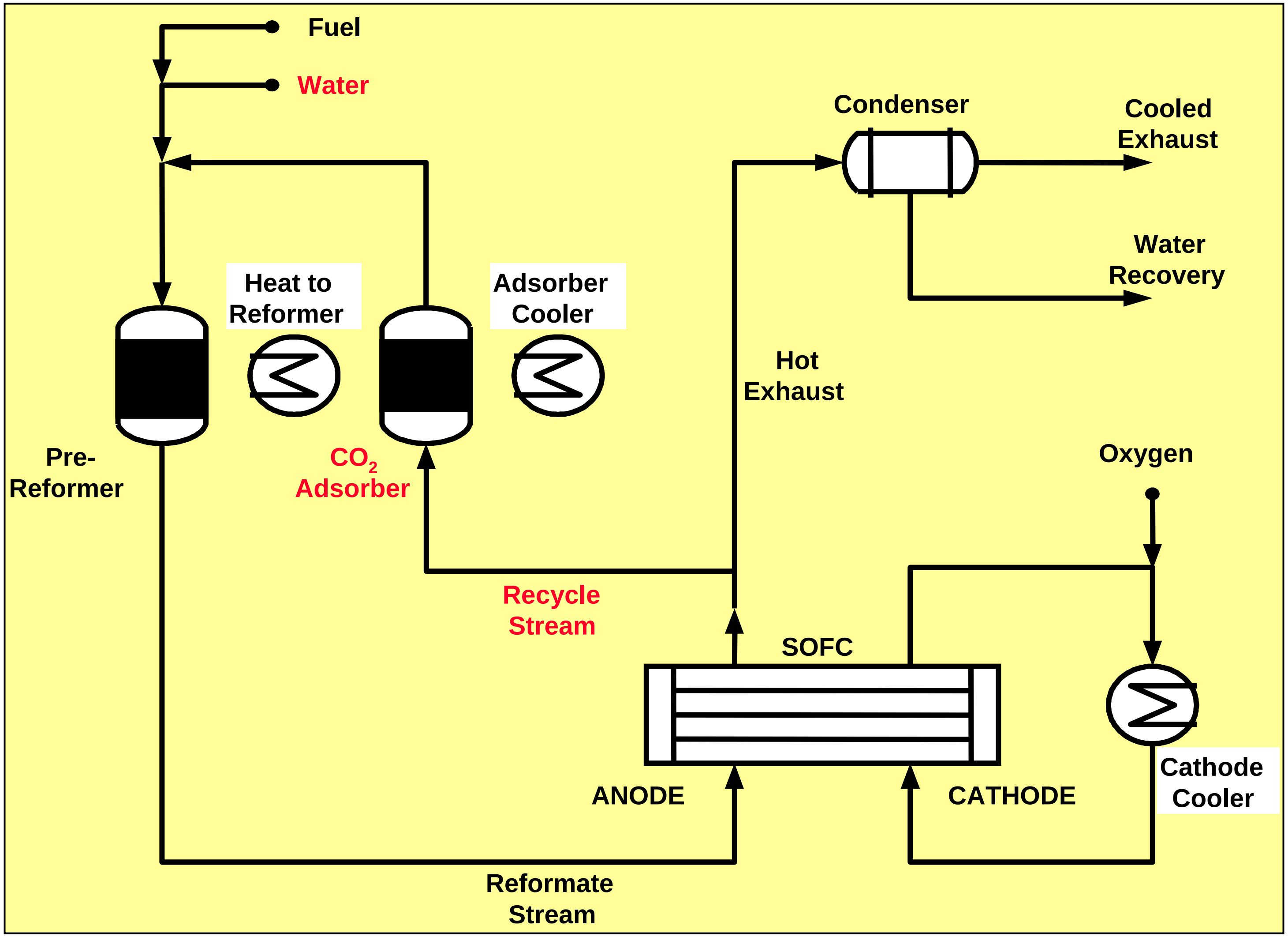
# Stack Performance, Dodecane Test, S:C = 3.63



# Approximate Design Point for Steady State Operation



# Proposed System Design with Anode Recycle

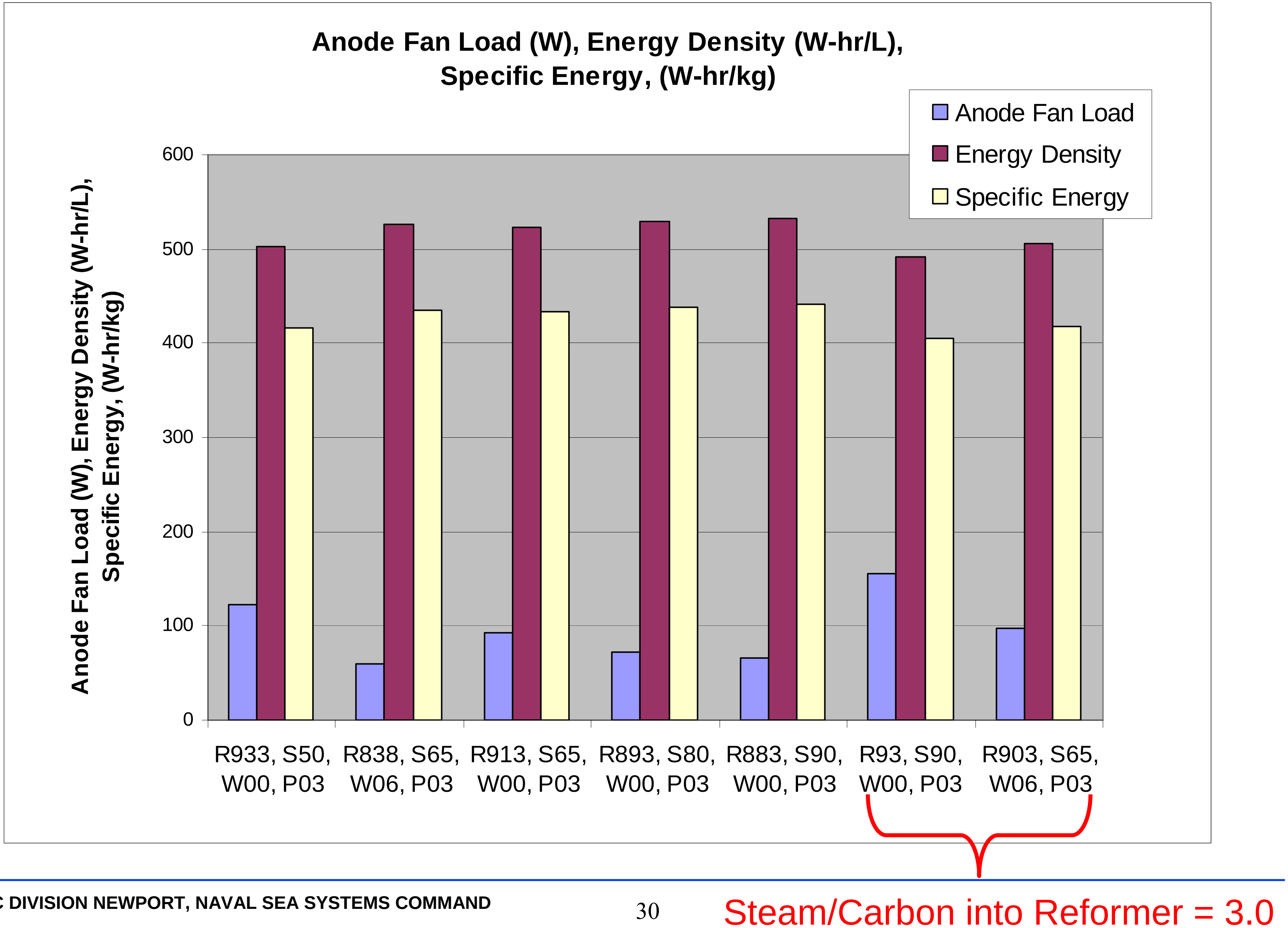


# Parametric Study of SOFC System

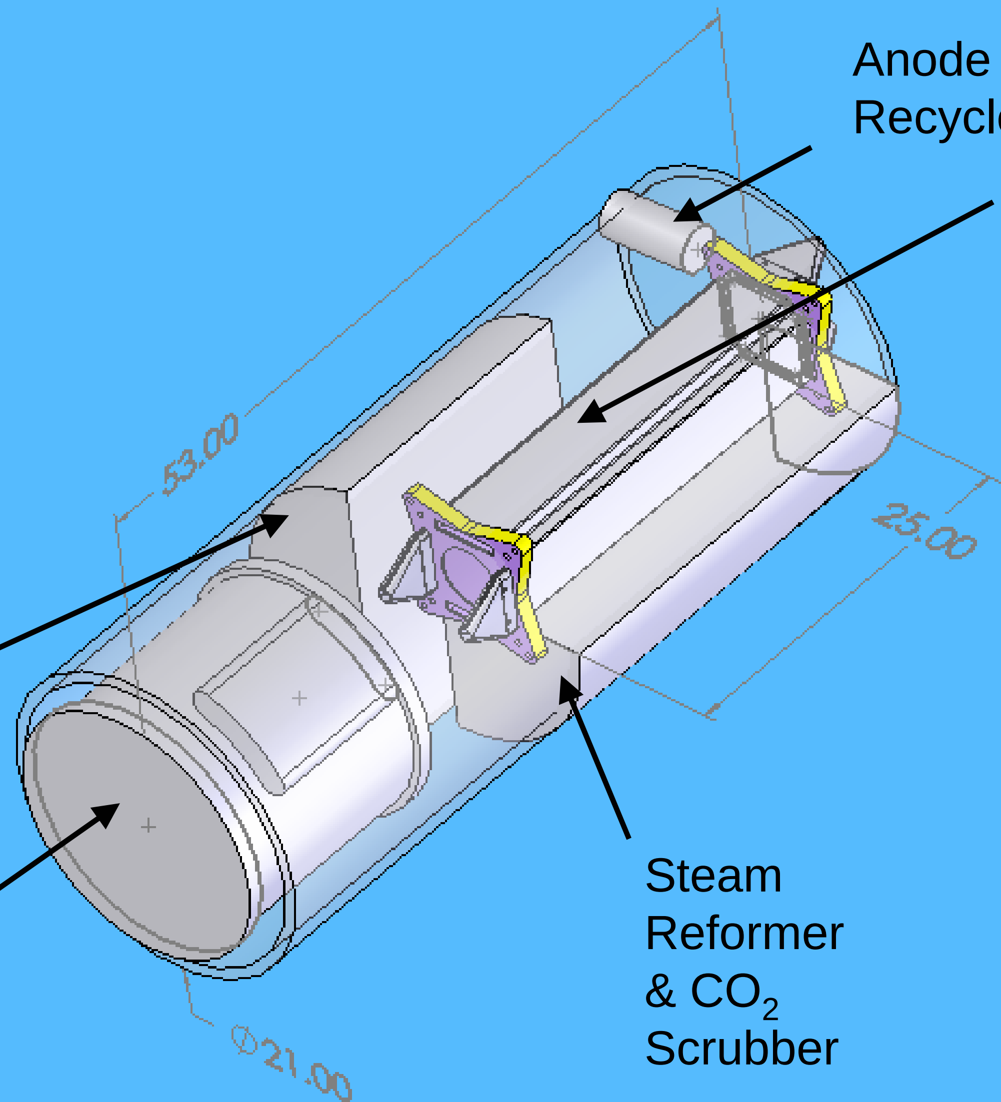
| Increased Variables | Anode Fan Load | **Energy Density** | **Specific Energy** | Parasitic Losses | Total Waste Heat | Total Gas Product | **S/C into Reformer** | Anode Flow | Cathode Flow |
|---|---|---|---|---|---|---|---|---|---|
| Recycle Fraction | ↑ | ↓ | ↓ | ↑ | ↑ | ↓ | ↑ | ↑ | ↓ |
| $CO_2$ Sorption Percentage | ↓ | **0** | **0** | ↓ | ↑ | ↓ | ↑ | ↓ | ↑ |
| Water Input | ↑ | ↓ | ↓ | ↑ | ↑ | **0** | ↑ | ↑ | ↓ |
| System Pressure | ↓ | ↑ | ↑ | ↓ | ↓ | **0** | **0** | ↓ | ↓ |

**Numerous Case Studies to Examine Trends in System Performance**

# Extended Scenario Studies



# Preliminary Energy Section for 21” UUV Platform



# Liquid Oxygen (LOX) Storage

**German built U212 & U214 submarines already employ Siemens fuel cell systems, which store hydrogen via metal hydrides and oxygen as LIQUID OXGYEN.**

**Spanish S-80 goes a step further, in that it will be producing LOX on the vehicle itself. UTC providing fuel cell system for this submarine.**

**LOX is becoming standard for air-independent propulsion (AIP), and it is an area that the U.S. Navy cannot afford to neglect.**

**50 kg liquid oxygen system**

**Sierra Lobo successfully demonstrated this technology in a Phase II STTR funded by ONR**

# Steam Reformer

- Low temperature pre-reformer (450-700º C)
- Light hydrocarbon slip is okay; SOFC stack can internally reform methane/ethane/butane
- Steam supplied by SOFC exhaust gas also contains $H_2$, CO, and $CO_2$ (how will this affect reforming catalyst?)
- Prototype from InnovaTek, Inc. now being tested with dodecane and biodiesel feeds
- Volume = 3-5 L and Mass = 5-10 kg (for 21” UUV)

# Anode Gas Recycle Blower

## Blower Attributes:

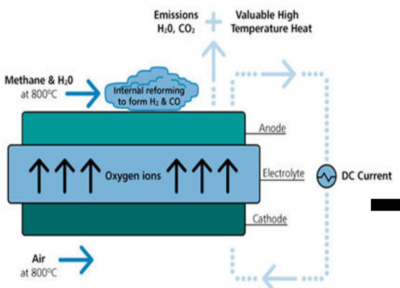
- Inlet T = 600-850º C
- Inlet P is atmospheric
- $\Delta$P ~ 4-10" water
- 100 SLPM gas flow
- Nominal composition of 46 slpm $H_2O$, 27 slpm $CO_2$, 20 slpm $H_2$, and 7 slpm CO
- $\eta$ > 40%
- Variable speed control with turn-down ratio of 5 to 2
- Tolerate at lest 30 thermal cycles

## Companies Funded under DoE Phase II SBIR contracts:

1. R&D Dynamics
2. Phoenix Analysis and Design Technologies

**Proposed phase II prototypes match 21" UUV design goals

# Advanced Fuel Cell Research for Weapon Applications




Student POC info: Eric Greene
Professor: Wilson K. S. Chiu
Mentor POC info: Maria G. Medeiros
ONR Sponsors: Michele Anderson
David Drumheller

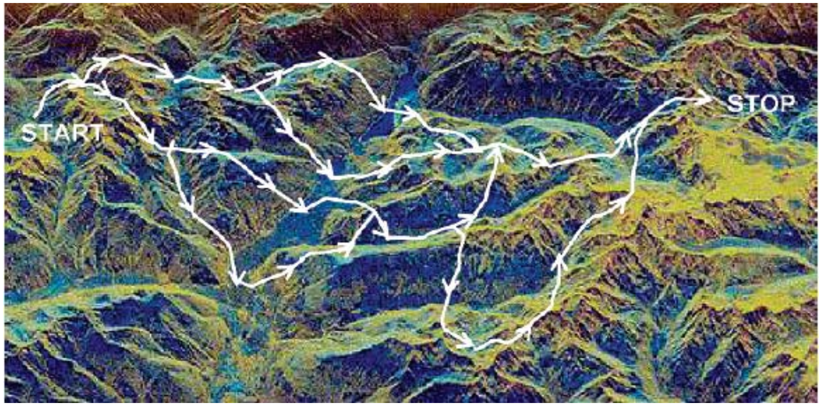
## APPROACH

- Develop full cell model
- Characterize/evaluate commercial cells
- Verify and expand model to a system model
- Evaluate cell structure before and after testing for signs of damage (using XRD & SEM)
- Investigate effects of gas mixes on performance to simulate reformed fuel gas
- Develop Transition Technology Candidates

## ACCOMPLISHMENTS

- SOFC test stand built and debugged
- Commercially developed cells procured
- 1-D and 2D full cell SOFC model developed and validated with literature and in house experiments
- Hydrocarbon operation established
- Pre and post experiment characterization performed on cells

# Logistic Fuel Reforming: A Building Block Approach to Mechanistic Structure and Microkinetics




**Project Start Date: May 2005**

**Student POC Info:** **James Liu**

**Professor POC Info:** **Ravindra Datta**

**Mentor POC Info:** **Alan Burke**

**ONR Sponsors:** **Michele Anderson**

**David Drumheller**

**Objectives:**

- Determine steam reforming reaction pathways and mechanisms for specific catalyst
- Refine Reaction Route (RR) Graph Theory
- First focus: methane steam reforming (MSR)
- Eventually extend modeling to more complex hydrocarbons, culminating in JP-8 fuel
- Examine autothermal reforming (ATR) that uses pure oxygen feed as opposed to air
- Synthesize and test promising catalyst materials for steam and ATR reforming

**Product Schedule/ Milestones**

- Determine promising catalyst candidates for MSR based upon RR graph theory and experiments
- Perform MSR and ATR studies

**Current Status/ Accomplishments**

- WGS analysis completed on various catalysts
- Ongoing MSR studies on supported nickel and ruthenium catalysts
- Developing reaction routes for MSR on nickel catalyst for RR graph theory

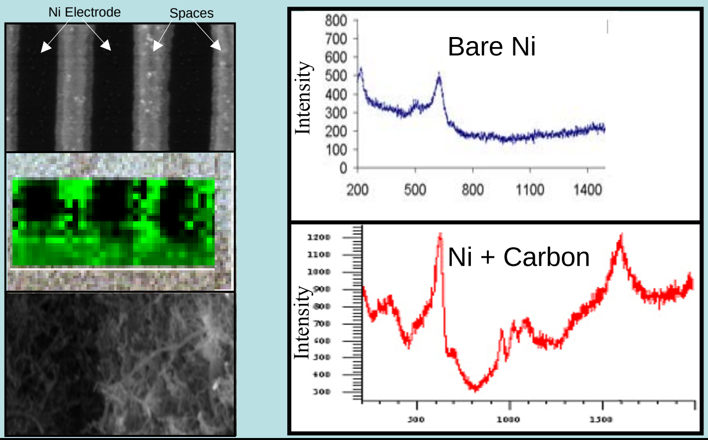
# Development of Novel Materials for Solid Oxide Fuel Cells That Use Logistic Fuels and Pure Oxygen

## Raman Spectroscopy on Patterned Electrodes

Bare Electrode

Raman Map

Carbon Deposits




**Student POC Info:** John Bennett

**Professor POC Info:** Meilin Liu

**Mentor POC Info:** Alan Burke

**ONR Sponsors:** Michele Anderson, David Drumheller

### Objectives:

- Develop SOFC technology for use in underwater Naval applications.
- Select sound materials for cell and interconnects.
- Reduce carbon formation at the anode.
  - Determine the species, mechanisms and kinetics of carbon formation.
  - Identify the areas on the anode surface that are electrochemically active for the formation of carbon.

### Project Schedule/ Milestones

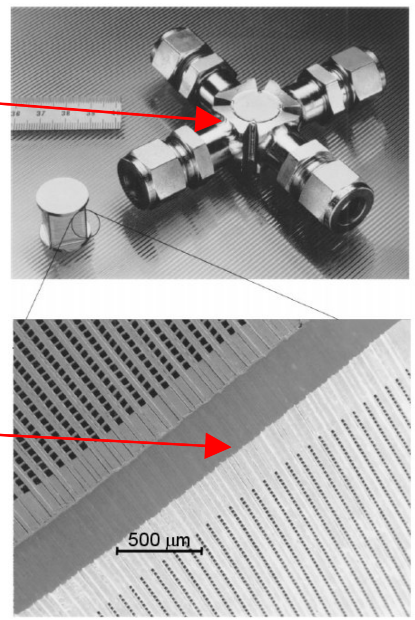
- Determine the species, mechanisms and kinetics of carbon formation using temperature programmed methods and Raman spectroscopy.
- Determine the areas on the anode that are electrochemically active for the formation of carbon using impedance spectroscopy on patterned electrodes and Raman spectroscopy.

### Current Status/ Accomplishments

- Developed a systematic approach for the micro-fabrication of patterned electrodes of well-defined geometry specific to SOFCs.
- Raman analysis of carbon-deposited Ni electrode shows $sp^3$-bonded carbon that is amorphous.

# Safe and Efficient Conversion of Hydrogen Peroxide for Air-Independent UUV Power Sources with Microchemical Systems

## Microchemical System




**Student POC Info:** Elizabeth Lennon

**Professor POC Info:** Ronald Besser

**Mentor POC Info:** Alan Burke

**ONR Sponsors:** Michele Anderson, David Drumheller

### Product Schedule/ Milestones

- Determine viable means of reactor & catalyst design by considering various methods (sol-gel, electrodeposition, colloid deposition, etc.)
- Initiate modeling studies to examine heat transfer & fluid dynamics of microchannel reactor operation
- Construct and test reactor under various temperature, [$H_2O_2$], and catalyst loading

### Objectives:

- Demonstrate high yield, controlled $H_2O_2$ decomposition
- Establish critical design parameters of microchemical $H_2O_2$ decomposition reactor
- Control temperature in the reaction zone
- Determine optimum reactor geometry

### Current Status/ Accomplishments

- Designing experimental reactor
- Investigating $H_2O_2$ analytical approach
- Simulating reactor using COMSOL Multiphysics

# “Swimlanes”- Fuel Cell Programs (Development Only – In Service Per Platform Lead)

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LD MRUUV

## CRANE

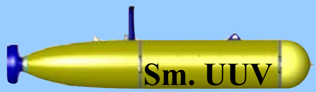
- Aerospace packaging and construction
- Air breathing
- Man-Portable Power
- Expeditionary Power
- Team w/ NUWC on air independent applications

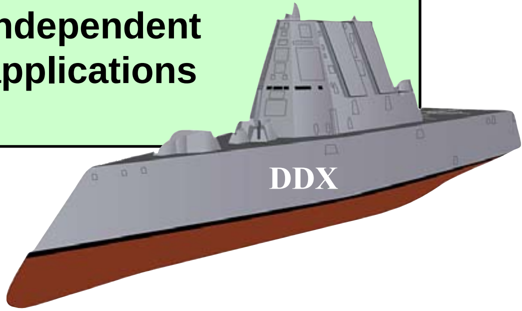
## NEWPORT

- Aerospace packaging and construction
- Air independent
- Specialty fuels
- Seawater activated
- $0_2$ and $H_2$ sources
- Team w/ NSWCCD on Logistic Fuels

## CARDEROCK

- Heavy duty packaging and construction
- Shore / Reformer Power
- Predominately air breathing for ships
- Submarine power application in the future
- Team w/ NUWC on air independent applications


<<100 kW

>>100 kW

Average Power (KW)

# DARPA UUV Energy Program


**Large-diameter UUVs**

**NUWC POC:** Maria Medeiros (Program COR)

**Sponsor:** DARPA

**DARPA POCs:** Valerie Browning, Leo Christodoulou

**Prime Contractors:** SRI, ITN, Contractor#3

**Objectives:**

- **Explore high-risk, high-payoff technologies that are likely to be beyond the scope of projects that the Navy will consider under the current UUV Master Plan.**
- **DARPA UUV Power Systems program would enable missions that the Navy has yet to consider.**
- **Novel UUV power systems that have the potential for demonstrating energy densities in the range of 1000-1500 Watt-hours per liter (W-hr/l) to include power plant, fuel and oxidant storage, power conditioning, controls, monitoring devices, etc.**

**Current Status/ Accomplishments**

- **Program to start September 2006**

# Critical Issues

- Oxygen Source
  LOX? Concentrated $H_2O_2$? Safety? Availability?

- SOFC reliability - multiple mission capability/economics

- Start-up/Pre-heating methods (heating elements? steam? thermal management?)

- Carbon Dioxide Scrubber
  Design and regeneration without oxidizing other system components (SOFC / reformer catalyst)

- Fuel Recycle System
  Fans/Blowers to recycle hot gas streams

- Lower BoP (parasitic) power requirements

# Summary

- SOFC technology has the potential to greatly increase endurance of UUV missions over current battery technologies.
- Even a minimal thermal cycling capability (10-15 cycles) will make SOFC economically competitive with Li-$SOCl_2$ batteries.
- Closed system operation of SOFC requires careful thermal management of all system components to avoid overheating.
- Stack performance has been validated while utilizing dodecane reformate and pure $O_2$. Biodiesel reformate has also been validated. The next step is to show long-term stability and cycling capability.
- NUWC is the Navy lead for testing SOFC stacks, integrating components and designing SOFC systems.

# *Thank you*