Solid Oxide Fuel Cells in Unmanned Undersea Vehicle Applications

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A. Alan Burke, Louis G. Carreiro

Naval Undersea Warfare Center,
Division Newport, (NUWCDIVNPT)

Newport, RI; USA


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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

"Swimlanes"- Fuel Cell Programs

LD MRUUV

CRANE

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

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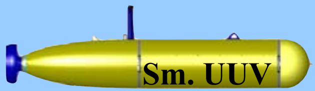
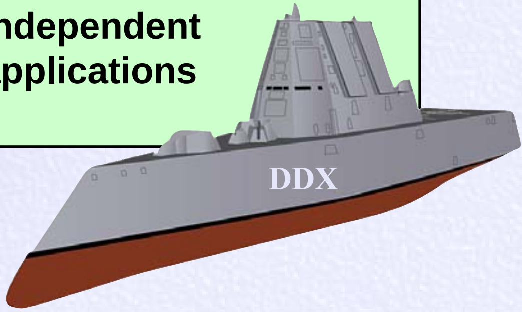
- Aerospace packaging and construction
- Air independent
- Specialty fuels
- Seawater activated
- 0_2 and H_2 sources
- Team w/ NSWCCD on Logistic Fuels



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)

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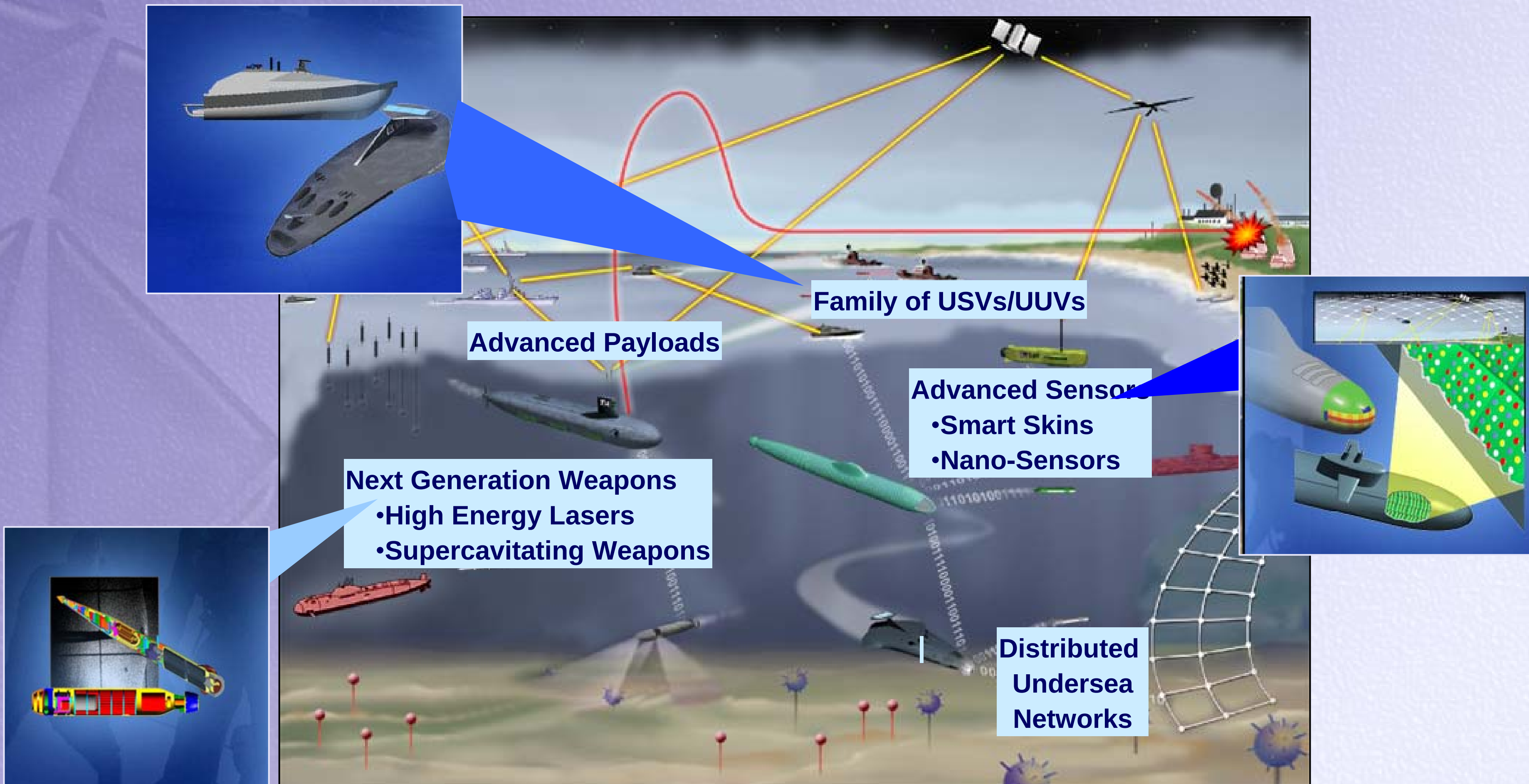
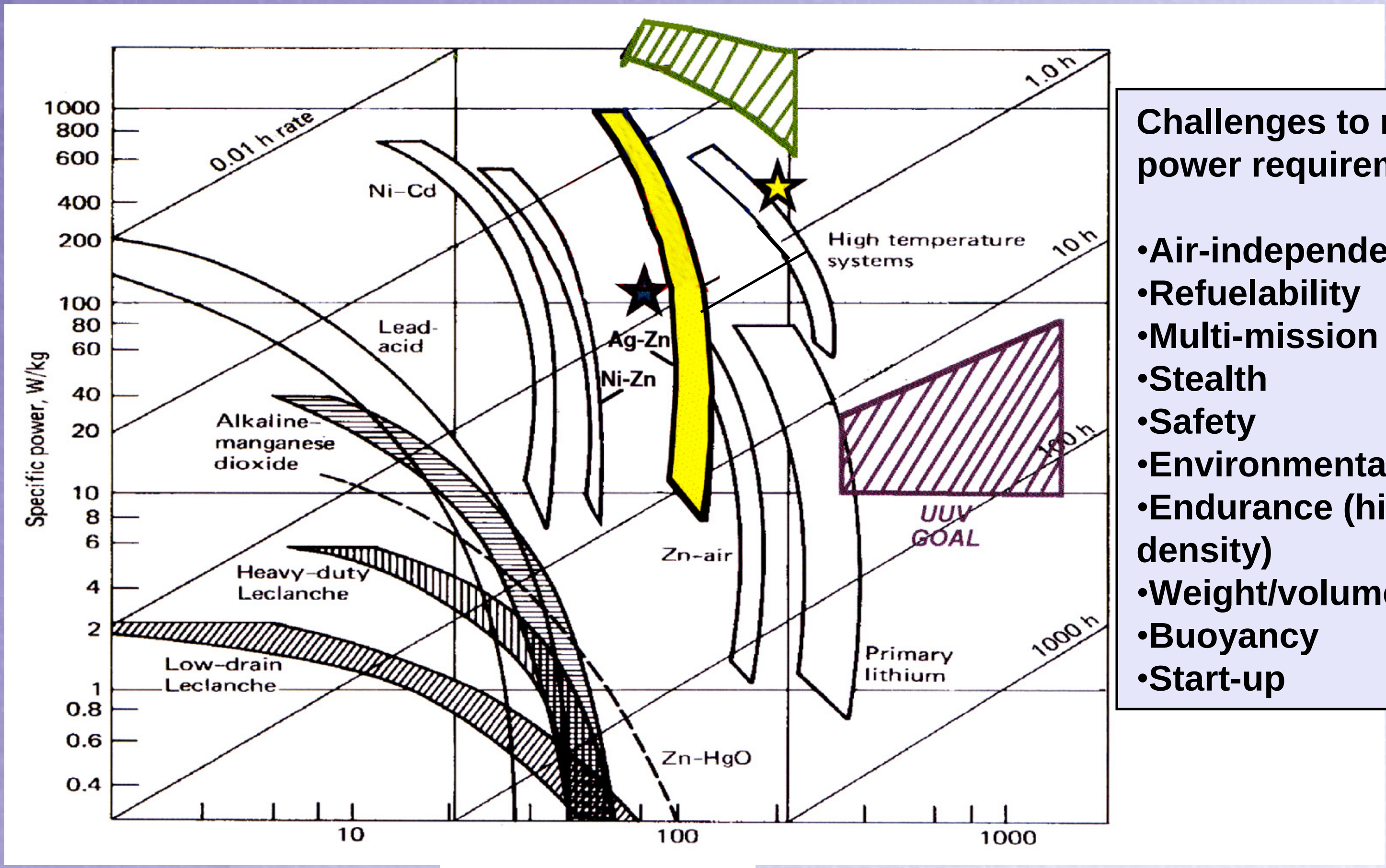
Autonomous Undersea Vehicles

NUWC's Contribution to the Navy After Next



SEAPOWER 21 – Transformation for the Navy

Ragone Plot



Specific energy, Wh/kg

* David Linden Handbook of Batteries, 2nd ed, 1995

Challenges to meeting UUV power requirements include:

- Air-independent operation
- Refuelability
- Multi-mission capability
- Stealth
- Safety
- Environmentally benign
- Endurance (high energy density)
- Weight/volume constraints
- Buoyancy
- Start-up

Existing Commercial Sector and Conventional Energy Sources will <u>NOT</u> meet the Navy UUV Future Requirements

Why SOFCs for UUVs?

- **Fuel Flexibility**
  - Pure H_2 not required for operation
  - Hydrocarbon fuels (diesel-type) can be utilized & rapidly refueled
  - Internal reforming of light hydrocarbons within fuel cell stack
  - Tolerates impurities such as carbon monoxide and sulfur (ppm level)

- **High Efficiency, 55-65%**
  (based on LHV of fuel conversion to electricity)

- **Noble metal catalysts not required for electrodes**
  and fast reaction kinetics at electrodes

- **Combined heat and power (CHP) - heat utilized for reforming**

PEM System, Reactants ONLY

Material	kg	L
9wt% H_2	10	15
LOX	7.2	8

2015 capability?

1300 W-hr/L

1750 W-hr/kg

Material	kg	L
4wt% H_2	10	15
LOX	3.2	3.6

Current capability

720 W-hr/L

1010 W-hr/kg

SOFC System, Reactants ONLY

Material	kg	L
S-8	10	13
LOX	26	29
CO_2 Sorbent	64	80

Current Capability

1070 W-hr/L

1300 W-hr/kg

Sorbent w/ ~50% mass gain,

Broad Fuel Comparisons

Fuel	Flashpoint,ºC	MP,ºC	Energy Content (LHV) MJ/L	MJ/kg
Methanol	12	-98	15-18	19-22
Ethanol	13	-114	18	23
Gasoline	-7.2	-58 (aviation)	31-34	42-46
Diesel	**40-50**	**-20 to 5 (cloud)**	**~36-40**	**42-47**
Liquid H_2 (no tank)		-252 (BP)	8	121
LNG (no tank)		-164(BP)	21	51
2015 H_2 Storage Goal (9wt% systems basis)			10-15	10
Glycerin	176	~ 17	22	18
Coal			13-25	15-30

Appropriate Fuel Selection

Fuel Type	Sulfur? Aromatics?	Flash & Cloud Pt.	Energy Density, MJ/L	Shelf life
FT-diesel (S-8)	< 5 ppm < 1%	40 - 50 C -47 C	~37	**8 yrs** *
JP-8	~ 500 ppm ~ 20%	> 38 C -47 C	34	1 yr
Biodiesel	~ 10 ppm ~ none	> 130 C ~ 0 C	33	6 months
Diesel	10-500ppm 10-25%	40 - 50 C -20 - 5 C	35-40	2 yrs Max

* FT Diesel specs from www.rentechinc.com & www.syntroleum.com, ***Energy*** & ***Fuels*** **1991,5, 2-21**

Fuel Processing (Reformers)

Catalytic Partial Oxidation (CPOX)

$$C_mH_n + m/2\ O_2 \longrightarrow n/2\ H_2 + mCO + heat$$

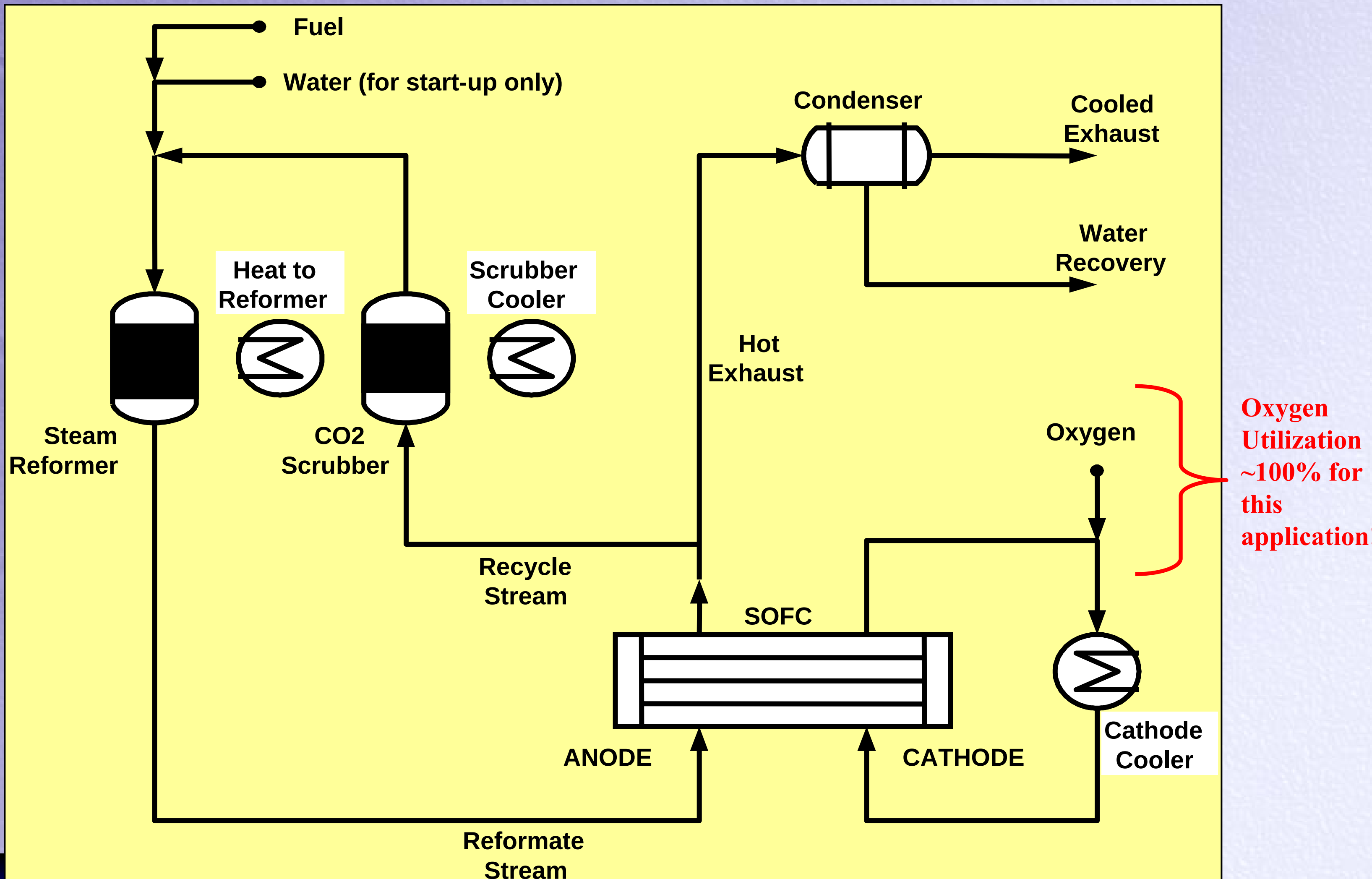
- Exothermic reaction - no additional heating required for heating inlet
- Fast kinetics - reformer starts and achieves operating temperature quickly
- Air-dependent operation; further studies needed to consider pure O_2 feed

Steam Reforming

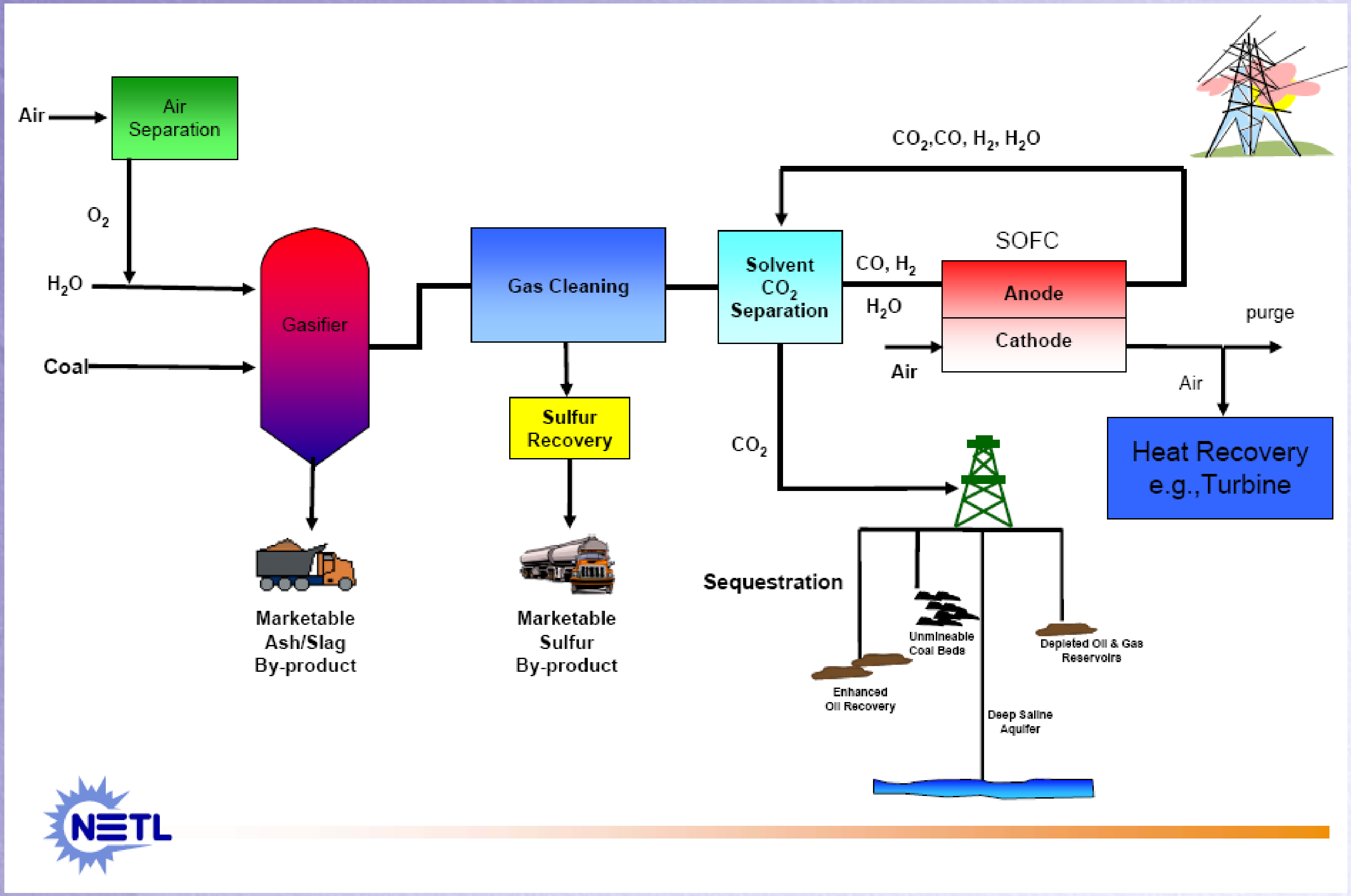
$$C_mH_n + mH_2O + heat \longrightarrow (m+n/2)\ H_2 + mCO$$

- Endothermic reaction - requires heat for reaction and fuel/water evaporation
  - Heat is supplied from fuel cell exhaust gases and CO_2 scrubber
  - Steam can be supplied by SOFC product gases (anode recycle)
- More hydrogen produced per mole of fuel than in CPOX
- Air-independent operation & 15% reduction in O_2 consumption vs. combustion

Proposed System Design with Anode Recycle



SECA Coal Based Systems



-Graphic courtesy of NETL, SECA Workshop 2007

Basis for SECA Collaboration with NUWCDIVNPT

NUWCDIVNPT serves as honest broker for stack and related-component evaluation as well as testing under unique operating conditions (i.e. pure oxygen).

Although SECA has a coal-based central generation focus, spin-off applications are encouraged. Testing under the demanding UUV conditions provides valuable insight into performance entitlement of current SOFC technology.

Niche military applications like UUVs can pave the way for commercial applications. Cost and operational lifetime not necessarily major concerns for military applications, as long as new technical capability can be delivered (reliably and safely).

Recent Stack Testing at NUWCDIVNPT

Delphi Stack, 10-cell

Delphi Stack, 30-cell

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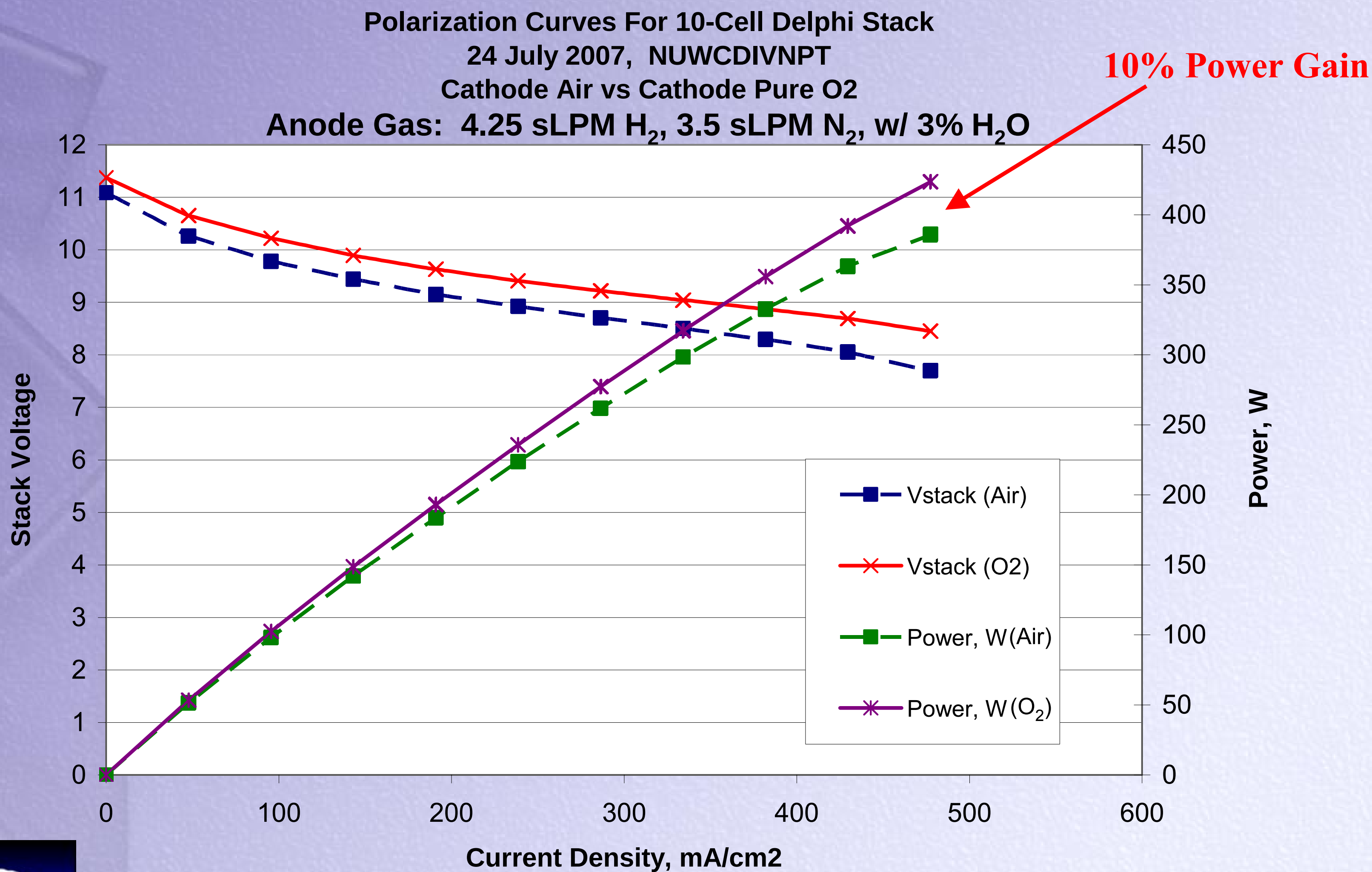
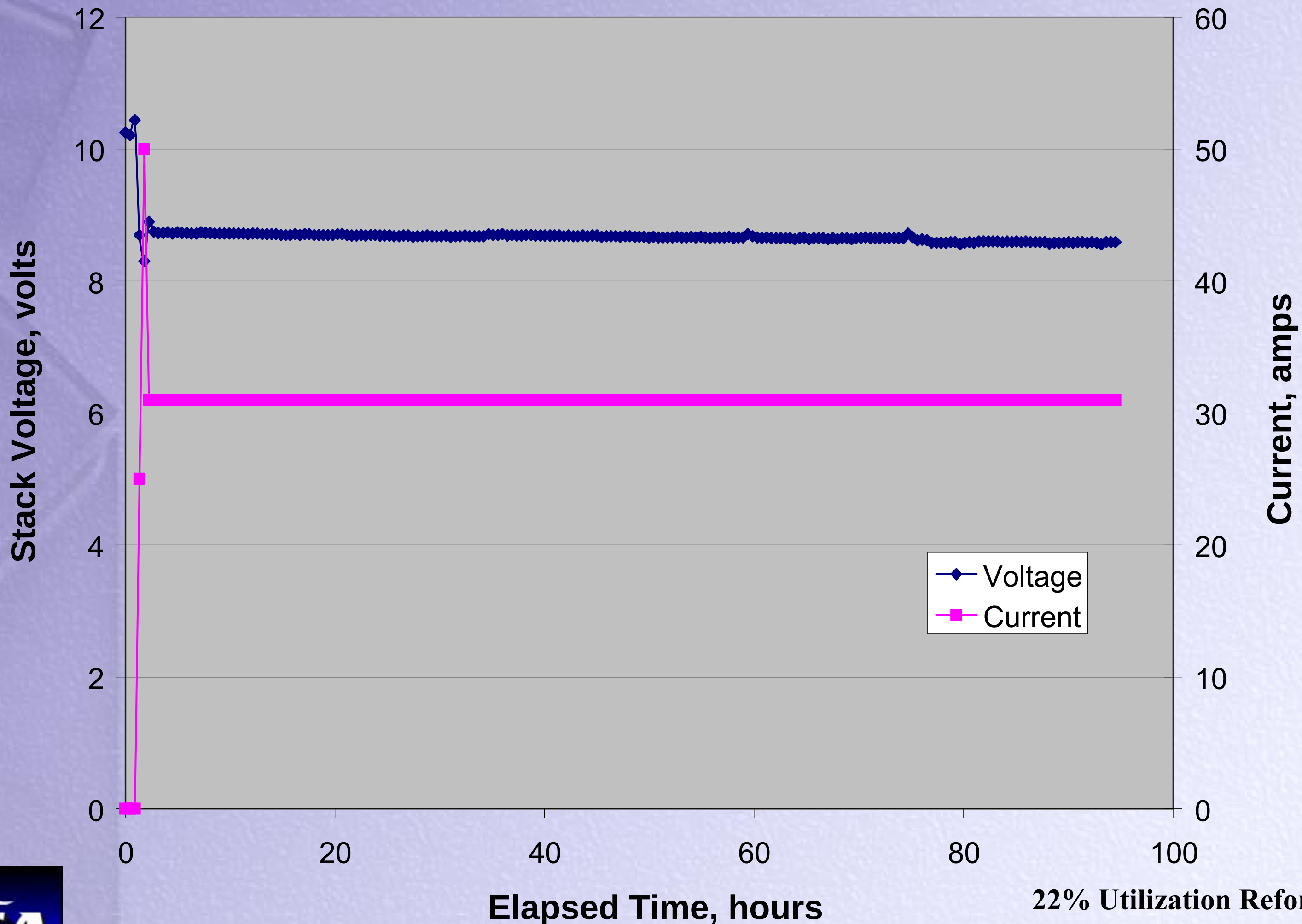
Pure Oxygen vs. Air



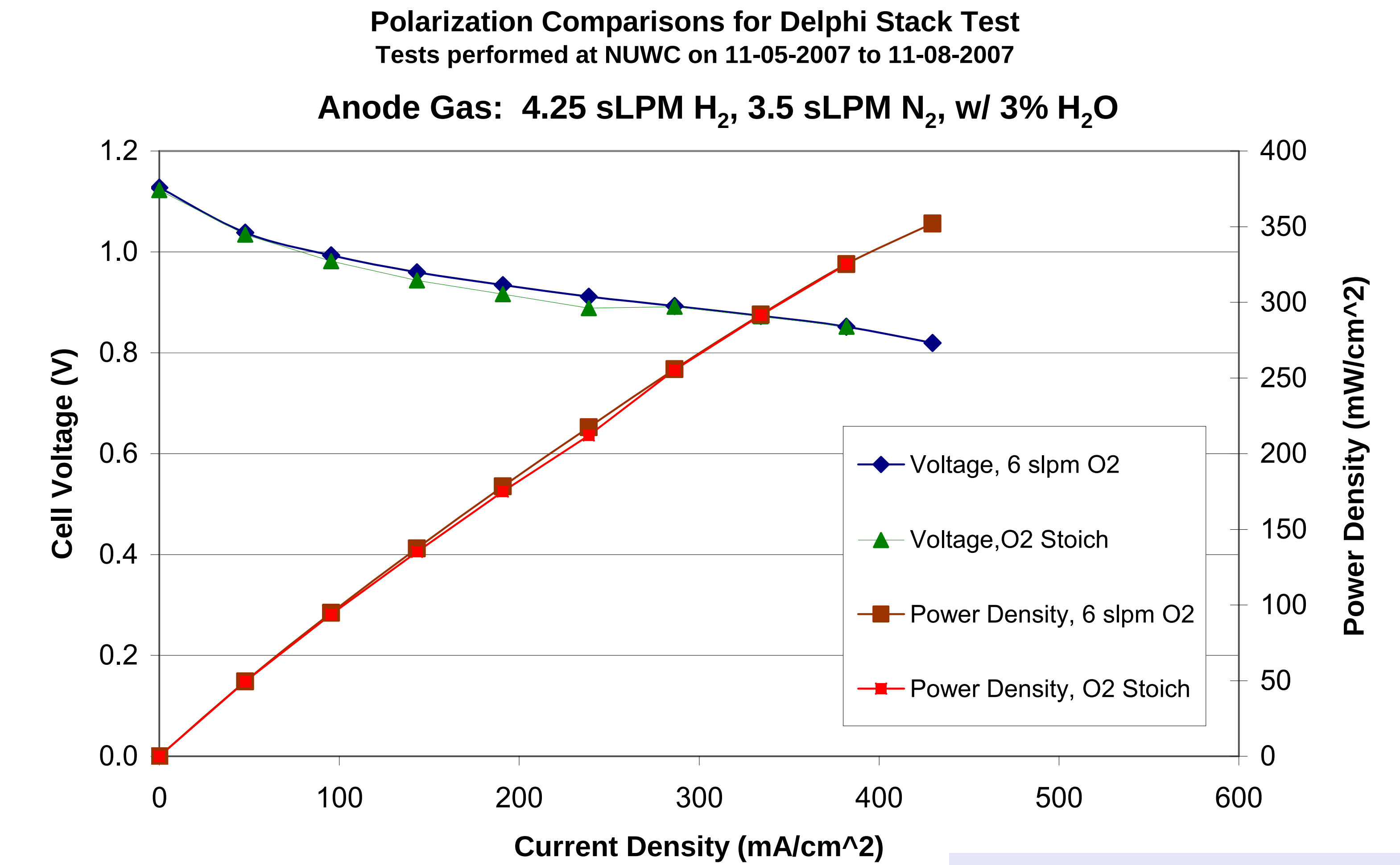
Steady-State, 100-hour Run

July 2007, Voltage versus time (at constant load) for Delphi 10-cell stack. Anode Feed: 6.91 sLPM H_2, 0.3 sLPM CH_4, 0.44 g/min S-8, and 2.9 g/min Steam



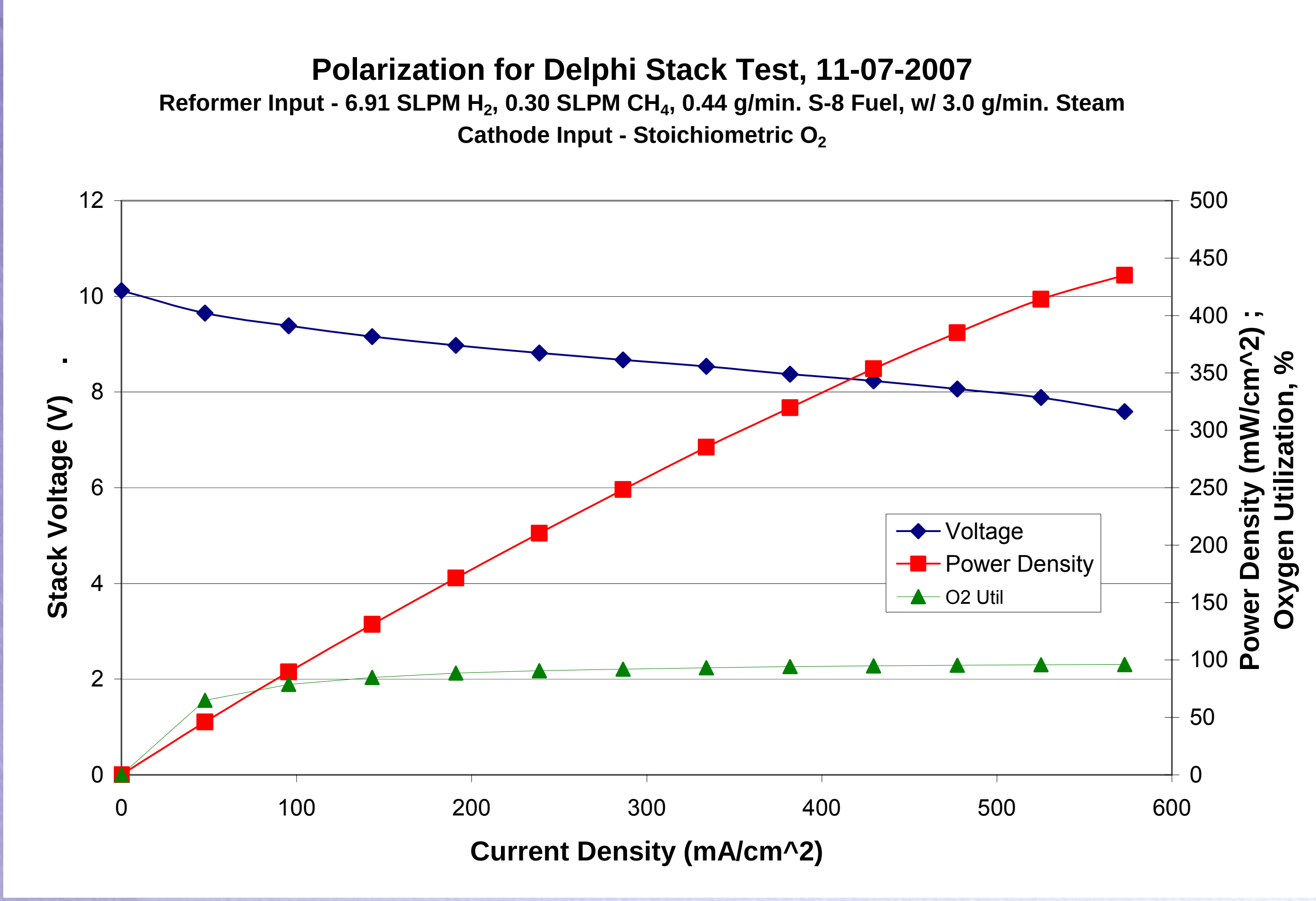
22% Utilization Reformate & ~20% Utilization Pure O_2
0.3 mA/cm^2

Stoichiometric Oxygen Control

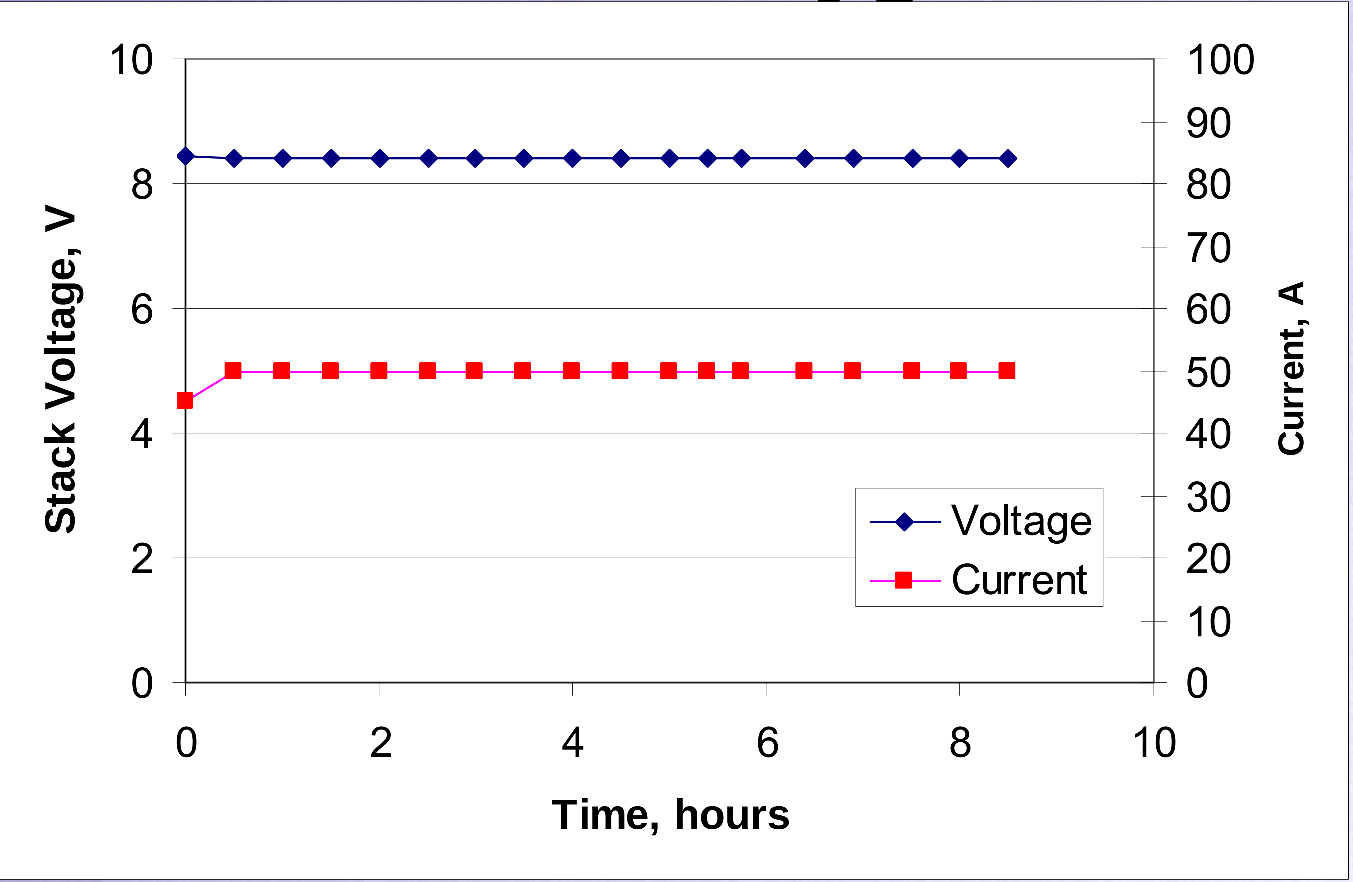


Comparison of IV plots shows that stoichiometric oxygen control has negligible effect on operating voltage.

IV-Plot with Reformate and Stoichiometric Oxygen

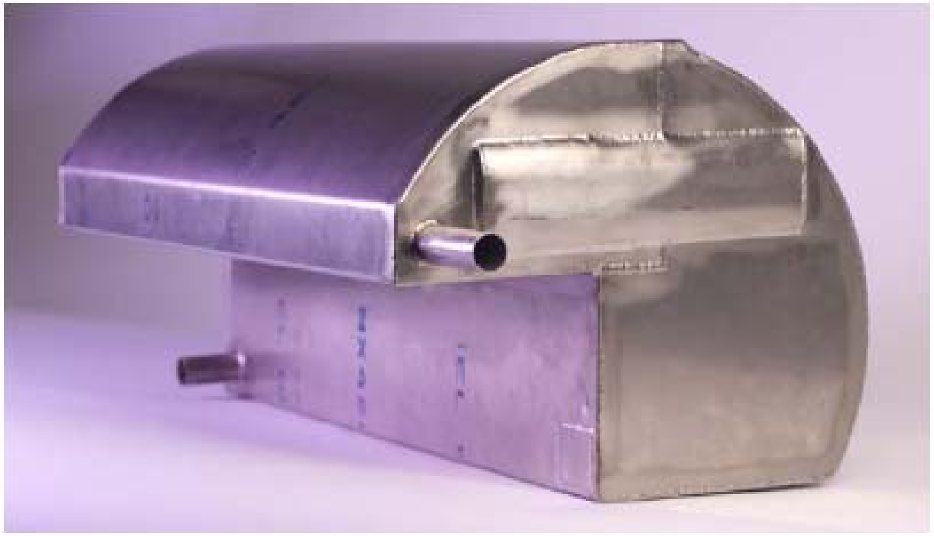


Steady State Operation using Reformate and Stoichiometric Oxygen



Steady state operation at 50 amps for eight hours using S-8 reformate and stoichiometric oxygen feed to the stack. At 50 amps, the single-pass fuel utilization was 35% and the oxygen utilization was 95%.

InnovaTek Steam Reformer



ONR STTR Deliverable:

-A compact, fully integrated steam reformer that operates on hydrocarbon fuels and a design concept for an integrated hot zone.

-Diesel-type fuels are converted to hydrogen and methane-rich reformate gas streams

INNOVATEK

$$C_mH_n + m\ H_2O_{(g)} + heat \longrightarrow (m+n/2)\ H_2 + m\ CO$$

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Steam Reformer Provided by InnovaTek

Reformer Inlet Streams for Delphi Test:

Gas stream: 6.93 L/min H_2, 0.33 L/min CO, 3.09 g/min steam

Liquid stream: 0.45 g/min S-8 fuel from Syntroleum

600˚ C

~ 1 atm

Reformer Outlet Stream for Delphi Test:

Dry Flow: 8.7 L/min (87.4% H_2, 3.4% CO_2, 3.9% CO, 5.3% CH_4)

~2.6 mL/min water

S/C ~ 2.8

Anode Gas Recycle Blower

Blower Attributes:

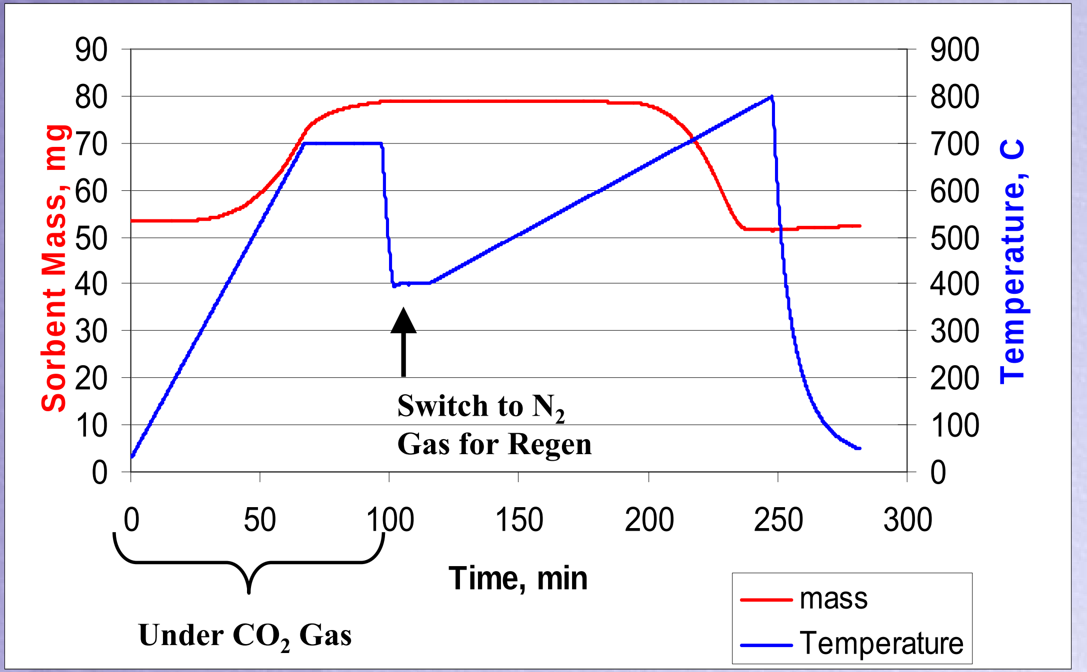
- Inlet T = 600-850º C
- Inlet P is atmospheric
- ∆P ~ 4-10” water
- 100 SLPM gas flow
- Nominal composition of 46 slpm H_2O, 27 slpm CO_2, 20 slpm H_2, and 7 slpm CO
- $\eta > 40\%$
- Variable speed control with turn-down ratio of 5 to 2
- 0.5 L, 4.26 kg

R&D Dynamics

**U.S. DOE-sponsored SBIR Phase II prototype matches 21” UUV design goals

Carbon Dioxide Scrubber

- $CaO + CO_2 \rightarrow CaCO_3$ + HEAT (178 kJ/mol)
- $CaCO_3$ Decomposes ~ 850° C



-Sorbent shows fast kinetics and stability for repeated cycles

-Production methods have been scaled up for this extruded CaO sorbent

-Sorbent provided by TDA Research, Inc.

-Sorbent tested at NUWC

Over 50% mass gain demonstrated

Laboratory System Demonstration

- 30-Cell Delphi Stack integrated with
  1) InnovaTek's Steam Reformer
  2) TDA Research's CO_2 Sorbent
  3) R&D Dynamics' High Temperature Blower
- Benchmarks achieved in first Demo:
  - > 75% S-8 Utilization
  - > 90% Oxygen Utilization
  - > 50% Efficiency (P_{SOFC} / S-8 LHV)*
  - > 1 kW

All achieved simultaneously in initial proof-of-concept study (several hours of operation).

*** Furnace power neglected**

Masses and Volumes of SOFC System Components

delivers 2.5 kW net output for 30 hours (75 kW-hrs)

Component	Mass, kg	Volume, L
Two 30-cell SOFC stack modules	**18**	**5**
Insulation	**3**	**23**
Steam reformer/burner	**40**	**6**
Oxidant storage (LOX)	***30***	***34***
LOX Tank	***70 (steel)*** ***~40 (aluminum)***	***100*** ***40 w/hull as vacuum jacket***
Dodecane/JP-8 Storage	**12**	**16**
Fuel Tank	**2**	**4**
Steam Recuperator/Condensor	**2**	**0.75**
Fuel Pump	**1**	**0.5**
AOG Recycle Compressor (R&D)	**5**	**2**
Bussing	**5**	**5**
Trim	**??**	**??**
CO_2 Scrubber (TDA to date)	**65**	**90**
BoP (piping, circuits, etc…)	**5**	**5**
Total	**~230 kg for 325 W-hr/kg**	**~235 L for 320 W-hr/L**

Available mass : 209 kg **Available volume: 189 L**

Conclusions

- SOFC technology has the potential to greatly increase UUV mission time compared with current battery technology.
- SOFC degradation and lifetime need further study using stoichiometric oxygen control
- Main challenges for UUV application:

  - Oxygen Storage
  - SOFC stack reliability for multiple thermal cycles
  - Thermal management of closed system

- NUWCDIVNPT is the Navy lead for testing SOFC stacks, integrating components and designing UUV systems.

Revolutionary Research . . . Relevant Results

U.S. DEPARTMENT OF ENERGY

Acknowledgements

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