Analysis of SOFCs for Air Independent Applications

12th SECA Workshop, July 2011

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Conclusions

- Methane vs. Diesel-type Hydrocarbons
  - Comparable energy metrics
  - Requires less O_2 and CO_2 sorbent per BTU
  - Should facilitate reformer operation and waste heat utilization for reforming
- Methane/NG Can:
  - Be a first generation fuel for SOFC-powered demonstration UUVs
  - Open the door to other SOFC-powered platforms
  - Offer a cleaner, more sustainable, and more secure energy infrastructure for the Navy

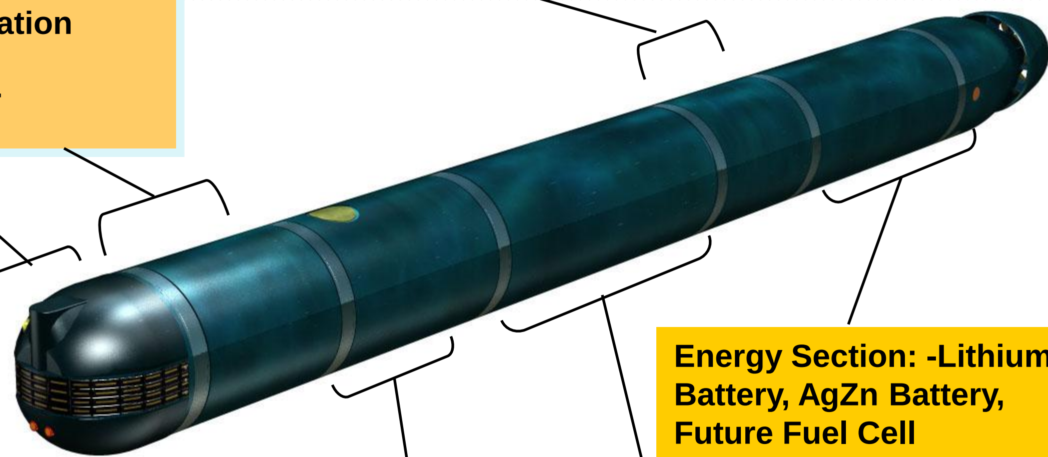
Conceptual UUV
(Unmanned Undersea Vehicle)

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

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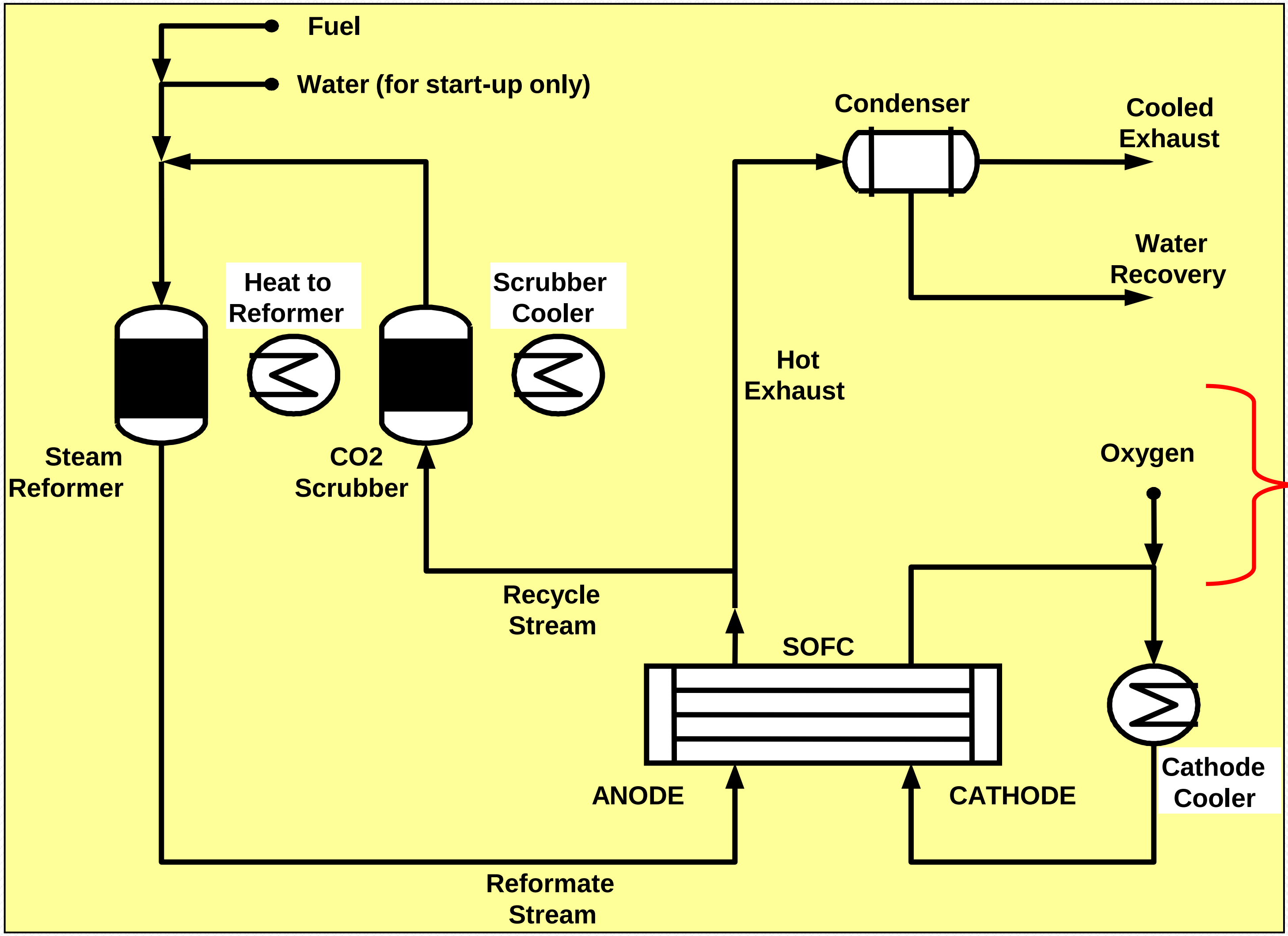
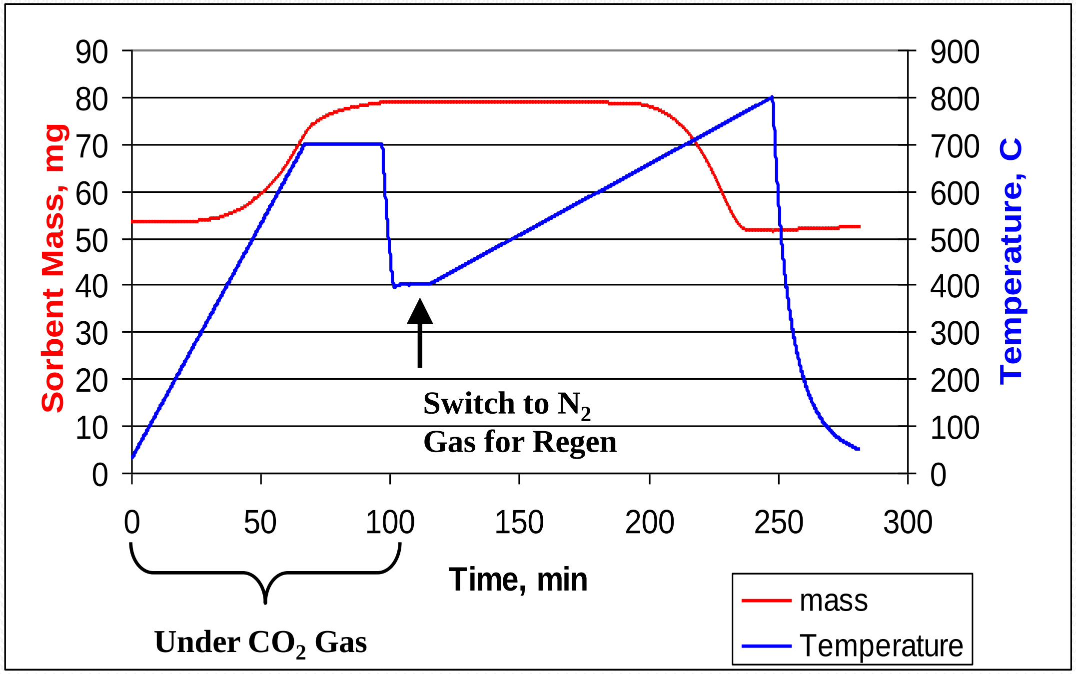
Proposed System Design with Anode Recycle



Oxygen Utilization nearly 100% for this application!

Carbon Dioxide Scrubber

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



Over 50% mass gain demonstrated

-Sorbent showed over 70% conversion of CaO in gas mixture of 21% CO_2/44% H_2/35% steam

-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

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2008 Laboratory System Demonstration

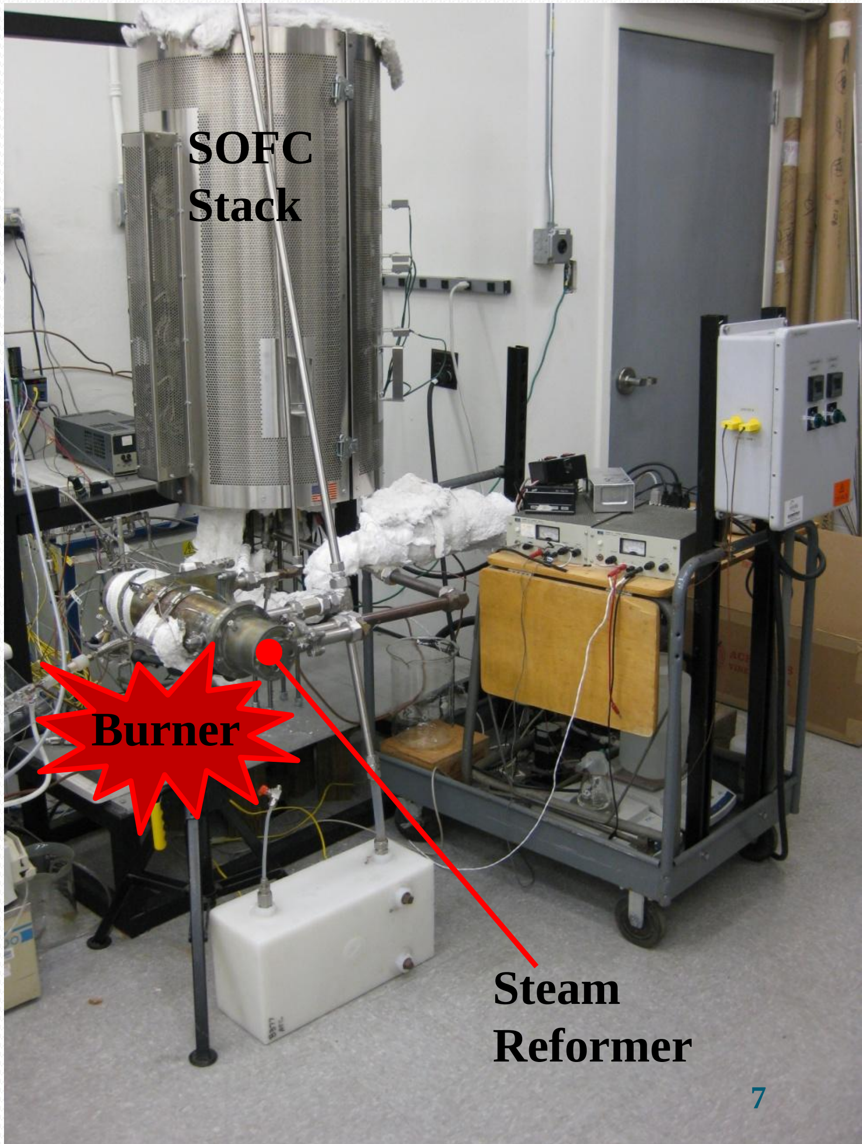
- 30-Cell Delphi Stack integrated with
  1) InnovaTek's Steam Reformer
  2) TDA Research's CO_2 Sorbent
  3) R&D Dynamics' High Temperature Blower
- Benchmarks achieved in first Demo:
  - > 75% S-8 Utilization
  - > 90% Oxygen Utilization
  - > 50% Efficiency (P_{SOFC} / S-8 LHV)*
  - > 1 kW

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

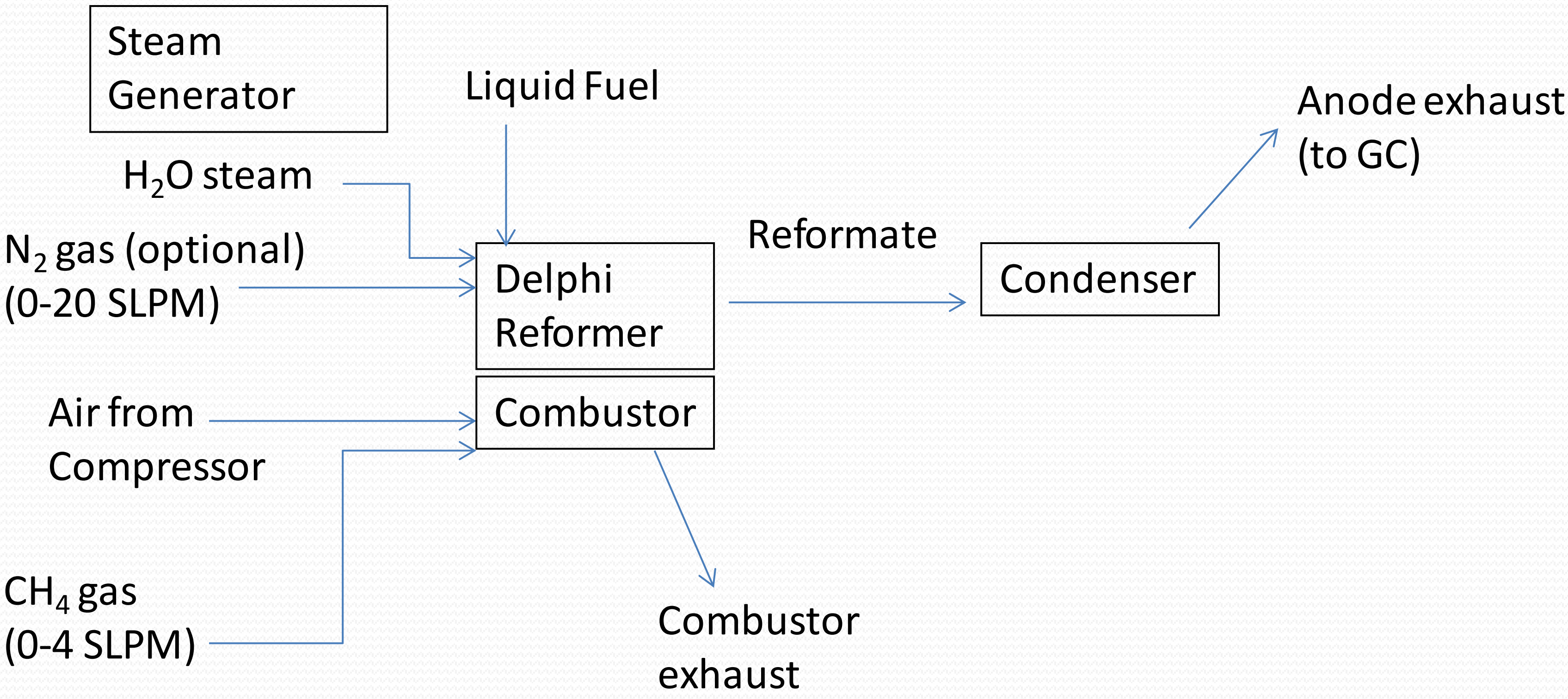
*** Furnace power neglected**

2010 Laboratory System Demonstration

- Goal: Show that Waste Heat from SOFC stack can be used to drive steam reformer (from Delphi Corporation)
- This task could not be accomplished without also using a burner to partially drive (heat) the reformer



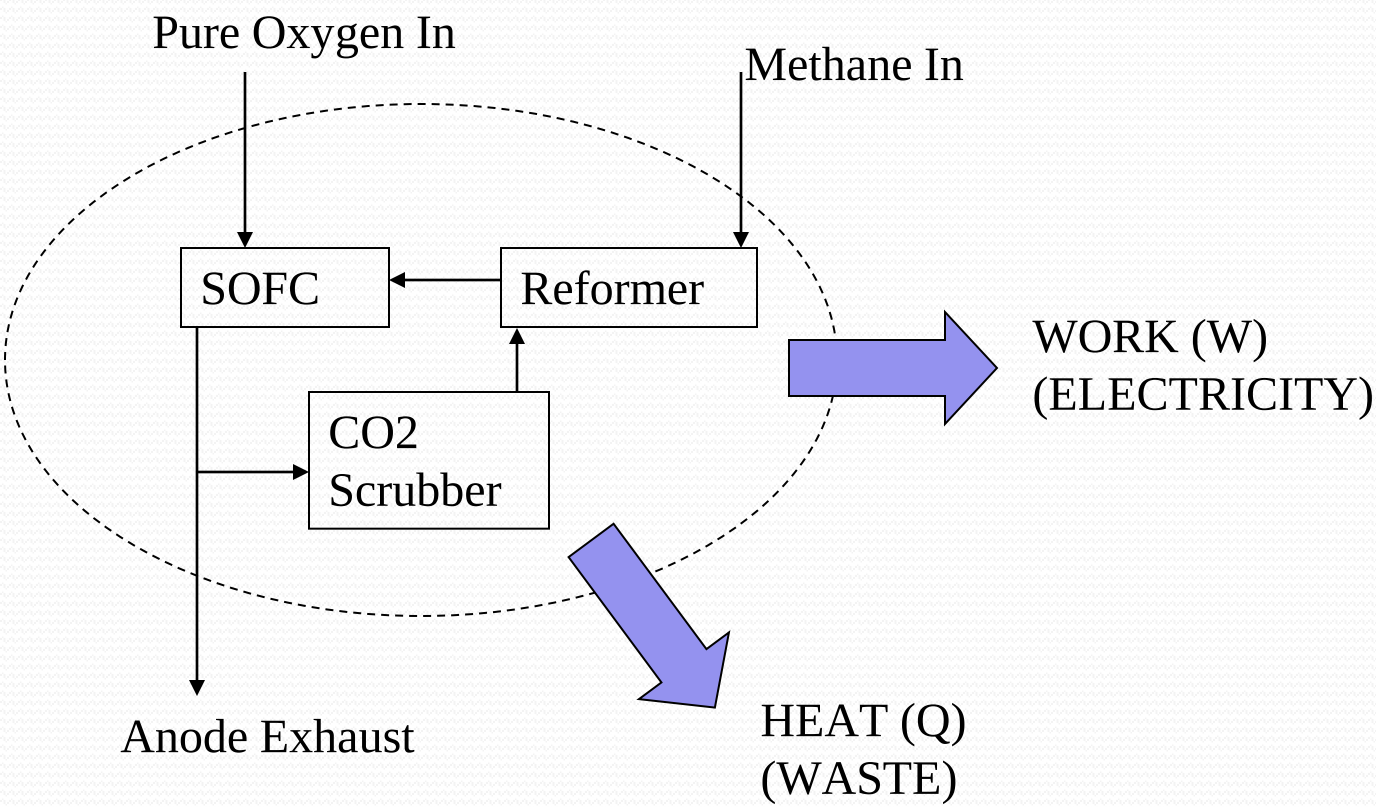
Isolated Steam Reformer Operation (Simulated Anode Exhaust)



Reformer Operation Notes

- JP-10 and S-8 fuels successfully steam reformed
- HC slippage when Ref outlet T < 500° C
  - Ethane, ethylene…
- Combustor T > 800° C used to verify proper reformer temperature / active catalyst
- Mass balances > 95%
- Efficiency of 100-120% achieved (based on "free" superheated steam)

System Energy Balance



Reactions:

$$CH_{4(g)} + 2\,O_2 \Rightarrow CO_2 + 2\,H_2O_{(g)} + 800\ \text{kJ/mol}_{CH4}$$

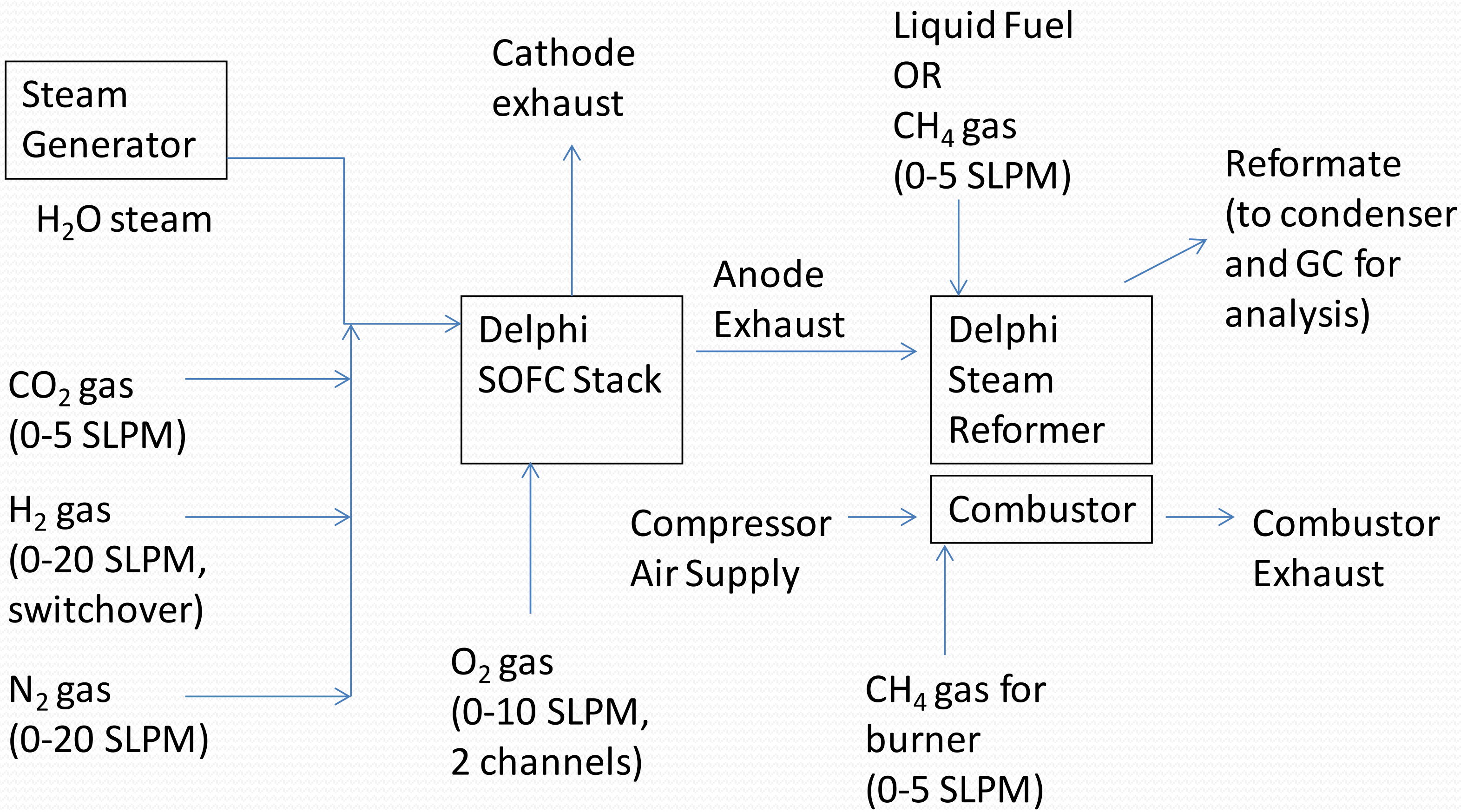
$$CO_{2(g)} + CaO_{(s)} \Rightarrow CaCO_{3,(s)} + 178\ \text{kJ/mol}\ CO_2$$

Process	Energy
Total HEAT of RXNS for 7.5 kg CH_4, 30 kg LOX, & 40 kg sorbent	**104 kW-hr from CH_4 23 kW-hr from sorbent (127 kW-hr Total)**
SOFC (output)	**-82 kW-hr electricity + -42 kW-hr heat**
Scrubber (output)	**-23 kW-hr heat**
Methane Steam Reformer (input)	**30 kW-hr heat**
LOX heat-up	**3 kW-hr heat**
Total Waste Heat (output)	-32 kW-hr or 25% of energy generated
Expected System efficiency based on LHV of methane	>60% after parasitic losses

Reactant-Based Energy Metrics

System Reactants & Fuel Cell Type	Specific Energy, W-hr/kg	Energy Density, W-hr/L
SOFC, S-8/LOX/CO_2 sorbent	1130	1050
SOFC, LNG/LOX/CO_2 sorbent	1420	1060
SOFC, JP-10/LOX/CO_2 sorbent	1180	960
PEM, 4wt.% H_2 / LOX	1010	720
PEM, Liquid H_2 / LOX	1150	710

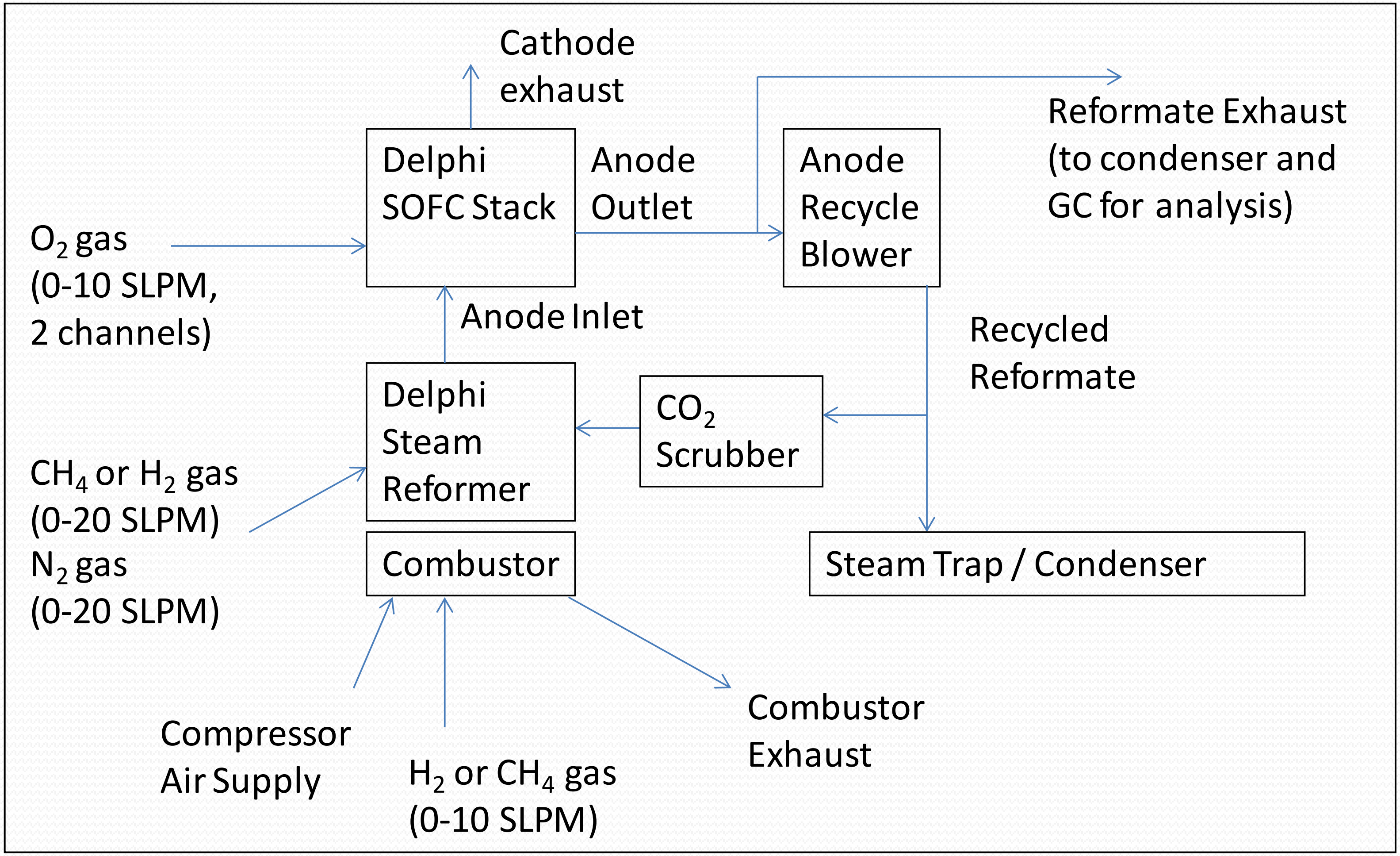
Reformer Testing with Real Anode Exhaust



During Methane UUV Test

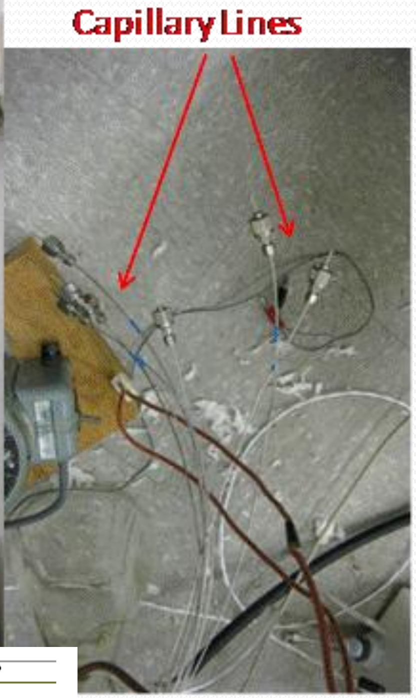
- SOFC Inlet:
  - 20 sL/min H_2 (65mol%), 4 sL/min CO_2 (13%), and 4.8 g/min steam (21%). (30.4 sL/min total)
- 45 Amps, 30-cell stack
- SOFC Exhaust Blended with 3 sL/min CH_4
- Reformer Outlet: 36.4 sL/min
  - 39% H_2, 3% CO, 4.8% CH_4, 41.7% H_2O, 11.2% CO_2,
- Reasonable reformate composition considering no CO_2 scrubbing and unreformed CH_4, but some water collection will be needed to avoid excessive steam accumulation in anode recycle loop

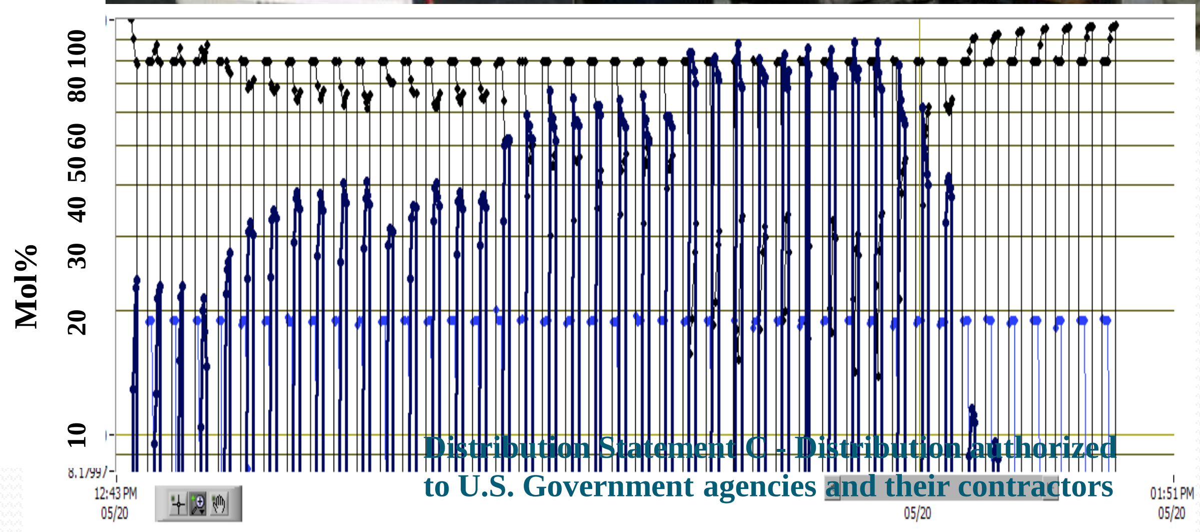
2011 Test Plans



System Level Demonstrations with only methane gas and pure oxygen reactant feeds

Mass Spectrometer





Steam levels of 25-75% were measured with the MS

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Issues Affecting Waste Heat Usage

- Two Primary sources of waste heat:
  - SOFC Stack & CO_2 scrubber bed
- Variable active locations in CO_2 scrubber bed
- Directing heat towards fuel vaporization
- Range of volatility in most liquid fuels, preventing carburization
- Variable SOFC power level

Methane Pros/Cons for UUV Application

- Pros
  - Easily vaporized, avoids carburization
  - Internal Reforming
  - “De-localized” Reforming
  - Help prevent coking in SOFC (C2+ HC’s)
  - Max H/C ratio, thus lowers O_2 consumption
- Cons
  - Decreased heat from CO_2 scrubber
  - Dewar for storage
  - Water separation from anode loop

Other Fuel Options?

- Liquid propane or butane
  - PRO: Facilitates distribution & storage
  - CON: Decrease H/C ratio
- Methanol
  - PRO: Can backfill reactant space with product water
  - CON: Toxic, corrosive, & generally accepted as more hazardous than NG
- Ethanol
  - PRO: Can backfill reactant space with product water
  - CON: Lower H/C ratio

Navy Goals for Fleet

- Reduce Foreign Oil Dependence (Energy Security)
  - NG from ocean floor or bio-feedstocks
- Energy Efficiency
- Environmental Cleanliness
  - Reduce Carbon Footprint
- Economics
  - Long-term availability & multiplatform uses

Conclusions

- Methane
  - Comparable energy metrics vs. liquid fuels
  - Requires less O_2 and CO_2 sorbent per BTU
  - Should facilitate reformer operation and waste heat utilization for reforming
- Methane/NG Can:
  - Be a first generation fuel for SOFC-powered demonstration UUVs
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Acknowledgements

- Sponsor
  - U.S. Department of Energy (DOE)
    - Interagency Agreement with National Energy and Technology Laboratory (NETL)
- Collaborator
  - National Aeronautics and Space Administration(NASA)
    - Lyndon B. Johnson Space Center/EP3; Houston, TX

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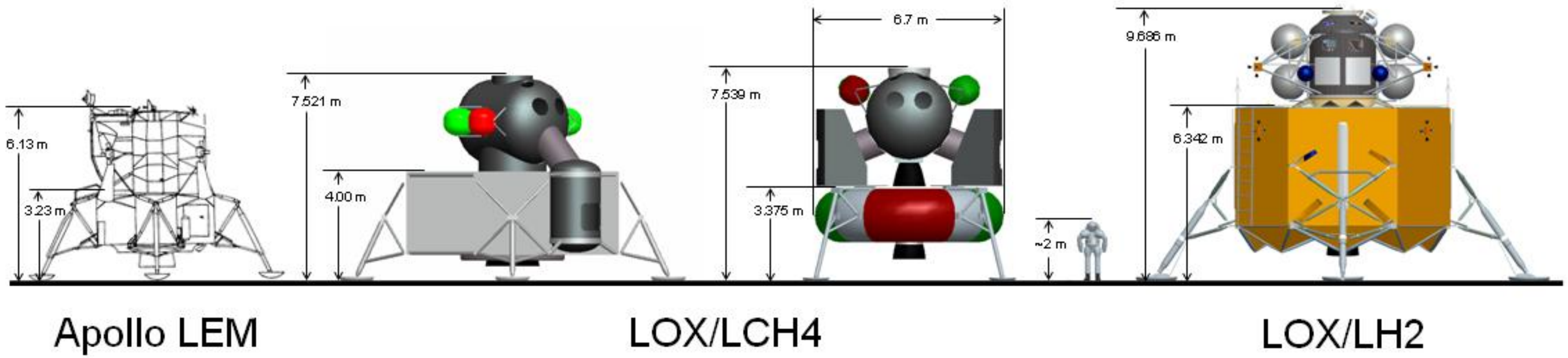
Conclusions

- Efficiency ~45% with fuel and oxidant utilizations near 85% is possible. 45% efficiency with 90% U_f results in a theoretical reactant specific energy of 4900 kJ/kg.
- Uncertainties remain regarding optimized CPOX design and operation using pure oxygen (pre-combustion, sooting, start-up).
- Optimized pure-O_2 CPOX design is of interest to the NASA and could be valuable for potential missions.

Motivation

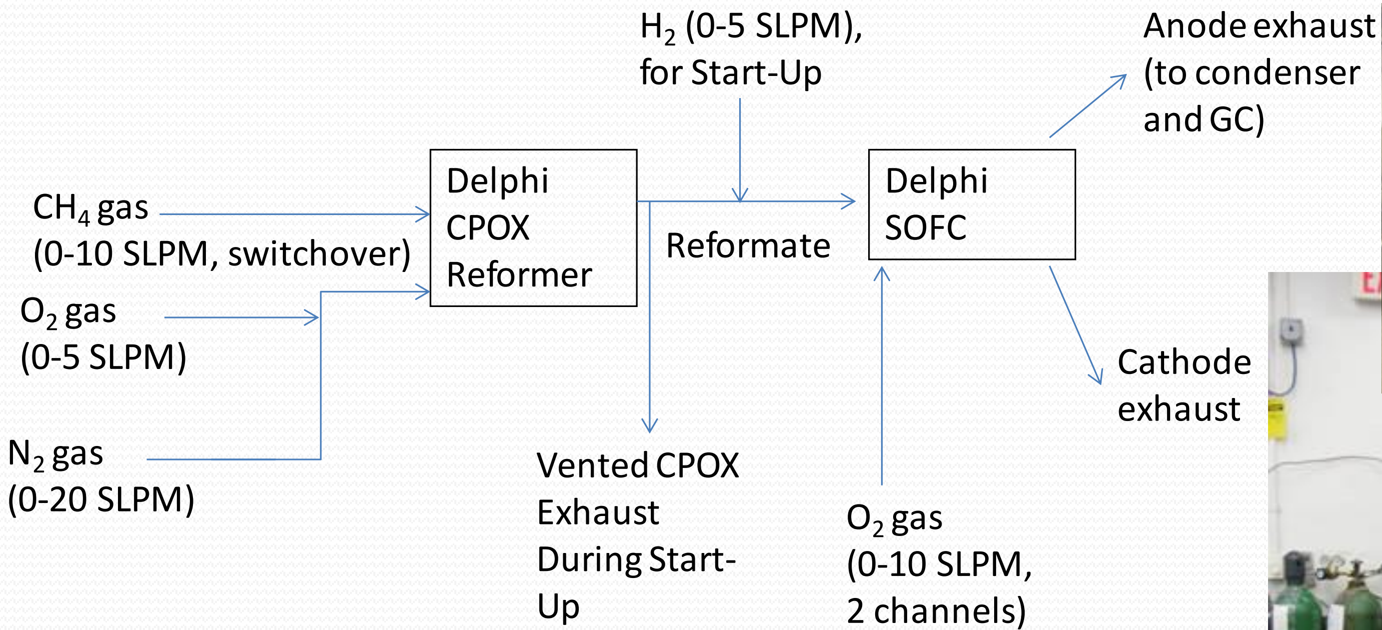
- LO_2/LCH_4 Offers a Significant reduction in the Size and Dry mass of a Spacecraft over LO_2/LH_2
- There are benefits to being able to have a power system that can share common fluids with the propulsion system

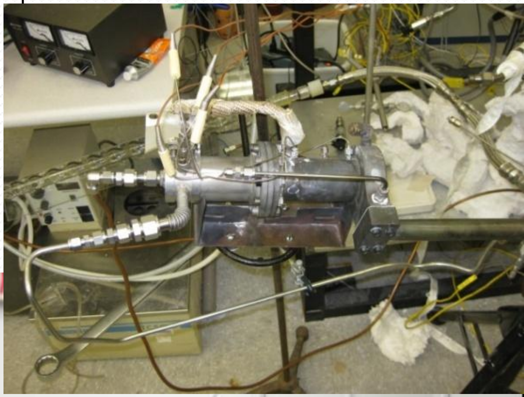


Project Morpheus

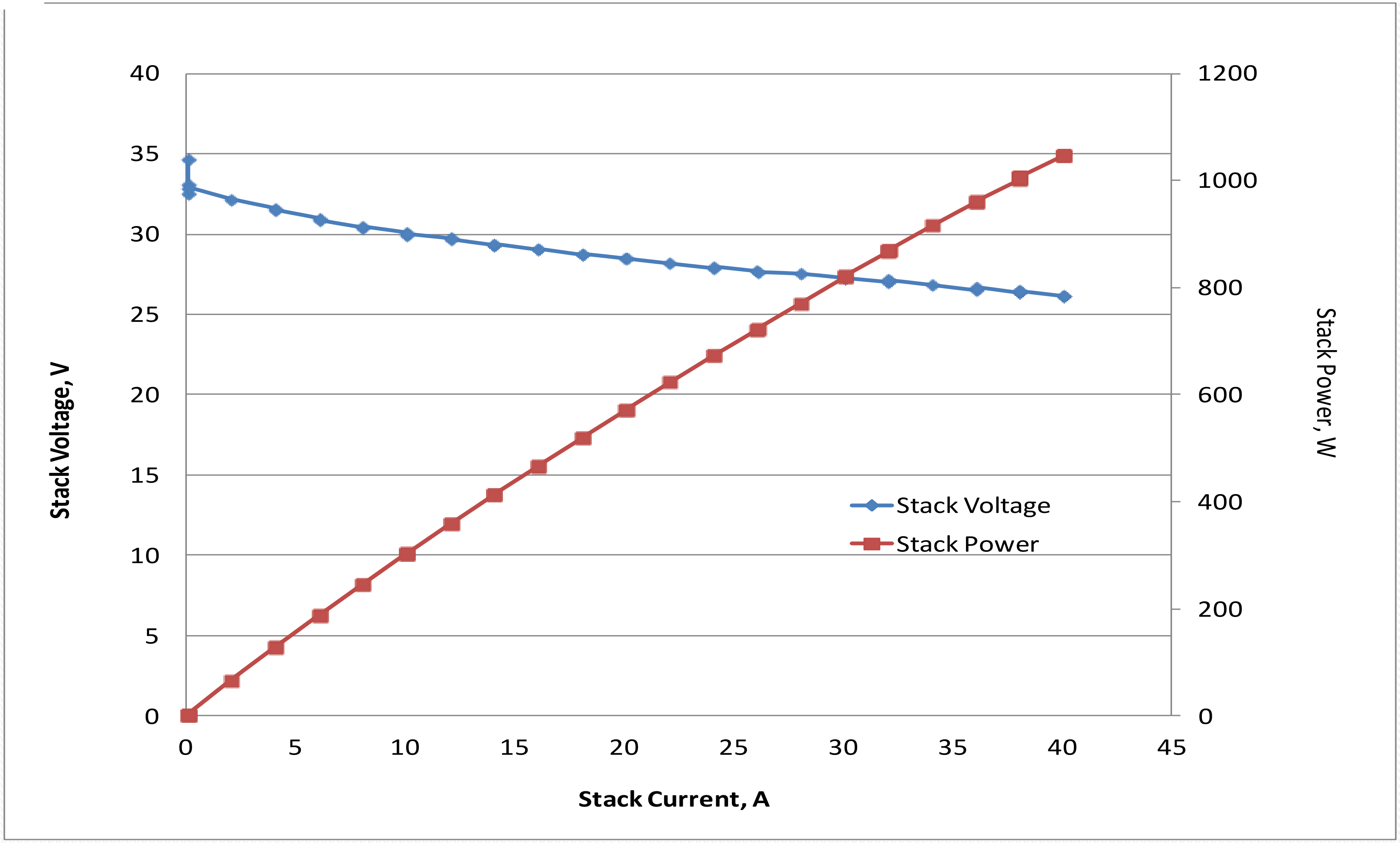
- Morpheus is a vertical test bed vehicle demonstrating new green propellant propulsion systems and autonomous landing and hazard detection technology. Designed, developed, manufactured and operated in-house by engineers at NASA's Johnson Space Center, the Morpheus Project represents not only a vehicle to advance technologies, but also an opportunity to try out "lean development" engineering practices.
- Solid Oxide Fuel Cells could provide power by using scavenged LOX\ CH_4 left as residuals in the propulsion tanks or by tapping into propellant made by In-Situ Resource Utilization(ISRU) processes.

System Layout for 2010 NASA Testing



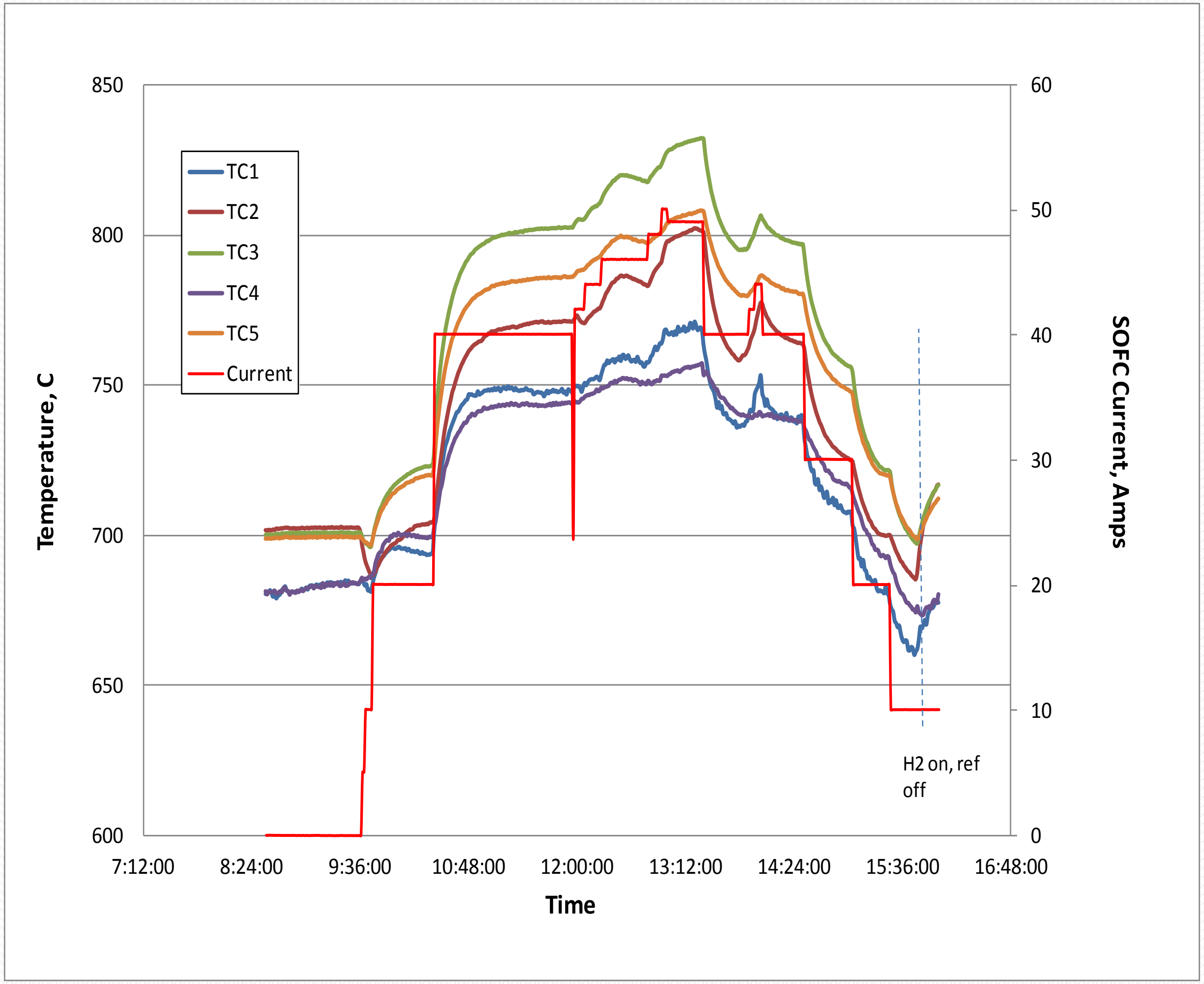


IV Plot for Stack Performance



Feeds to the CPOX reformer were 3.3 L/min O_2 and 4.9 L/min CH_4.   Cathode Inlet Feed was 5.5 L/min O_2.

Transient Analysis



Response of internal SOFC thermocouples during peak power excursion and transient power stepping analysis.

First order response

$$T' = (I')^2 K_P (1 - e^{-t/\tau_p})$$

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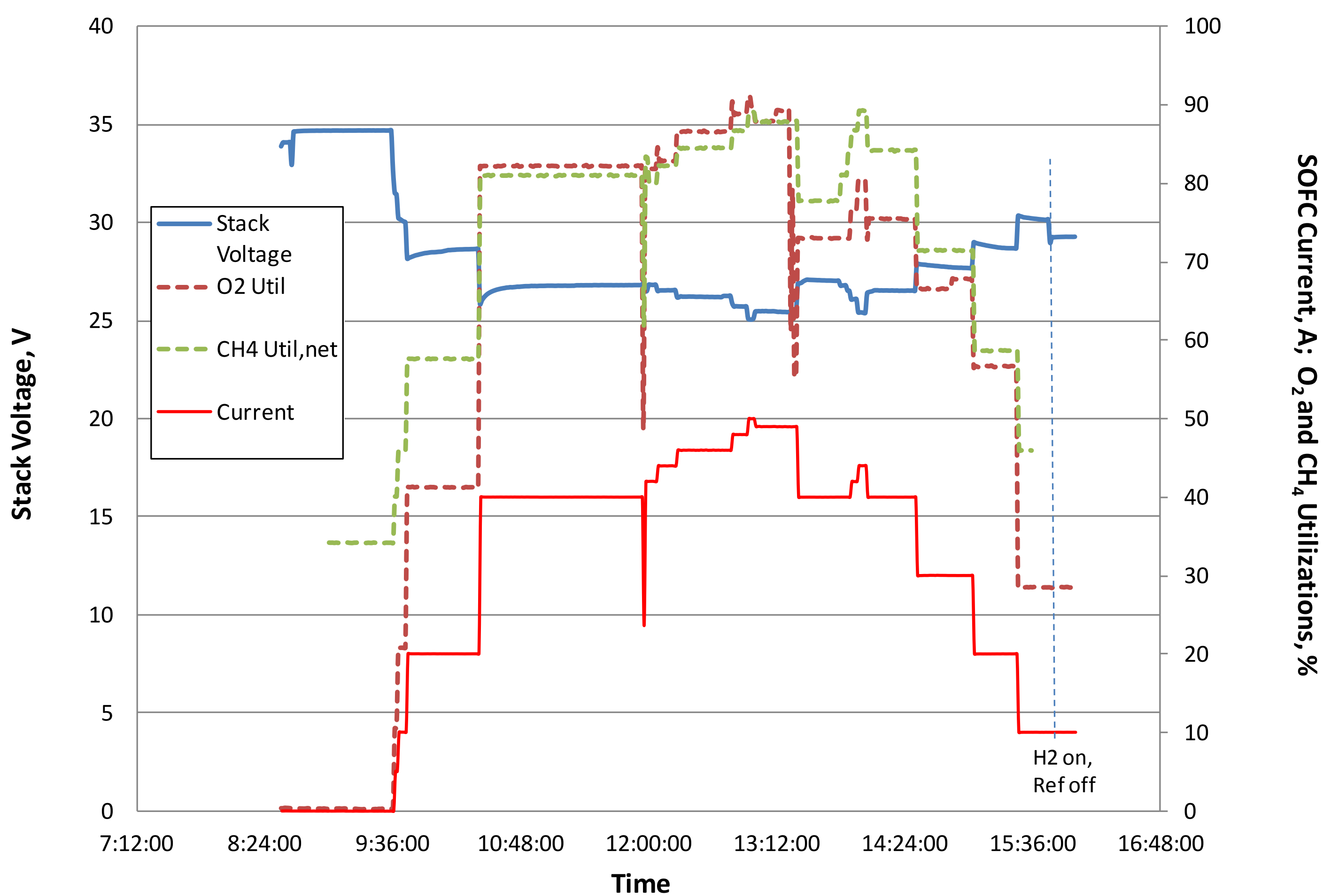
Stack Voltage, Current, & Utilizations over second day of testing



Summary of Performance

	Peak Performance	Notes
Steady State Feeds into CPOX Reactor	CH_4 Flow: 5.1 SLPM N_2 Flow: 0 SLPM O_2 Flow: 3.3 SLPM O/C = 1.30	Fuel flow slightly increased from steady state to meet original O/C target
SOFC Stack with cathode feed of 5.5 SLPM pure O_2	46 Amps 85% CH_4 Utilization 86% O_2 Utilization ~ 0.88 V/cell 1210 Watts ~ 43% $CH_{4,\ LHV}$	Stack was pushed to 50 amps to achieve ~90% fuel utilization & 45% efficiency, but cells 1,3,5, and 13 suffered from fuel starvation
SOFC Exhaust	2.4 SLPM H_2 (16%) 8.4 SLPM H_2O (50.5%) 4.1 SLPM CO_2 (27%) 1.0 SLPM CO (6.5%)	Mass balance > 95%

	Planned Targets	Actual Steady Performance	Comments
Start-up Combustor Flow	CH_4 Flow: 2.15 SLPM N_2 Flow: 20 SLPM O_2 Flow: 5 SLPM	CH_4 Flow: 2.15 SLPM N_2 Flow: 10 SLPM O_2 Flow: 5 SLPM	We had to lower N_2 gas to get combustor to ignite at these flows, which are lower than typical start-up flows
Steady State Reformate Product	8.13 SLPM H_2 (60.5%) 0.83 SLPM H_2O (6.2%) 0.52 SLPM CO_2 (3.8%) 3.96 SLPM CO(29.5%)	5.3 SLPM H_2 (44%) 1.8 SLPM H_2O (15%) 0.9 SLPM CO_2 (8%) 3.0 SLPM CO(25%) 1.0 SLPM CH_4 (8%)	With reformer outlet temperature ~600 C, equilibrium favors 5-10% methane

Future Plans

- Forward Plan at NASA-Johnson Space Center(JSC)
  - Continue breadboard CPOX reformer and stack testing at JSC to establish baseline performance on pure oxygen and methane reactants.
  - Investigate SOFC capabilities for potential integration into future spacecraft missions

Acknowledgements

- DOE/NETL for SOFC stack & Support
- NUWCDIVNPT for Preliminary Testing