PCI
Precision Combustion

Revolutionary Research . . . Relevant Results

Advanced Fuel Reformer Development

Putting the 'Fuel' in Fuel Cells

Subir Roychoudhury

Precision Combustion, Inc. (PCI), North Haven, CT

Shipboard Fuel Cell Workshop

March 29, 2011

Clean Power Solutions for the 21st Century®

Precision Combustion, Inc.

- Established in 1986
- Privately held, Small Business
- Located in North Haven, CT
- Two major platform technologies under development
  - *RCL® catalytic combustors for gas turbines applications*
  - *Microlith® catalytic reactors for multiple markets*
  - *65 patents*

38,000 sq ft total space

- Collaborators include: Large & small corporations, Universities, …..
- Develops advanced catalytic reactors & systems; manufactures limited-volume catalytic products

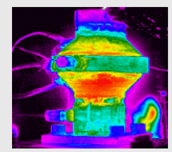
→ for fuel reformation for syngas/H_2 generation for fuel cell application

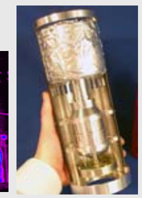
PCI Technology Overview

- RCL® Catalytic Combustion
  - Best New Technology Award 2006 – IGTI, ASME
  - Full scale GT engine testing underway at OEM's

- Microlith® Catalytic Reactors – Tibbetts & Army Innovation awards
  - Catalytic Burners & Converters

    Anode gas & Start burners, Stirling Engine Burners
    Catalytic after-treatment - automotives





  - Ultra-compact Fuel Processing

    Reactors & Turnkey Systems

    Stack-specific solutions

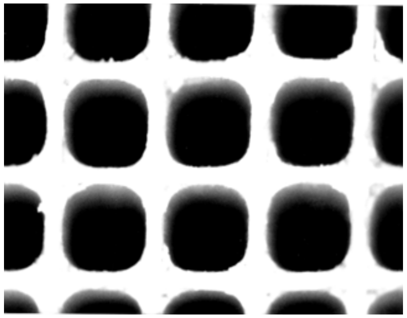
    Small & Large scale

  - Regenerable Sorption Reactors:

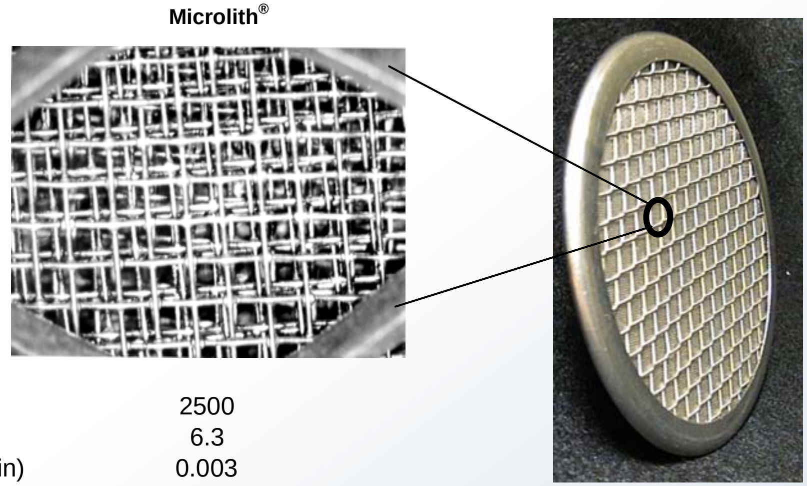
    Chem-bio filters
    Air revitalization for long-duration manned spaceflight

Microlith Technology

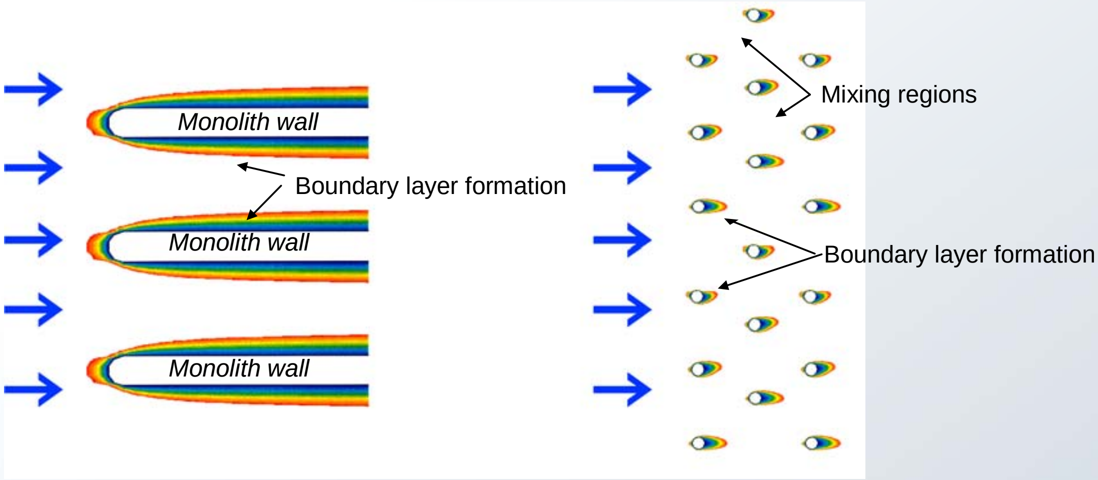
Conventional Monolith



Microlith®



Conventional Monolith		Microlith®
400	Cells/in^2	2500
2.64	GSA (m^2/l)	6.3
3.0 - 5.0	Channel Length (in)	0.003
70 - 120	Length to Diameter Ratio (L/d)	0.3
1050 - 1200	Operating Temperature (^oC)	1050 - 1200
70	Frontal Open Area	72

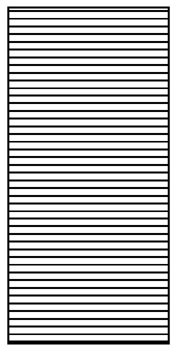


High surface area & high mass transfer capability at comparable ΔP

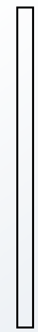
Comparison of Substrate Performance

(Steady State Operation w. propylene in air at 350 C, vel. 1.5 m/s.)

2.54 cm(1") long monolith



7 Microlith elements
(Length = 0.11cm, 0.042")

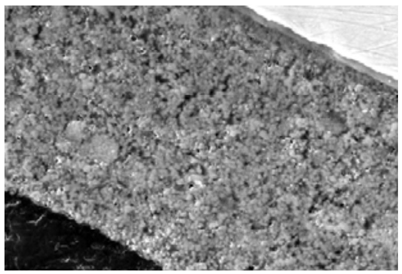


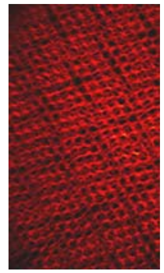
2.54 cm(1") long monolith		7 Microlith elements
5.3 cm/s	Mass Transfer Coeff (k_c)	77 cm/s
7620 cm^2	GSA	568 cm^2
75	Observed Conversion (%)	78

Equivalent conversion with 20-fold size reduction.

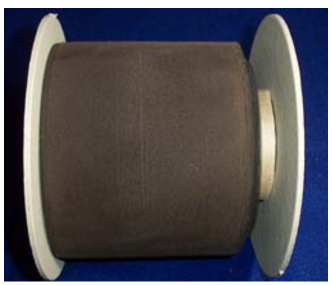
More Efficient Use of Catalyst Surface Area

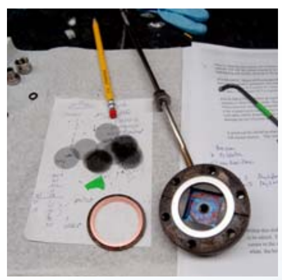
Microlith Technology





Small, durable, catalytically coated metal mesh with very high surface area





Continuous catalyst coating line with batched furnace and rigorous QA, QC in place

Microlith® Catalytic Reactors

Ultra compact

Short contact time

Rapid thermal response

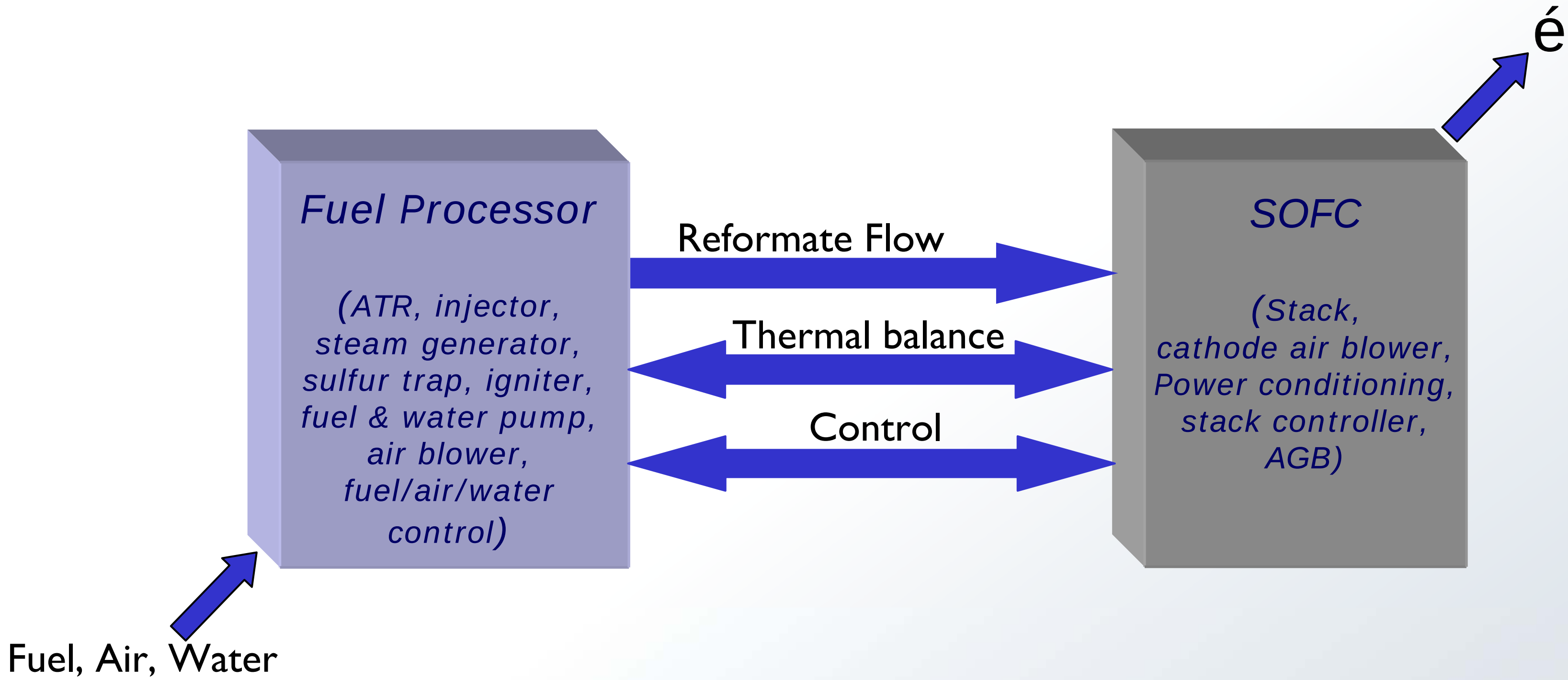
High heat & mass transfer

High surface area/unit volume

Low cost

PCI holds multiple patents on catalyst structure, reaction methods and apparatus

Stack Fueling

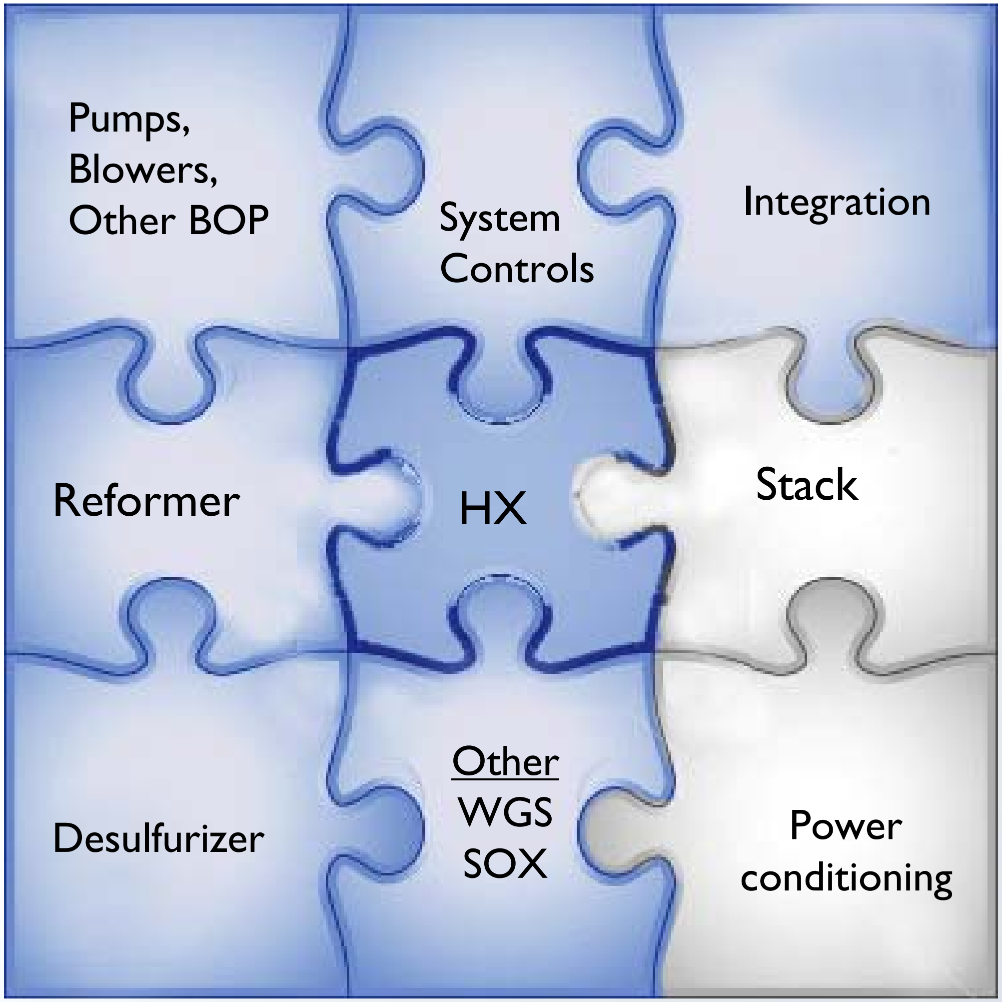


- Startup, stack heatup
- Load following
- Auxiliary startup power needs

Reformer Controls

- Automated start, shutdown, load changes
- Real-time air/fuel/water flow control; continuous monitoring during steady state
- Closed-loop feedback control w. safety interlocks
- Fuel flexibility: capability of sensing & operating on different fuels
- Control algorithm interface with stack controller & power conditioner

Fuel Cell Subsystems



PCI supporting ONR in these areas

Challenges in Developing Fuel Cell Based Power Systems

- High overall efficiency, power density, and specific power to be practical & viable
- Water neutral operation to avoid/minimize water storage
- Fuel Cell-quality reformate (sulfur, HC and CO cleanup)
- Reduced system complexity
- Optimized BOP components to reduce parasitics
- Robust & intelligent control system
- Fuel flexibility
- Performance durability
- Reactor & system modularity
- Thermal integration to maximize overall system efficiency
- Simplified packaging & manufacturing to reduce cost

Development at PCI

Reforming Processes:
Auto-thermal reforming
Catalytic Partial Oxidation
Steam Reforming
Scales: 1 kWe – 5 MWe

Fuel Processing Reactors:
WGSR, PROX, Sulfur Cleanup
Burners (startup, AGB, purge)
Scales: 1 – 250 kWe

Fuels:
Liquids: Diesel, JP-8, Jet-A, E-85
FT fuels, Biofuels, Gasoline
Gases: Natural Gas, Propane

BOP:
Pumps, Blowers, Nozzles
Igniters, HX, Steam generation,
F/A/S mixing, Controls
System Integration

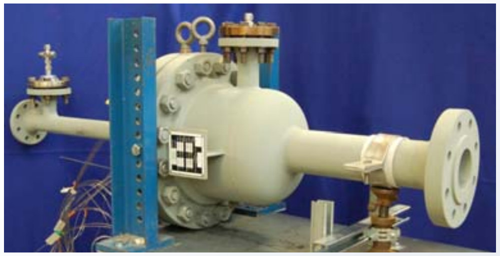
Enabling '*Fuels*' for 'Fuel Cells'?

Reforming Technologies at PCI

1. Catalytic Partial Oxidation (CPOX)

$2\ CH_4 + O_2 \rightarrow 4\ H_2 + 2CO\ \{H_2O + CO_2 - \Delta H\}$

5 kWth Diesel CPOX



5 MWth CPOX

2. Catalytic Autothermal Reforming (ATR)

$3\ CH_4 + O_2 + H_2O \rightarrow 7\ H_2 + 3\ CO\ \{H_2O + CO_2 - \Delta H\}$

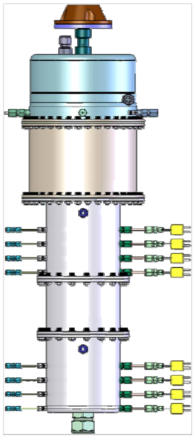
5 kWth & 1 MWth Diesel/JP-8 ATR, St. gen. S-trap, Injector

3. Catalytic Steam Reforming (CSR)

$CH_4 + H_2O \rightarrow 3\ H_2 + CO\ \{H_2O + CO_2 + \Delta H\}$

3 kWth Diesel SR w. endo & exothermic sections

Fuel Purification Technologies at PCI



- Water Gas Shift Reactor (WGSR)

  $CO + H_2O \rightarrow H_2 + CO_2$ $\{CH_4$ - $\Delta H\}$

- Preferential Oxidation of CO (PROX)

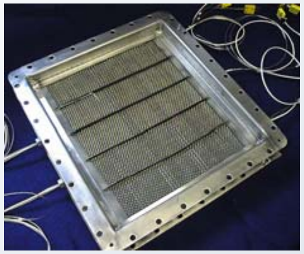
  $CO + \frac{1}{2} O_2 \{H_2\} \rightarrow CO_2 \{H_2O$ - $\Delta H\}$

- Sulfur Cleanup

  Liquid and gas phase approaches

- Pressure Swing Adsorption (PSA)

  H_2 selective sorbents

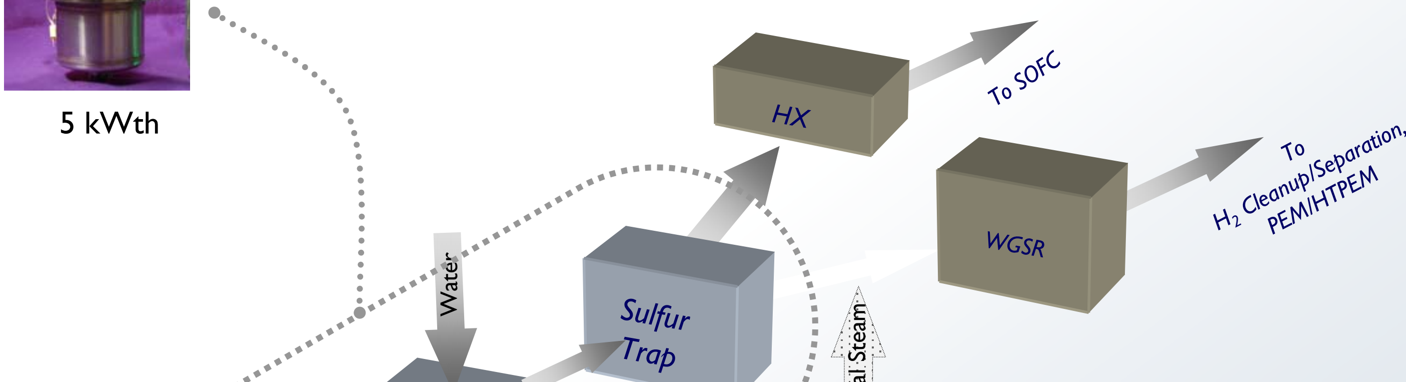


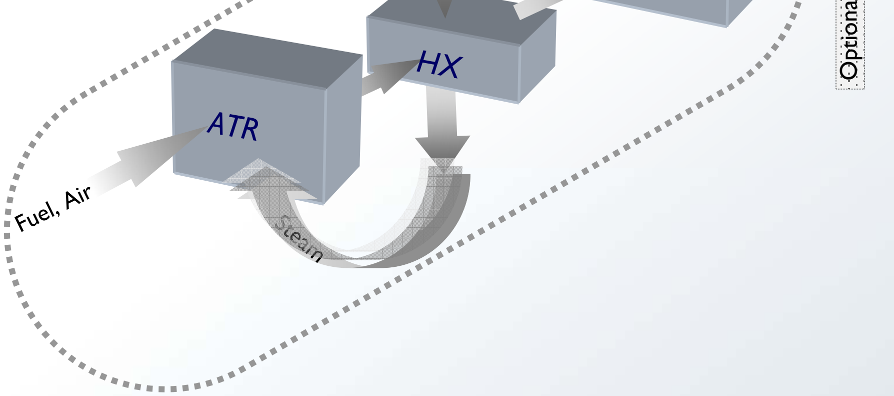
ATR + WGSR Development

ATR w. fuel/air/steam injector, igniter, steam generating HEX, sulfur trap

~1 MWth

5 kWth





25 kWth

~1 MWth

….+ WGSR

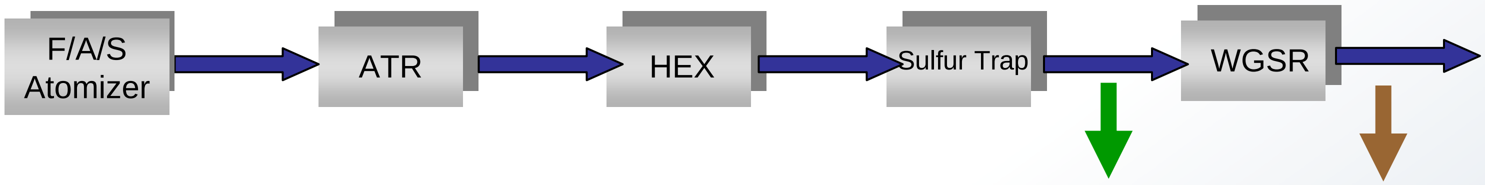
Integrated ATR

Considerations during reformer development:

- Reactor design: space velocity, linear velocity, flow dynamics
- Catalyst formulation: synthesis, application, physical properties
- Operating parameters: Steam-to-carbon, O/C, catalyst bed temp
- Reactant introduction: fuel/air/steam mixing
- Thermal integration: steam generation, sulfur/CO clean-up

ATR Reformate Compositions

(mole %, wet basis)

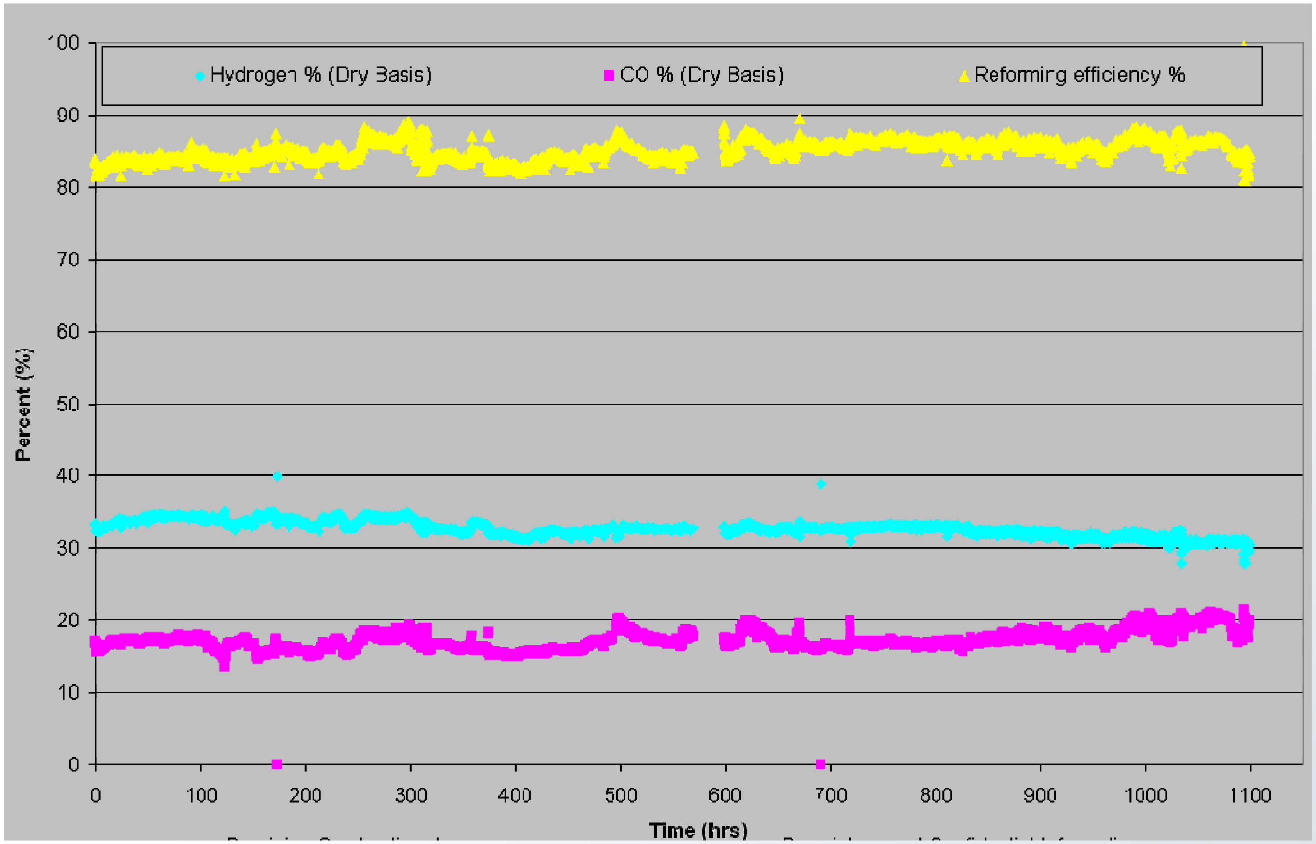


Fuel	S/C	O/C	H_2O	H_2	N_2	CO	CO_2	CH_4	C2 + C3	S
JP-8 (Equil)	0.90	0.95	12.1	29.5	37.5	15.3	5.7	0.01	-	
JP-8 (Exptl)	0.90	0.95	12.7	28	37.7	16.3	5.4	0.16	<50 ppm	<1 ppm
After WGSR			10-15	30-35	39	1.6-4*	12-14	0.3		

[*: Fn of St/C]

- Reforming efficiency (LHV reformate/LHV feed) = ~85%
- Sulfur removal to <1 ppm
- Current PCI's target for coke precursors (i.e., C2s and C3s) is <50 ppm_v total

Reformer + Stack Interface Testing

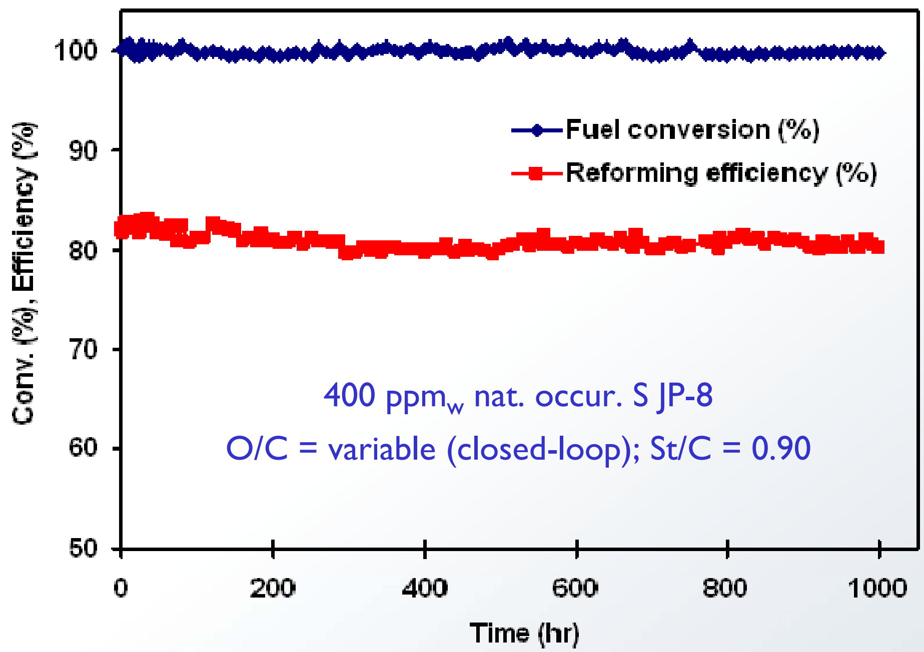


JP-8 w. low S (Average ~15 ppm_w S); Higher HC's < 20 ppm.

Operated with 1 kW_e SOFC stack – Stable Operation w/o coking for 1100 hours

Operation w. Sulfur Containing Fuels

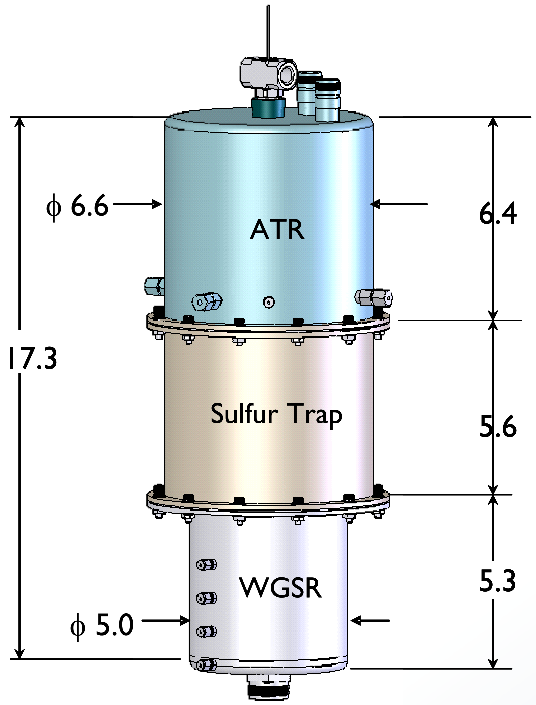
ATR performance and durability testing w. 400 ppm_w sulfur JP-8



- Sulfur speciation: ASTM D5623; Total sulfur analysis: ASTM D2622 (Wavelength Dispersive X-Ray Fluorescence)

- Complete fuel conversion, stable LHV-based efficiency & H_2+CO mole % over time.
- Total organics (primarily C2s, C3s) <150 ppm_v (wet basis) at end of test.
- Fuel-bound sulfur converted to H_2S and removed (<1 ppmv) downstream of reforming reactor

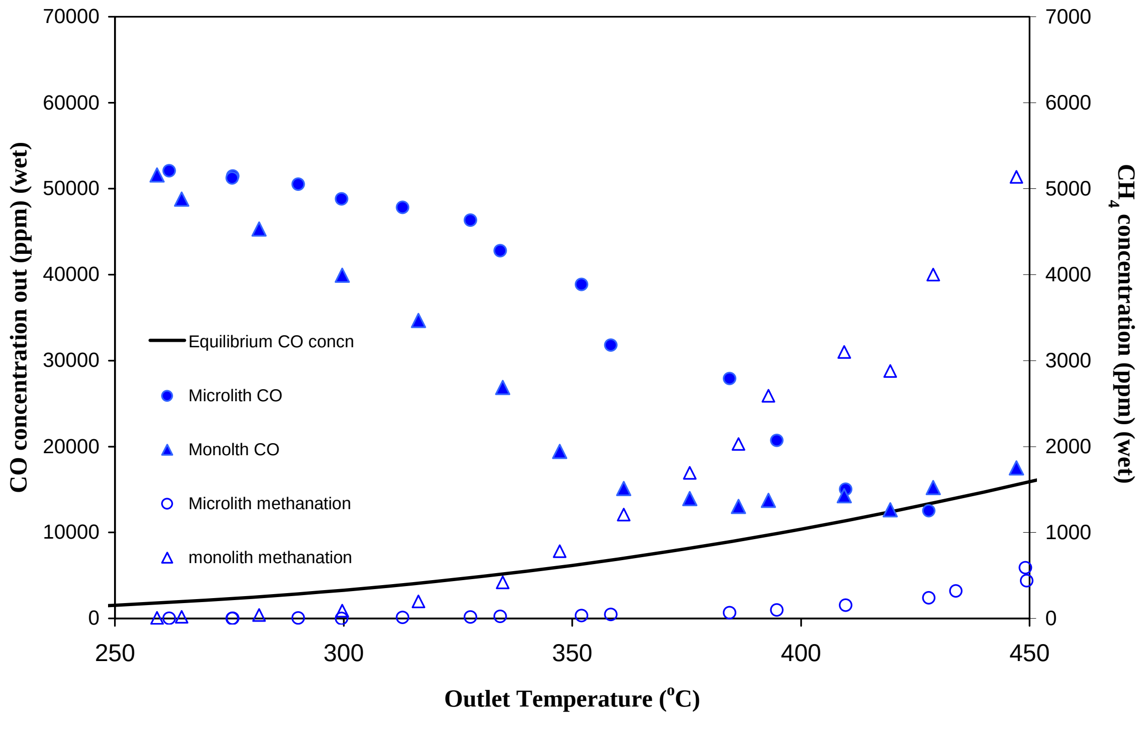
Integrated ATR + WGSR



25 kW_{th} ATR w. fuel/air/steam injector, igniter, steam generating HX, sulfur trap, single stage WGSR

Convert fuels into low CO (<2-3 vol.%), sulfur free (<1 ppm_v) reformate: HT-PEM stack ready

WGSR Performance



Order of magnitude reduction in methanation side reaction

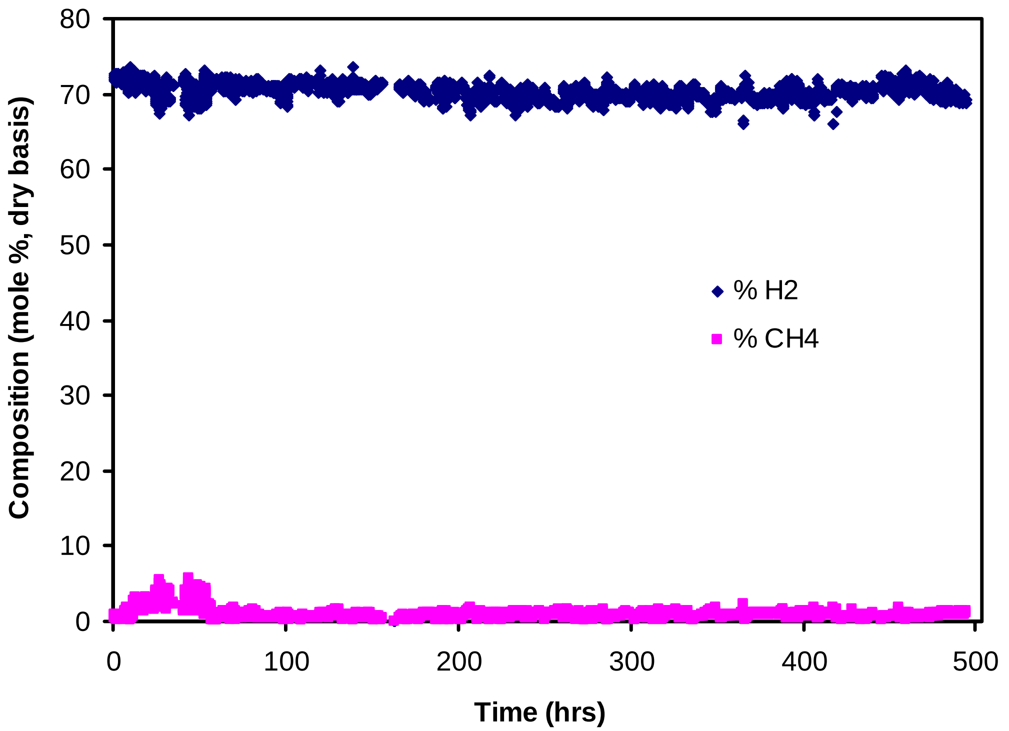
Compact, Heat-Integrated 3 kW_{th} CSR

	Exptl Product Mol %, St/C=3.0, P = 1 atm	Equilibrium Mol. %, St/C=3.0, 1 atm, 650°C
H_2	69-71	70.8
CO	10.7-14.0	11.8
CO_2	14.0-19.3	15.6
CH_4	0.8-4.0	1.9
LHV-based efficiency (w. CH_4)	~119% (synfuel)	115%

- CSR prototype consists of catalytic exothermic (burner) & catalytic endothermic (CSR).
- Catalytic burner instead of flame-stabilized burner increases thermal uniformity, distribution, durability & control.
- Operation at S/C of 3.0 & 4.0 (without coke formation); Fuels : n-C12, IPK (similar to S-8), natural gas, propane
- Operation very sensitive to fuel-sulfur

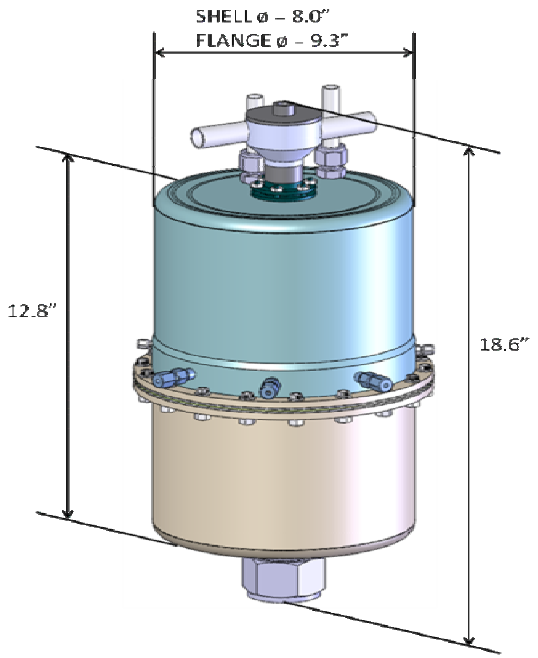
500-hr Durability of Heat-Integrated CSR

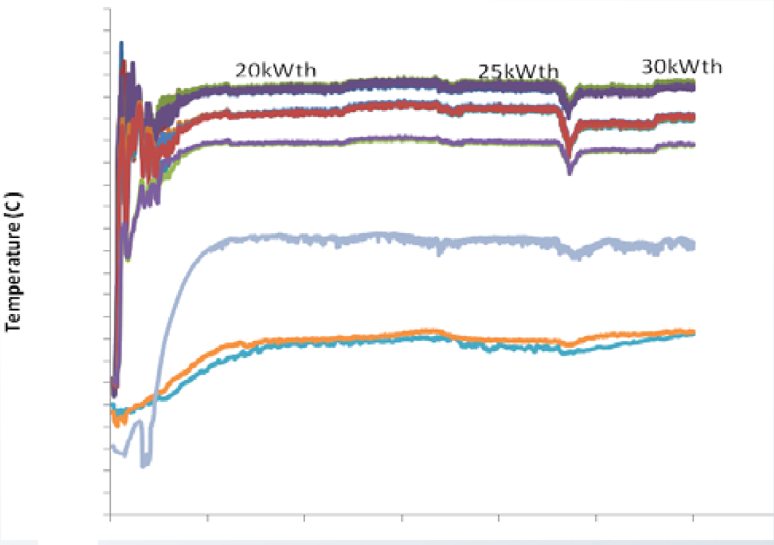
Product composition vs. time
(500-hr test w. 3-5 ppm sulfur in fuel)



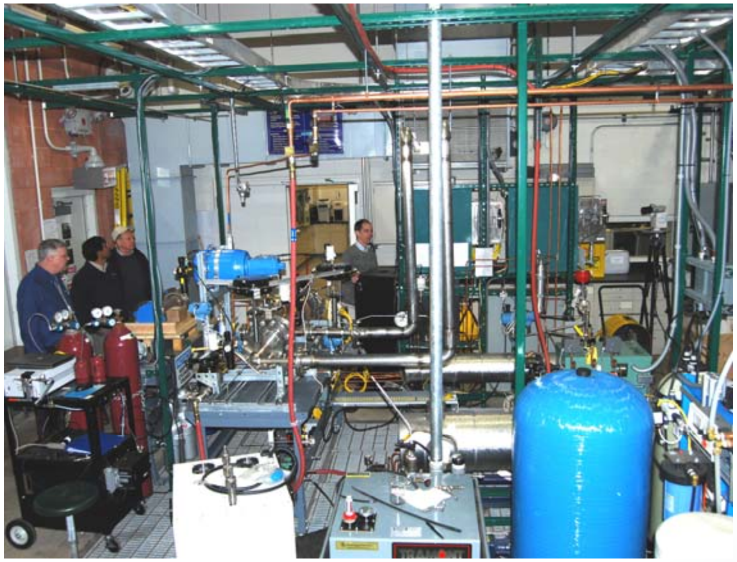
Equilibrium vs. experimental	H_2	CO	CO_2	CH_4
Equil. mole %	72	10	16	0.27
PCI prototype at ~1 kWth, mole %	72	10	17	0.58

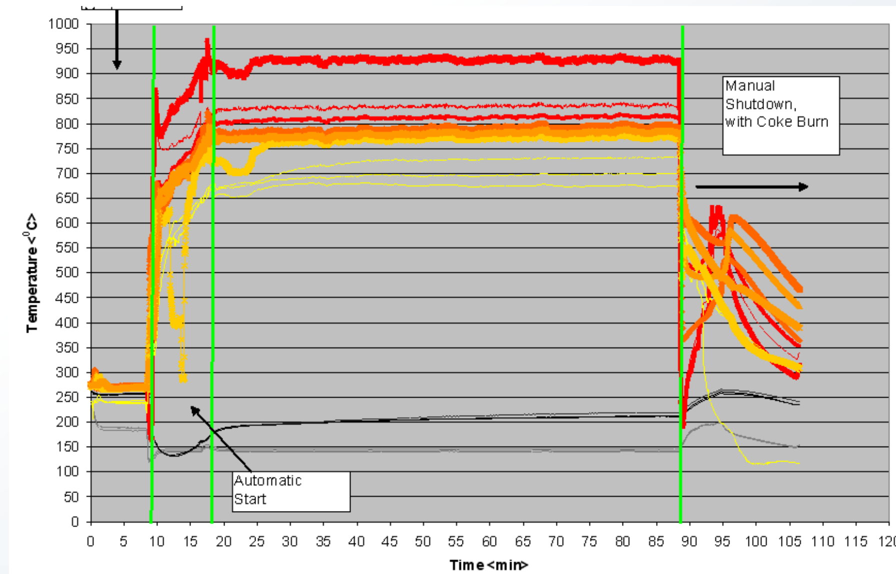
Scale-up: 40 kWth ATR Prototype





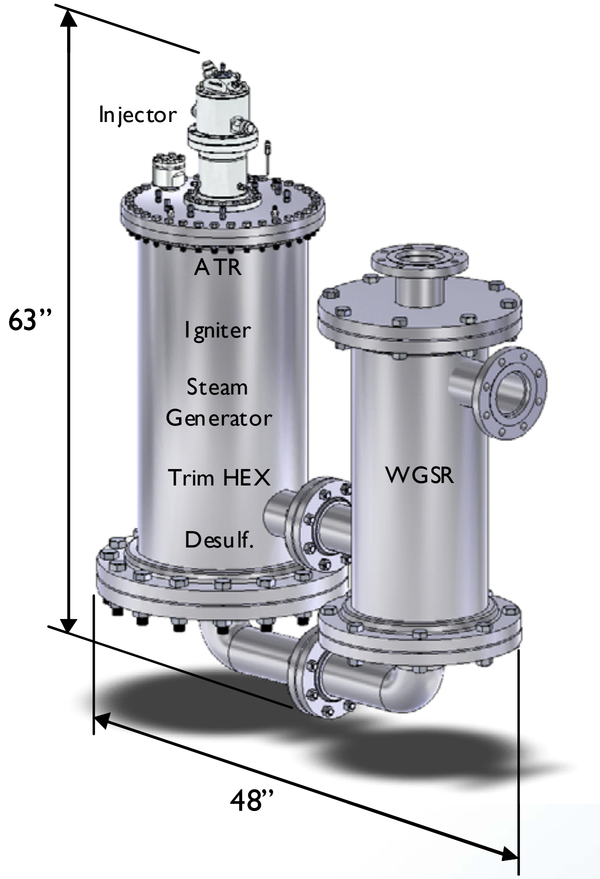
Scale-up (200 kWth Turnkey at Philly)





- Component performance demonstrated (c.2008)

Scale-up: 1 MW_{th} ATR System



Modular, 250 kW_e Fuel Processing System consisting of fuel/air/steam injector, ATR, steam generator hex, and sulfur clean-up

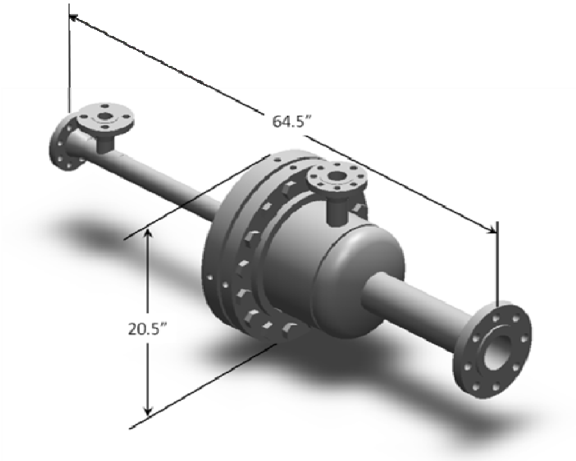
Scale-up: 1 MWth Industrial ATR

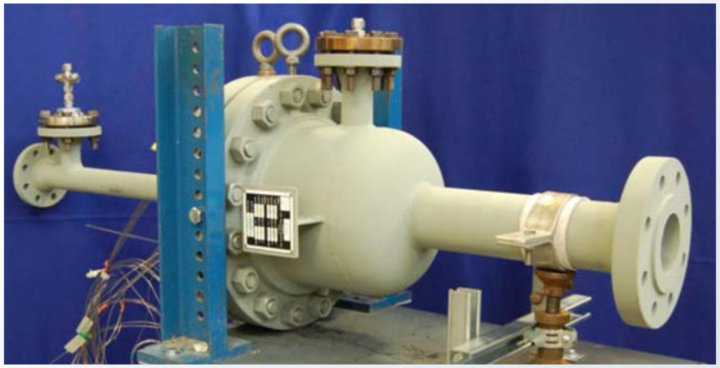
1 MWth Microlith® ATR to reform VOC from process waste streams

- Operation for over 6 months in industrial environment

5 MW(th) Natural Gas Reformer

- Reform pipeline natural gas; 5 MW(th); → H_2 + CO
  - Prototype tested & delivered.





- Initial testing successfully completed
- 1000 hrs of sub-scale durability completed (Target 8000).

Benefits of Biofuels

- Bio-fuels: Bio-alcohols, Bio-diesels, Tuned distillates
- Minimized System Complexity
  - Avoids bulky sulfur cleanup
  - Avoids sorbent recharge and disposal needs
  - Reduction of auxiliary components
- Greater Operational flexibility
  - Wider O/C, S/C
  - Minimized system design constraints
- Higher Reforming Efficiency → Greater System Efficiency
  - Enhanced reaction kinetics
  - Improved fuel properties
- Longer Life
  - Catalyst, Stack performance
  - Minimized coking
- Readily scalable to shipboard scales
  - Compact, 250 kWe and higher, modular systems feasible

Summary

- Reformer requirements for stack fueling:
  - System size and weight: Process intensification
  - Reforming efficiency
  - Fuel flexibility
  - Durability: multiple 1000+ hrs of operations
  - Reformate cleanup (sulfur and CO)
  - Water neutrality
  - Thermal and flow integration with stack
  - Full BOP implementation
  - Control hardware, protocol/algorithms
  - Stack-quality reformate production & long term testing
  - Cost and scale-up

Acknowledgment

We are grateful to the ONR & DOE for their support,

And

The engineers and technicians at PCI.