Long Duration, Safe Power for Unmanned Underwater Vehicles

Protonex™

Joint Service Power Expo 2015

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THE NEXT GENERATION OF PORTABLE POWER.™

What We'll Explore

- UUV Power History
- Fuel Cells vs Batteries & Engines
- Hydrogen and Oxygen Generation
- Next Steps

Protonex™

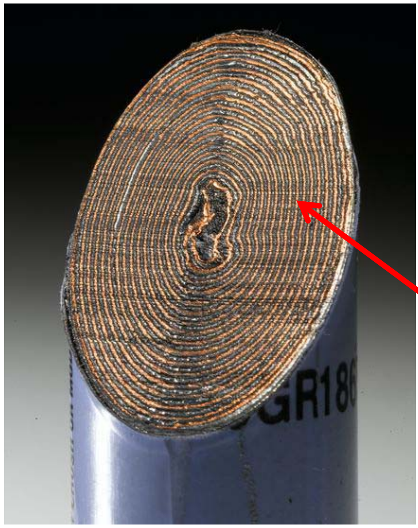
UUV Power History

- Why doesn't the Navy like lithium batteries?

PEM Fuel Cell – inherent safety vs battery

Battery

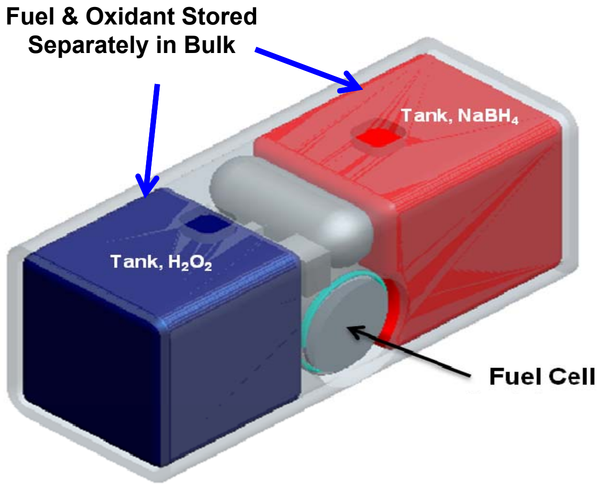
- Must package anode and cathode chemicals in close proximity to produce efficient power
- Vulnerable to individual cell damage leading to uncontrolled reaction
  - Thermal run away
- Limits selection of chemistries
- Complicated charge/discharge management to keep cells stable and prevent run away



Andode & Cathode chemicals in close proximity

Fuel Cells

- Fuel & Oxidant fed into stack in small amounts <u>on demand</u>
- Never have significant quantity present or near one another
- Fuel & Oxidizer stored separately
  - Simplifies safety design (avoid leaks)
- Fuel & Oxidizer <u>non-flammable</u>



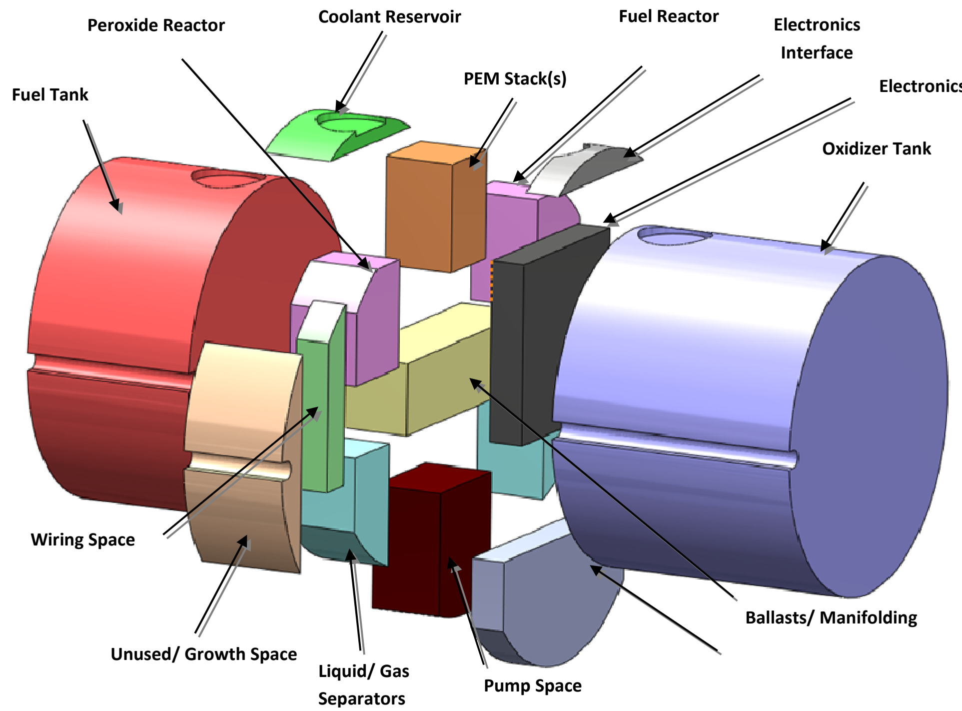
Underwater Power System Approach

The Solution – Fuel Cells

- Scalable power and energy
- Performance driven by fueling solution(s)
- Hybridization with batteries provides wider dynamic range
  - Turn down and peaking capability

Protonex Focus

- Leverage proven stack & fueling technologies
- Improve safety over existing batteries
  - PEM Stacks – TRL 9
  - H2 storage via sodium borohydride
    - TRL 8, numerous patents pending
    - Delivered kW scale subsystem to NUWC
  - O2 storage via 59% H_2O_2
    - TRL 5 – scaled from existing rocket technology
- Provide operational capability at depth



Protonex fuel cell systems provide significant performance advantage over incumbent battery technology (3x to 5x), <u>safely</u>

Protonex Adhesive Bonded Stack Technology

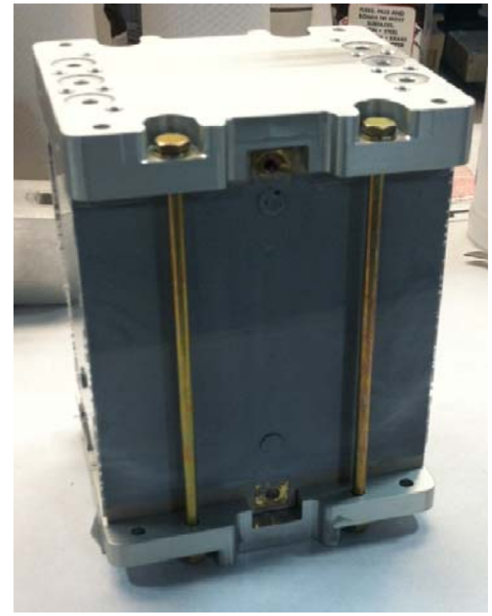
- **Cost-effective, high performance design**
  - Simple construction enables fast build cycles and automation
  - Low part count
  - Reduced component complexity enables vendor flexibility
  - Membrane supplier independent
- **Rugged and highly durable**
  - No gasket compression set
  - No exterior leakage paths
- **Liquid cooled design provides**
  - Extended temperature range -40˚C ~ 65˚C
  - Long life
  - Stable performance

Adhesive bonded stack manufacturing provides high reliability

High Power Oxygen PEM Stack Technology

- **Proven Protonex PEM stack design and construction**
  - Adhesively bonded
  - MEA and flow channel design tailored for pure oxygen
- **High cell active area ($50cm^2$)**
  - 38 cell variant = $1900cm^2$ total
  - 48 cell variant = $2800cm^2$ total
- **Compact physical size**
  - 4.2-in x 4.9-in cross section
  - 38 cell = 6.5-in tall
  - 48 cell = 9.1-in tall
  - 17% height reduction possible
- **Demonstrated up to 3 kW**
  - 38 cell = 0.9/2.4 kW nom/peak
  - 48 cell = 1.2/3.0 kW nom/peak
  - Readily scalable

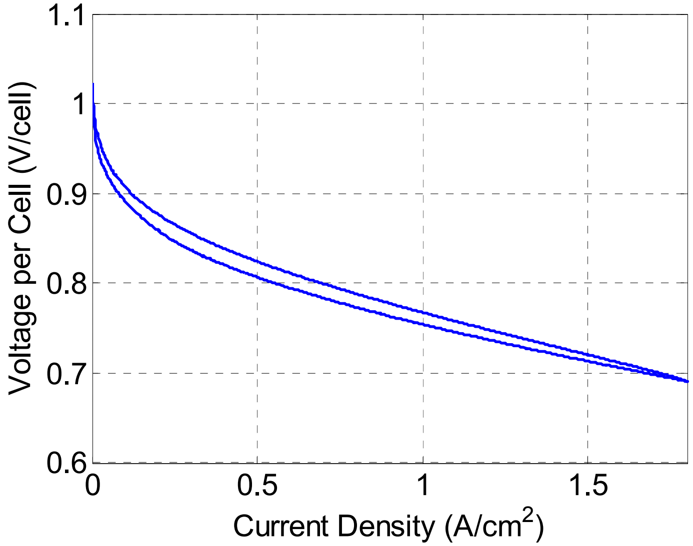
38 Cell Stack

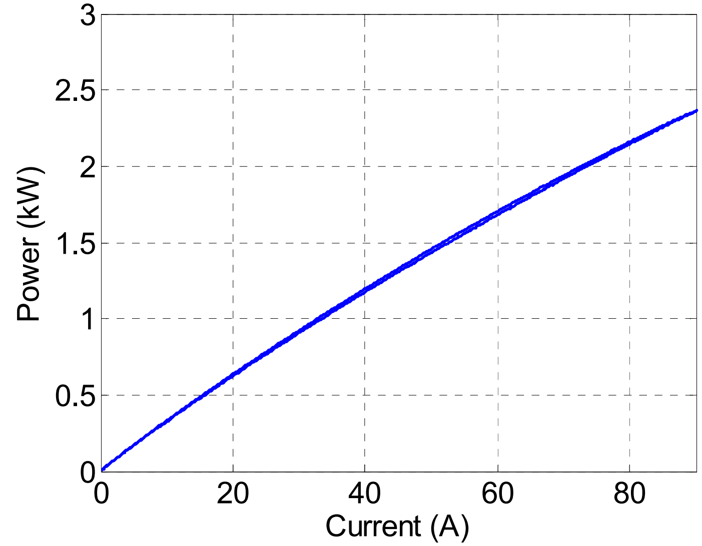


48 Cell Stack

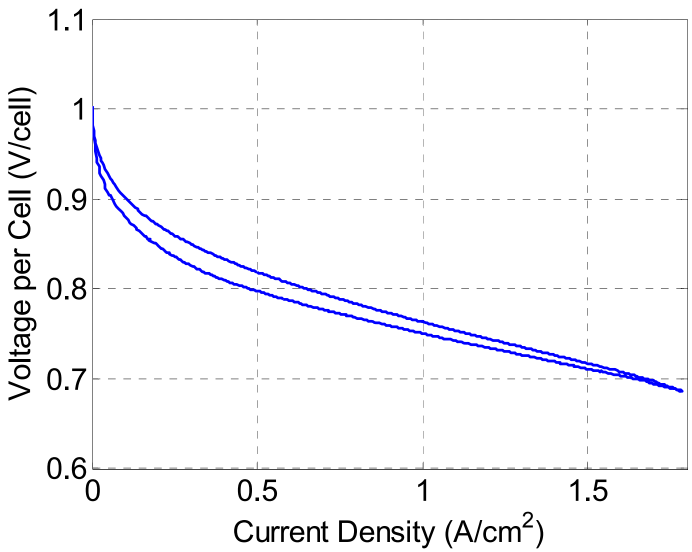
High Power Oxygen PEM Stack Performance

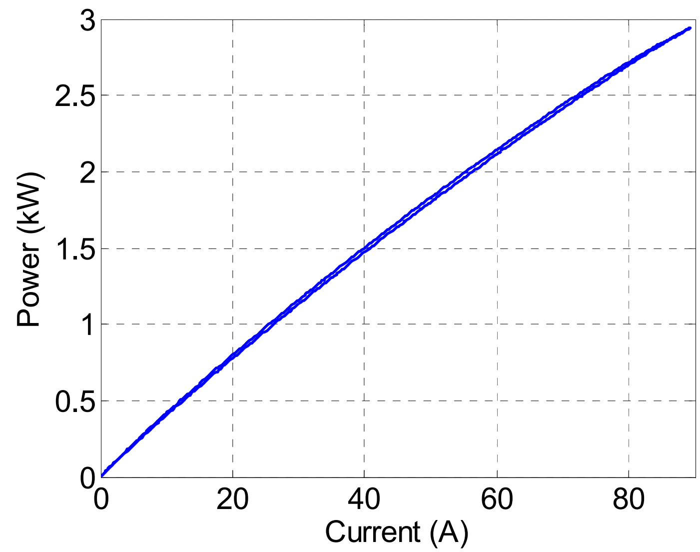
38 Cell Stack





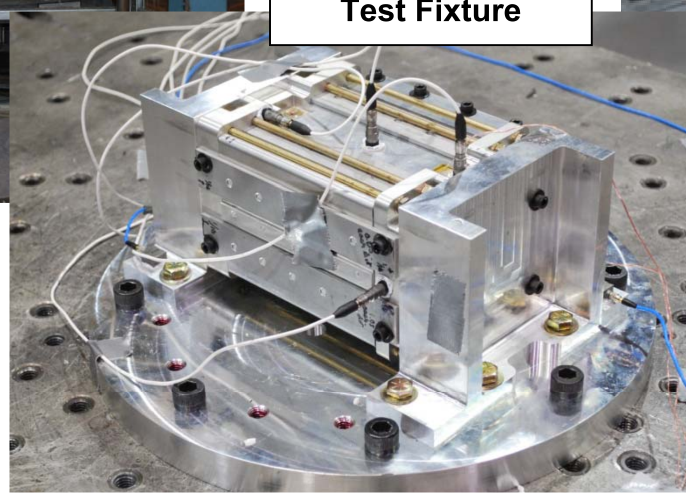
48 Cell Stack



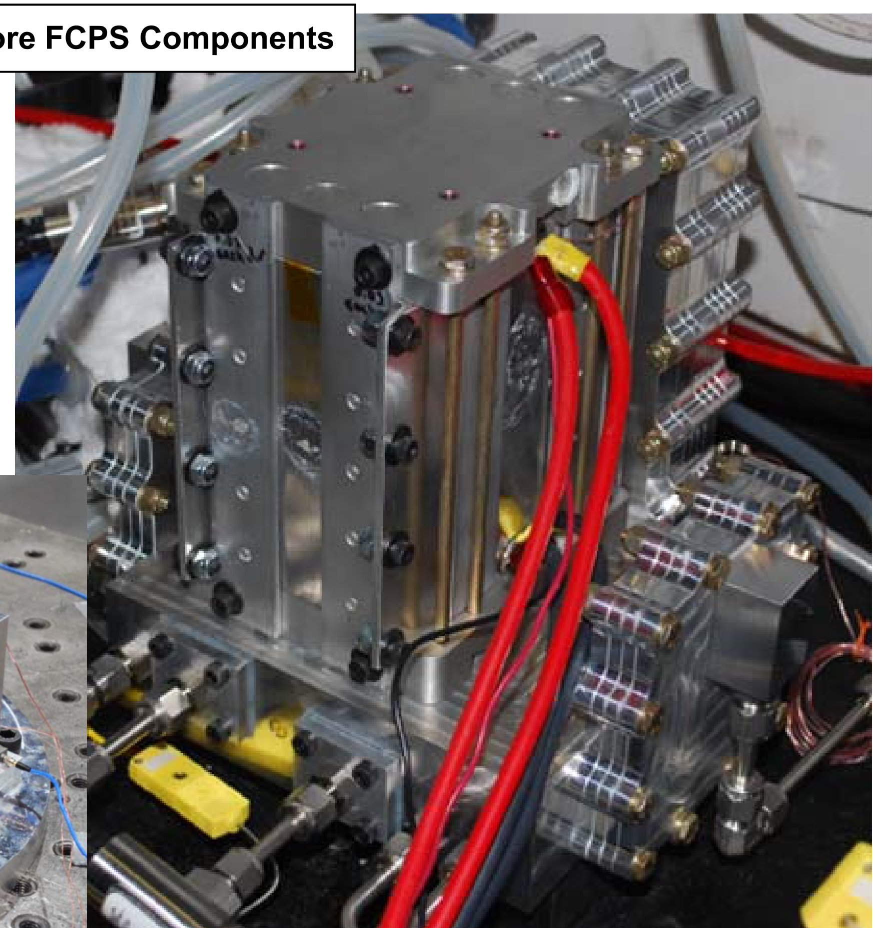


Oxygen PEM Stack Environmental Testing

Shock Test Fixture



Random Vibration Test Fixture



Core FCPS Components

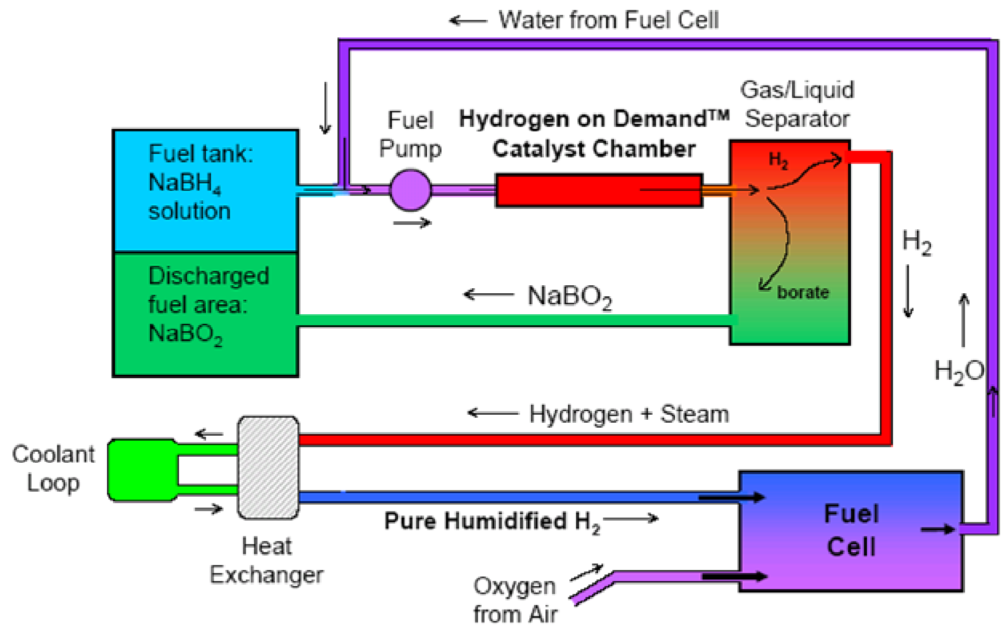
The FCPS fuel cell stack has been subjected to customer qualification level shock and random vibration dynamic environments.

The FCPS has undergone preliminary thermal and electrical performance testing as an integrated unit

Sodium Borohydride (SBH) for Hydrogen Storage

- **Strong design heritage**
  - High TRL, >10 yrs development
  - Automobile and UAS applications
- **High storage metrics**
  - 0.045 – 0.064 g H_2/g Solution
  - Liquid, SG = 1.0
- **Hydrogen as needed**
  - Fast start-up
  - Rapid load following
  - Reliable control scheme
- **Safe chemical hydride**
  - Non-flammable, non-toxic
- **Low cost materials**
- **Wide operational temperature range**
- **Reusable or single-use configurations**

Typical SBH System Implementation



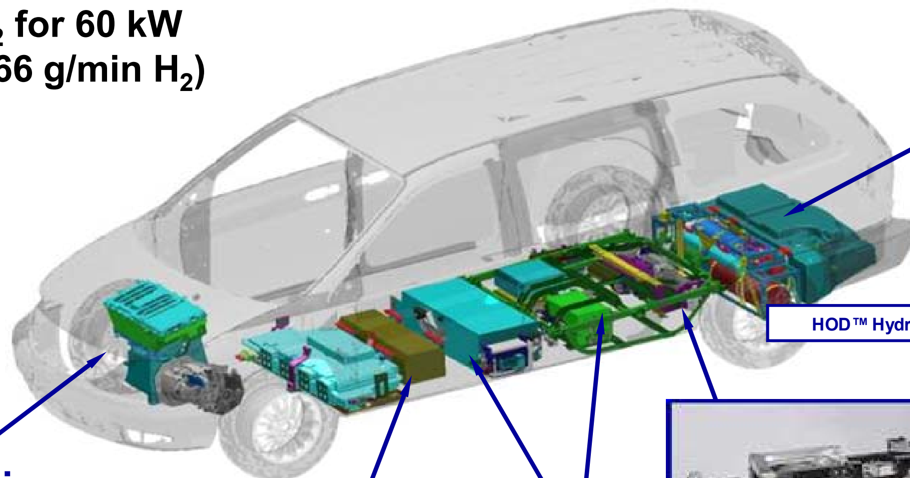
Development History Millennium Cell

- **In 2010 Protonex purchased the IP portfolio of Millennium Cell**
  - >$100m spent on Sodium Borohydride for hydrogen storage
  - US patents: 6,534,033; 6,683,025; 7,220,290; 6,932,847; 7,530,931; 7,316,718; 7,282,073; 6,939,529; 7,105,033; 7,540,892; 11/521351
- **IP focused around aqueous SBH formulation, hydrolysis reactor design, and effluent management**

Demonstrated - ***Chrysler Town & Country Natrium®***

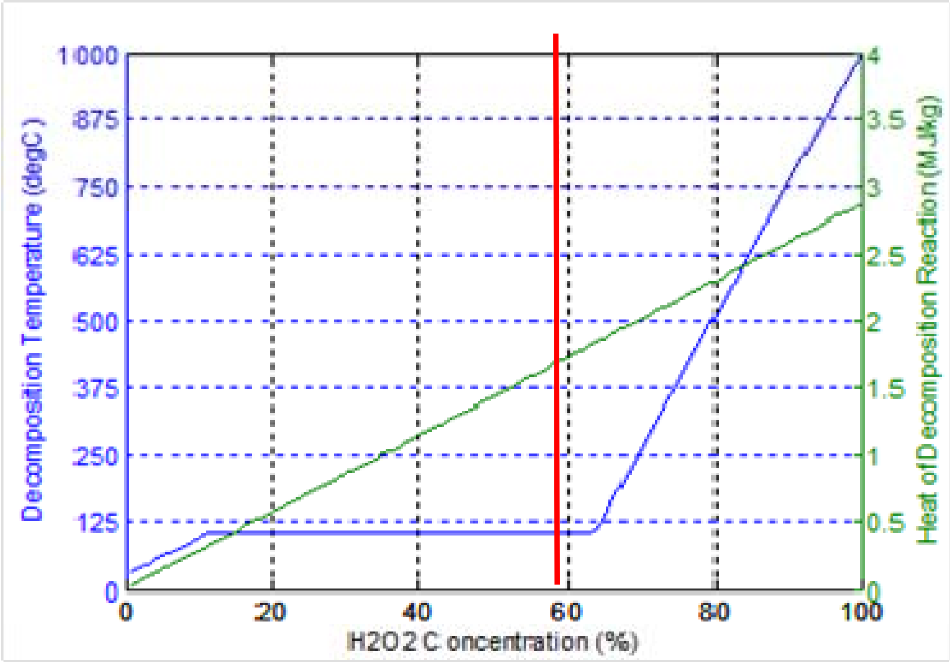
2002 What's new award by *Popular Science*

SBH System Provided H_2 for 60 kW Fuel Cell Power Output (~66 g/min H_2)



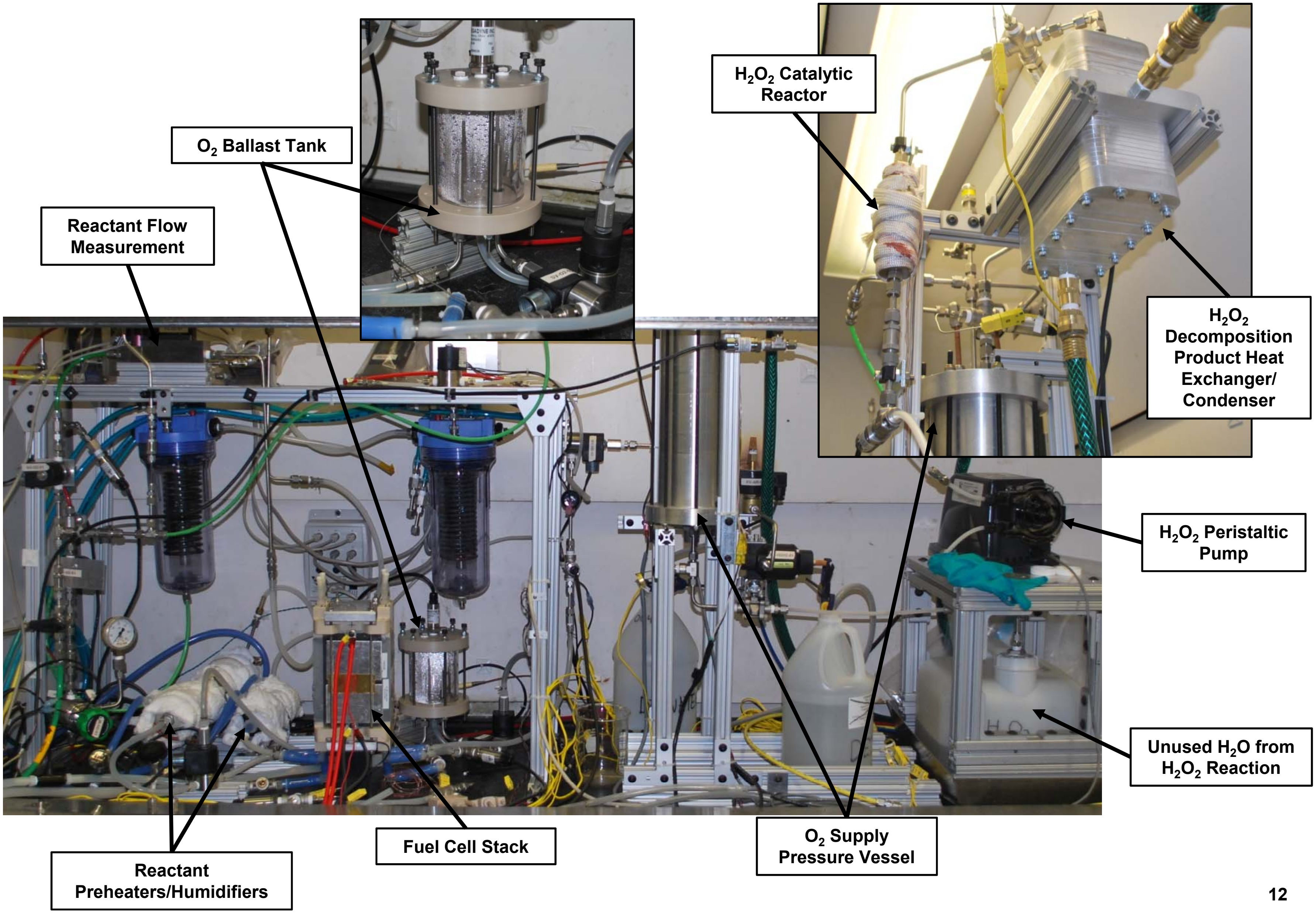
Hydrogen Peroxide (H_2O_2) for Oxygen Storage

- **Safety at 59%**
  - Concentration is a key differentiator
  - 59% solution cannot generate enough heat to boil away water in the solution
- **Simple system design**
  - Catalytic decomposition
  - Similar to SBH system
- **High density**
  - Specific Gravity =1.2 (@ 59% H_2O_2)
- **Oxygen on demand**
  - 250 L O_2 per L 59% H_2O_2
- **Storable (non-cryogenic)**
  - Liquid at room temp
- **Non-flammable**
- **Extensive industrial production capacity exists**
  - 1.5 billion lbs/year in North American market
  - Largest plant produces 240 million lbs/year
  - 70% of H_2O_2 produced is 70% H_2O_2

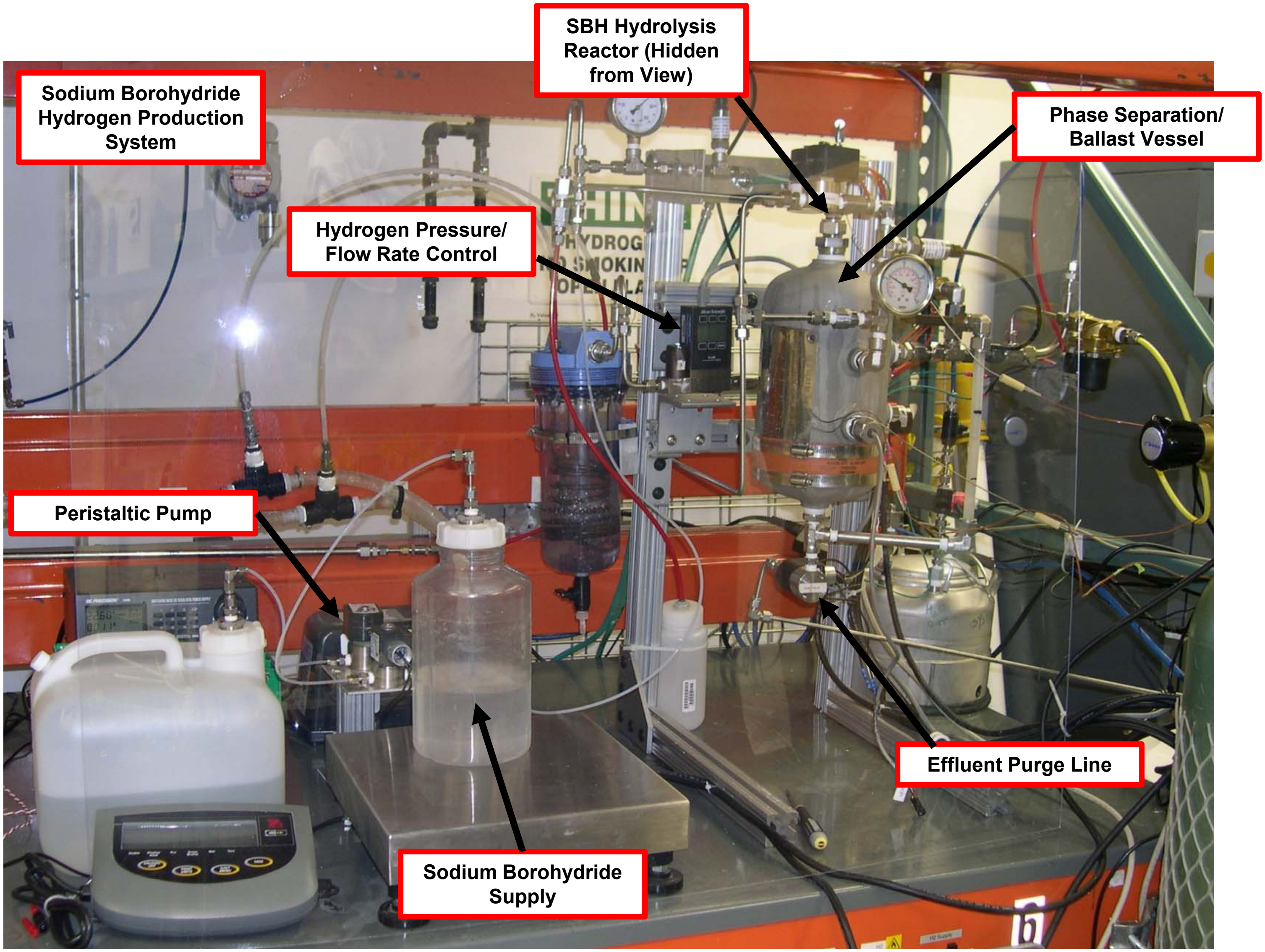


Thermochemistry of hydrogen peroxide decomposition reaction: At 59% concentration heat liberated is only enough to reach water normal boiling point (100 degC).

Oxygen PEM Fuel Cell Test Stand



Bench-Top SBH Hydrogen Generation System



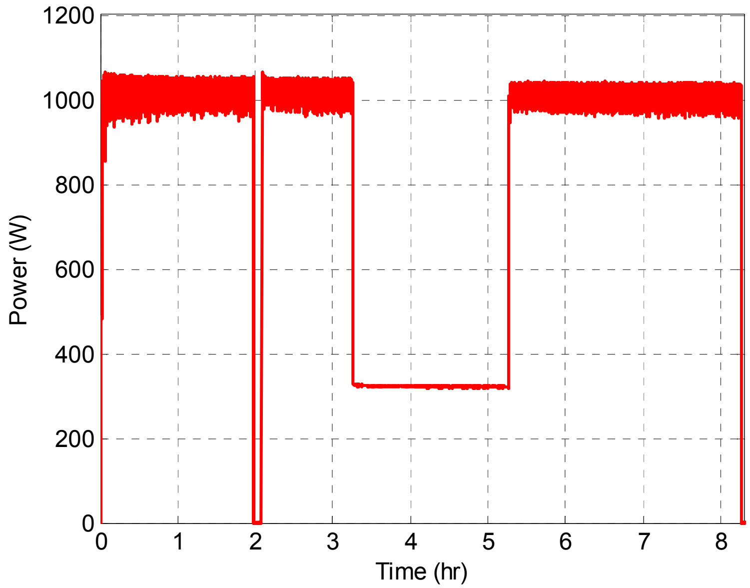
Integrated System Test Results

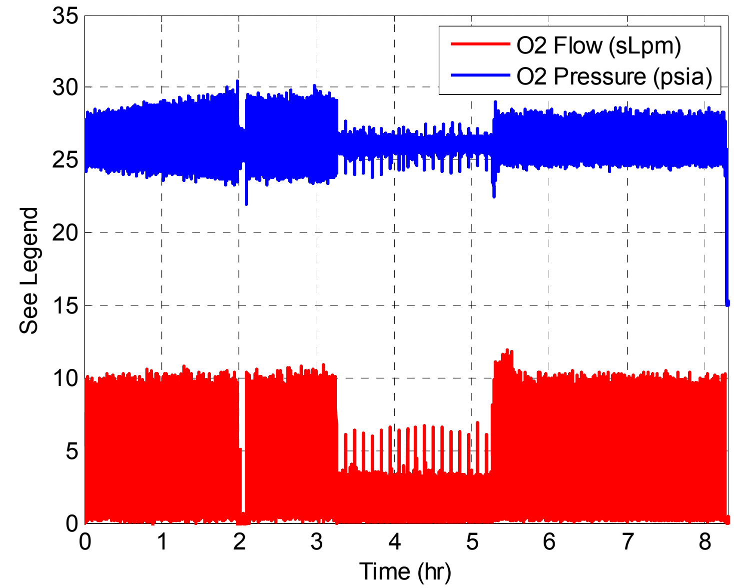
- **8 hr test completed simulating notional load profile**
  - Cathode operated with high utilization purge recovery scheme
  - Anode operated in dead-headed mode (single purge valve)
  - ~3.0 gal Aqueous SBH load in SBH tank
  - ~3.0 gal 59%wt H_2O_2 load in H_2O_2 tank
- **All systems operated without issues**
  - Brief hydrogen flow interruption from inadvertent SBH system safety trigger

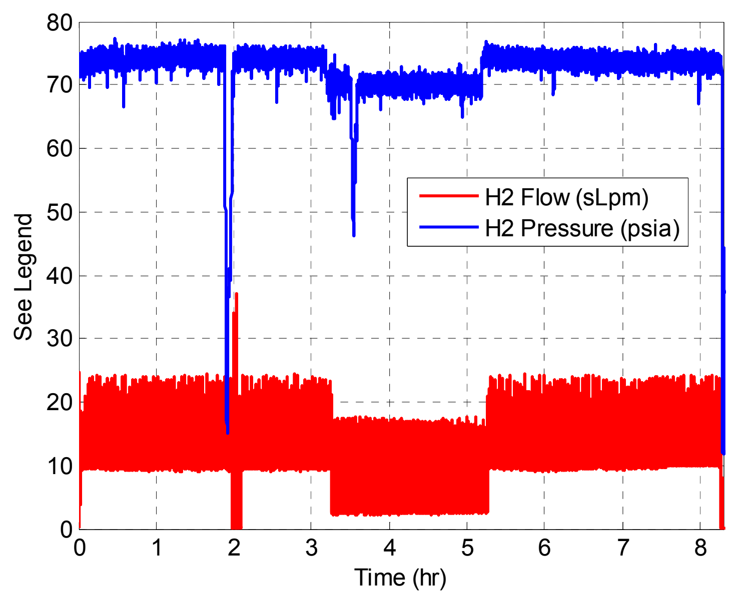
Test Segment	1	2	3
Power (W)	1031	323	102
Duration (hr)	3.1	2.0	3.0
H_2O_2 Flow Rate (mL/min)	21.4*	7.9*	21.4*
Stack O_2 Flow Rate (sLpm)	5.1	1.5	5.1
Stack O_2 Utilization (%)	99.8	97.1	99.8
SBH Flow Rate (mL/min)	25.3*	8.6*	26.7*
Stack H_2 Flow Rate (sLpm)	10.7	3.5	10.8
Stack H_2 Utilization (%)	93.9	80.8	93.7

* Includes H_2O_2 or SBH necessary to produce gas relieved from test system upstream of stack (not used in power generation)

Integrated System Test Results







Fuel Cell Power System Status

- **Demonstrated key subsystems/components in test operations:**
  - High power density O_2/H_2 stack
  - SBH H_2 generation system
  - 59%wt H_2O_2 O_2 generation system
  - Very high stack O_2 utilization scheme
    - Approach previously demonstrated in H_2 system of Protonex UAV fuel cell product
  - Component technologies are high maturity → TRL 7-8
- **59%wt H_2O_2 / SBH combination capable of 450-530 $Wh/L_{reactant}$**
  - Demonstrated these levels were practically achievable
  - Dependent on stored SBH concentration
- **System currently at TRL 5**

Next Steps

- **Future development focused on further TRL advancement**
- **Prototype demonstration in subsea environment → TRL 6**
  - Representative power, energy, and envelope
  - Mature system packaging for depth
  - Evaluate reactant effluent management schemes
  - Demonstrate quick refuel/recharge
  - Confirm overall system performance
- **Detailed system design for specific subsea platform**
  - Well defined power, energy, and envelope specifications
  - Thorough packaging for depth
  - Estimate integrated system performance
- **Demonstration on subsea platform → TRL 7**