PCI
Precision Combustion

Diesel Fuel Processing: Water Neutrality, Sulfur Cleanup, Coke Minimization

DOE Phase II SBIR (COTR: Joe Stoffa)

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

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Clean Power Solutions for the 21st Century®

Precision Combustion, Inc.

- **Established in 1986, 30 employees; Located in North Haven, CT**
- **Develops advanced catalytic reactors & systems; manufactures limited-volume catalytic products**
- **Two major platform technologies**
  - ***RCL® catalytic combustors for gas turbines and downhole applications***
  - ***Microlith® catalytic reactors for multiple markets***

PCI Technology Overview

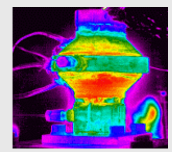
- RCL® Catalytic Combustion
  - Best New Technology Award 2006 – IGTI, ASME
  - Full scale GT engine testing underway at OEM's

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

    JP-8/Diesel/H_2/anode gas burners

    Stirling Engine Burners (as low as 50 We)

    Catalytic after-treatment - automotives



- Ultra-compact Fuel Processing

  ATR, Waterless CPOX & CSR for liquid and gaseous fuels

  (e.g. JP-8, diesel, methane, propane, biofuels)

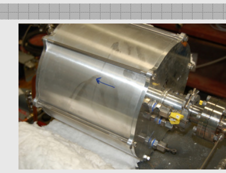
  Reformers for SOFC, PEM & MCFC applications

  1 - 250 kWe Fuel processing Systems

- Regenerable Sorption Reactors:

  Chem-bio filters

  Air revitalization for long-duration manned spaceflight



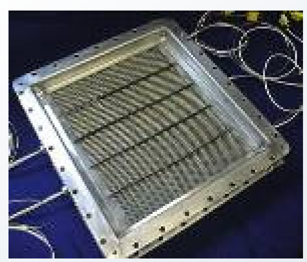
Reforming Areas Under Development At PCI

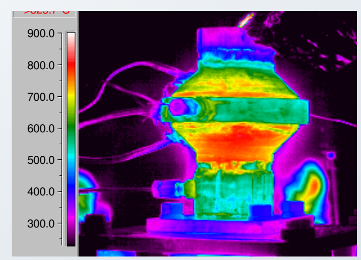
Reforming Processes:
Auto-thermal reforming
Catalytic Partial Oxidation
Steam Reforming

Reforming reactors:
WGSR, PROX
Burners (startup, AGB, purge)
Scales: 50 We – 250 kWe

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

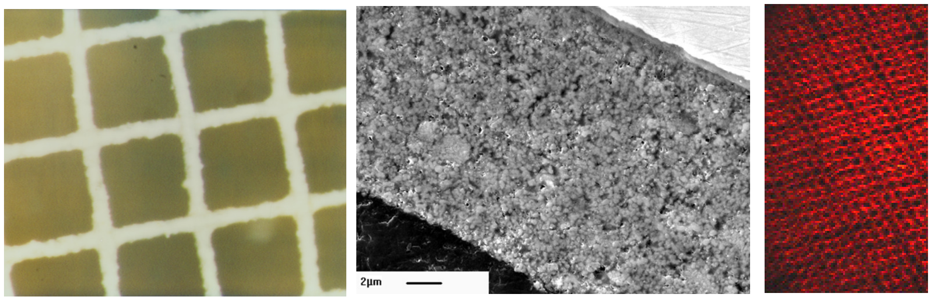
BOP:
Pumps, Blowers, Nozzles
Igniters, HX, Steam generation,
F/A/S mixing, Controls
Sulfur Cleanup, System Integration





"Put The Fuel in Fuel Cells"

Microlith® Technology



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

Microlith® Catalytic Reactors

- Ultra compact
- Short contact time
- Rapid thermal response
- High heat & mass transfer
- High surface area/unit volume
- Low catalyst usage & small size ⇒ Low cost

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

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

Significant Results

- Microlith Auto Thermal Reformer (ATR)
  - System layout
  - Water neutrality
    - Condensation
    - Anode Gas Recycle
  - Catalyst sulfur tolerance and sulfur cleanup
  - Coke minimization for operation w. SOFC stacks
- Microlith Waterless Diesel reformer (CPOX)
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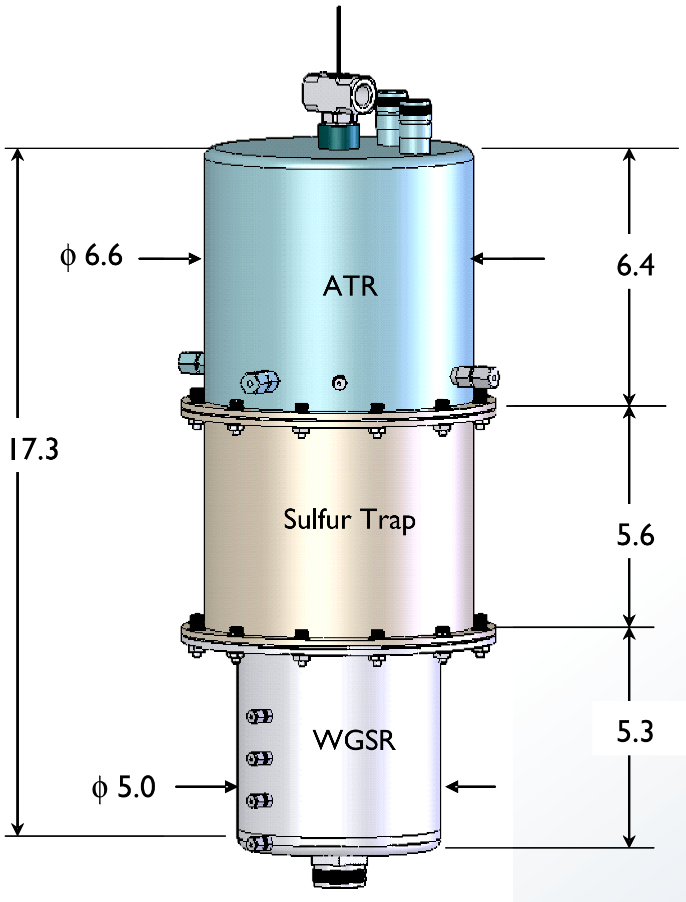
  - Long term operation w. sulfur containing distillate fuels
- Larger scale reformers w. gaseous/liquid fuels

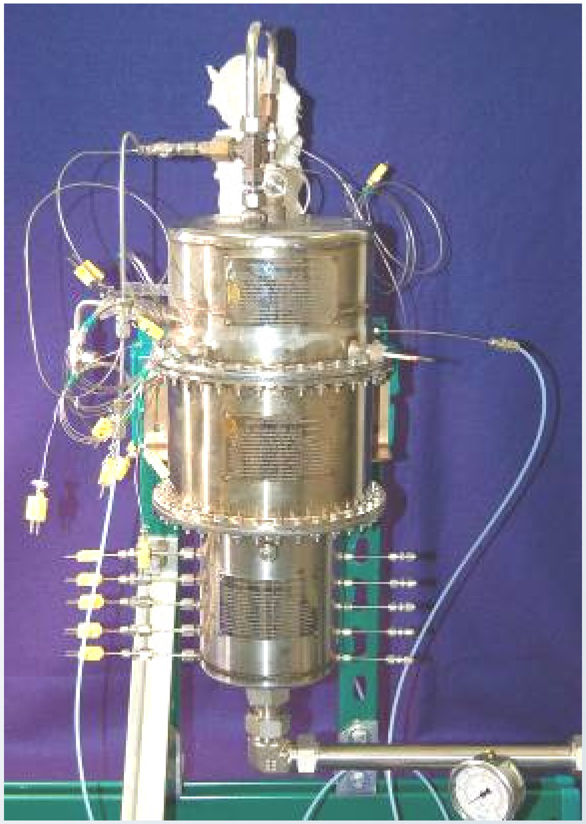
Integrated Fuel Processor

5 – 10 kW_{th} reformer integrated w. fuel/air/steam injector, igniter, steam generating HX, sulfur trap.

Cabinet w. balance of plant components (fuel, water tanks, pumps, contols, power supply, etc.)

Standalone Fuel Processor (HT-PEM/PEM)





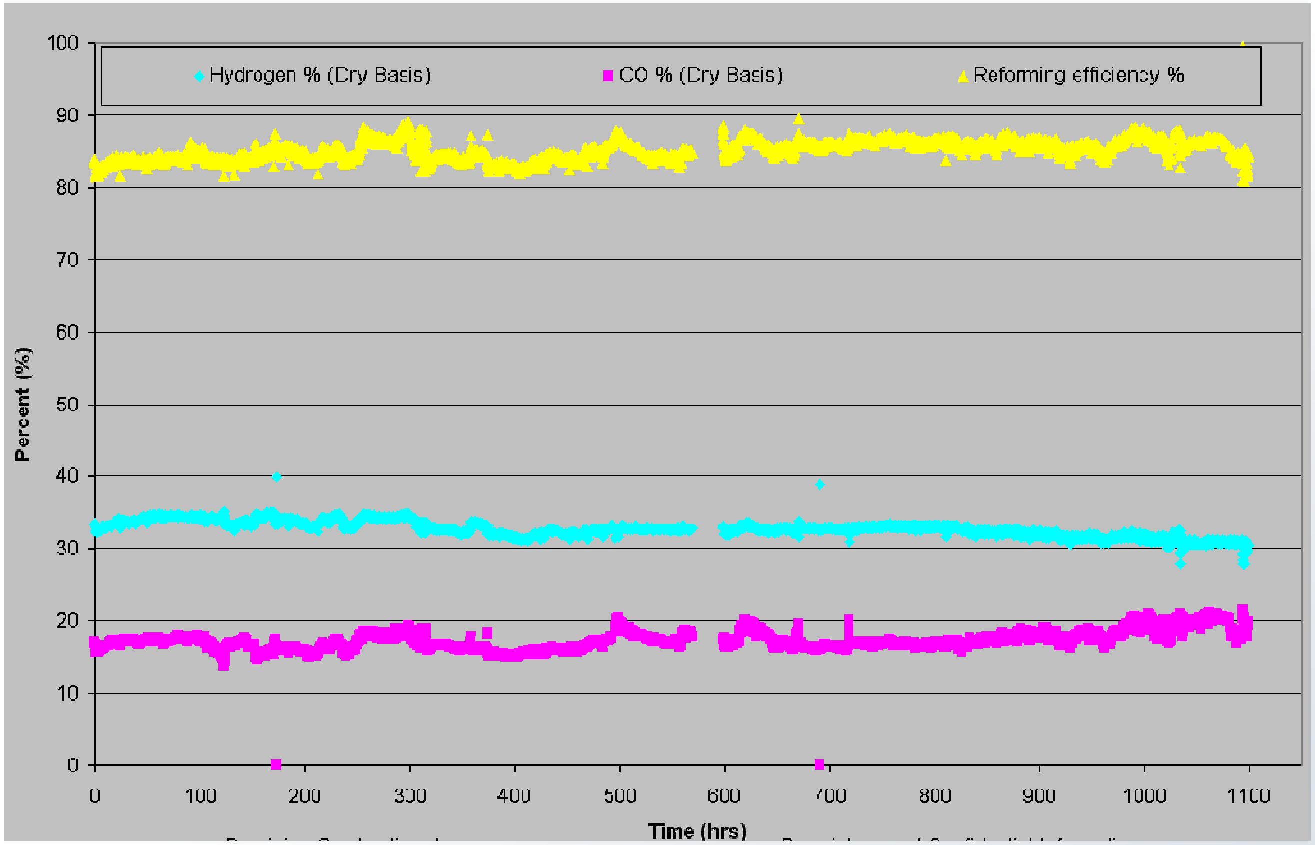
25 kW_{th} ATR w. fuel/air/steam injector, igniter, steam generating HX, sulfur trap, WGSR

Standalone Fuel Processor Metrics

- Reforming efficiency: ~85% (ratio of LHV)
- Size: 3 liters; Weight: 5 kg (for 5 kW_{th})
- Operate at low S:C ratios (AGR/water)
- Start up in CPOX (1 min), transition to ATR (7 min)
- Modular, readily-serviceable components
- Stand-alone pumps & blowers implemented
- 12 V battery for startup & controls
- Readily integrated w. SOFC, PEM, H_2 generation systems
- Durability: 1000 hrs w/o failure w. JP-8 (~400 ppm_w sulfur)

Convert JP-8*/Diesel+ into sulfur free (<1 ppm_v) reformate

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

Test Summary

- Automated start, shutdown, load changes
- Closed loop feedback control w. safety interlocks
- DC Gross efficiency of 34% achieved
- Maximum power of 1.5 kWe obtained
- On post inspection, no carbon detected

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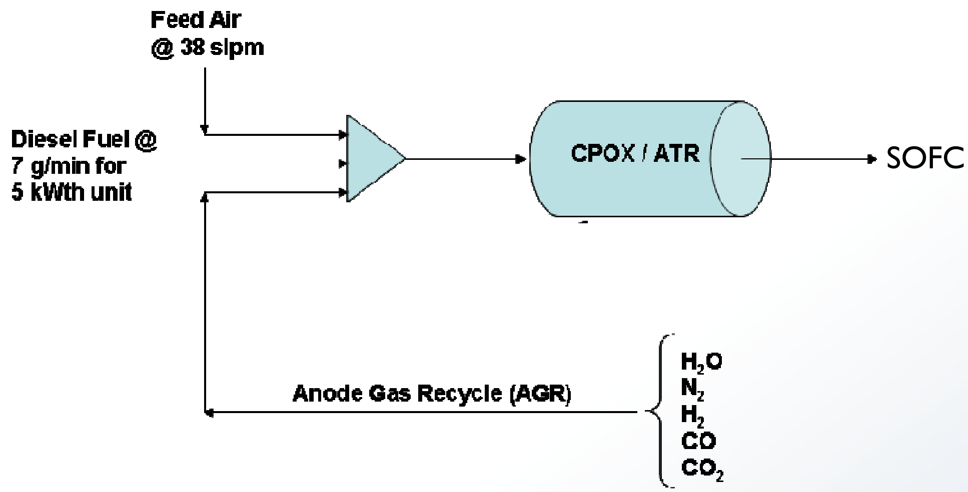
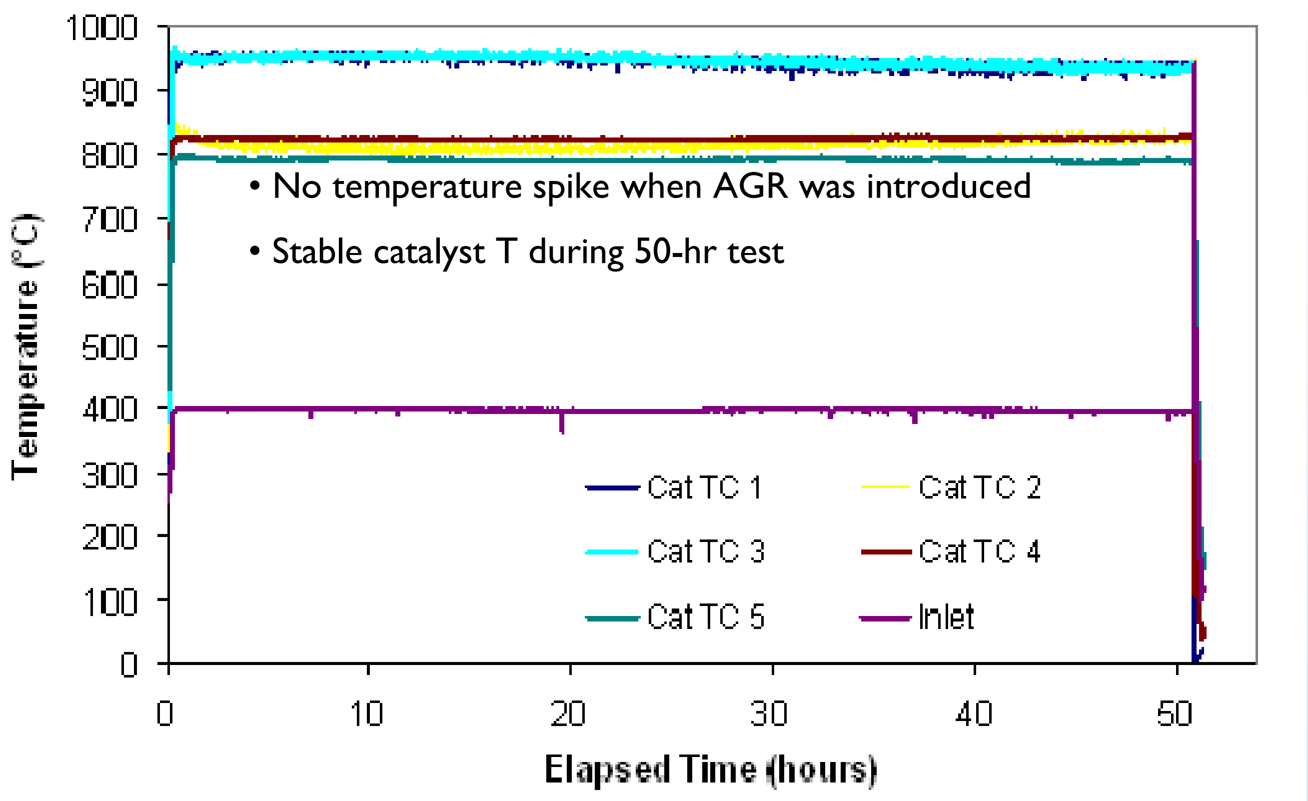
Water Recovery: Direct Anode Recycle (AGR)



- Used surrogate gas mixture to simulate AGR composition and flow rate
  - Assumptions: 60% SOFC Fuel Utilization; 50% AGR split to achieve target O/C and S/C
- Reactor startup under CPOX (waterless); then transitioned to ATR (w. AGR)
- Stable reactor operation w. no temperature excursions
- Successfully demonstrated 50-hr durability of ATR using AGR for water neutral operation
- Test results in good agreement w. thermodynamic equilibrium analysis; no HCs slippage

AGR Approach – T Profile (50-hr Durability Test)



AGR Approach 50-hr Durability Test: Product Composition

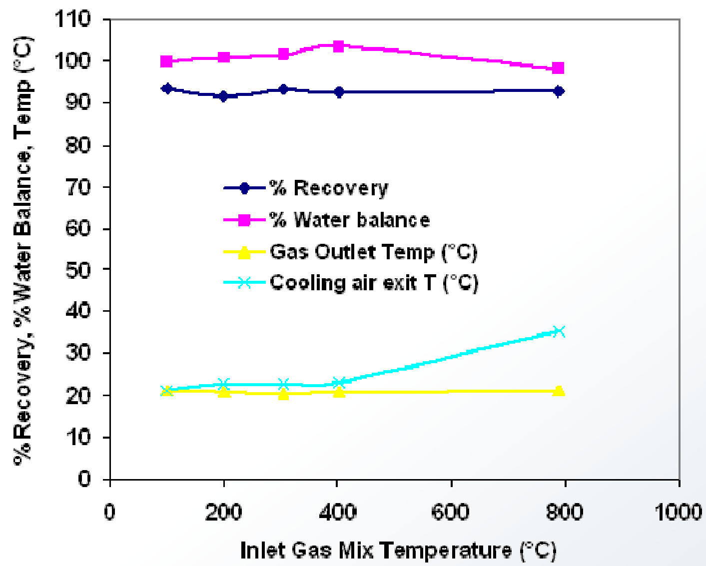
Species	Conc. (mole %, dry basis)	
	50-hr test (average)	**ASPEN model**
H_2	12.4	12.4
CO	14.8	15.3
CO_2	12.6	10.9
N_2	60.2	61.4
CH_4	0.02	0

Water Recovery: Condensation Approach

Required % H_2O recovery is a function of:

- % hydrogen in the hydrocarbon feed
- Reformer product H_2 and H_2O
- Fuel Utilization in the Fuel Cell
- Location of anode gas burner in the system
- Bypass ratio & Recycle ratio
- Ambient conditions

Results from Increasing Condenser Inlet T



- Condenser inlet T was increased from 100 to ~800°C.
- 21°C cooling air, 32.7 mol% H_2O, 5 kWth system.
- ~93% water recovery achieved at 800°C.

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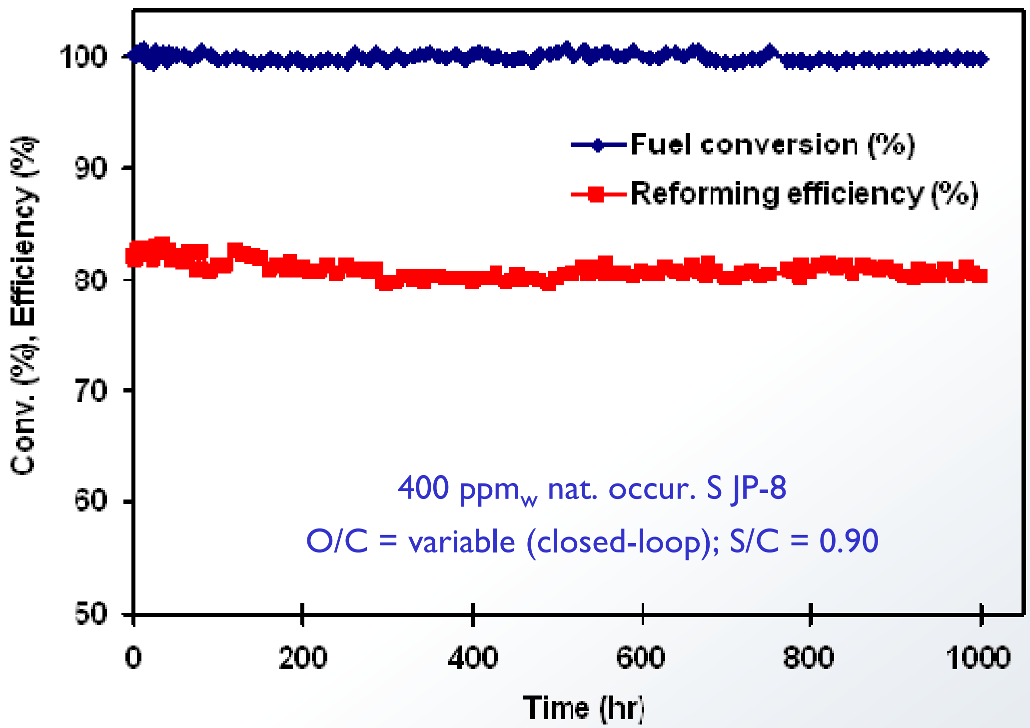
Effect of 400 ppm_w "Real S" for 1000 hrs



- Stable/complete fuel conversion, Reforming efficiency, H_2+CO mole % over time
- Total organics (primarily C2, C3) <100ppm at end of test.
- Fuel-bound S converted to H_2S and removed (<1 ppm) downstream of reforming reactor
- NETL Rh-pyrochlore formulation adapted to Microlith. Significant cost reduction potential identified.

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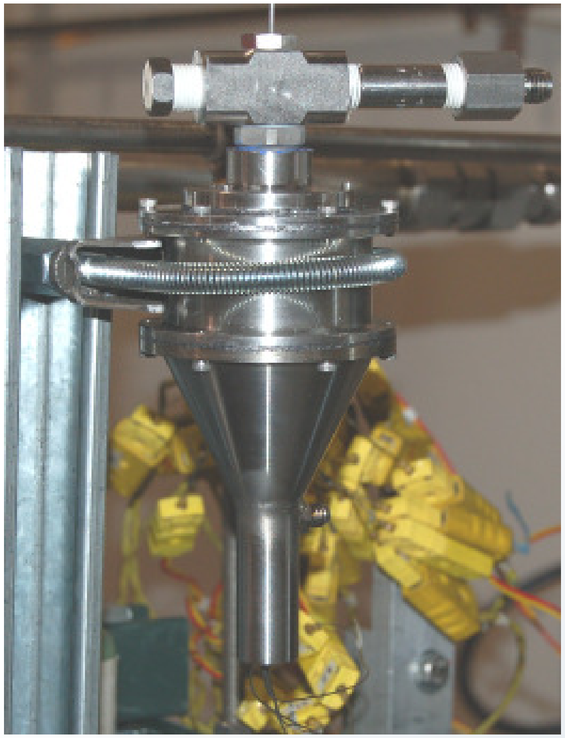
Diesel CPOX Reactor embodiment



~30 cc reactor + fuel/air injector + igniter

Reformate Composition

H_2	O_2	N_2	CH_4	CO	CO_2	C_2H_4	C_2H_6	Propylene	Propane
22	0.0	54	0.4	21	2	0.3	0.0	0.1	0.0

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CSR Reactor 500-hr Durability Test Summary

- 500-hr durability testing successfully completed (one catalyst w/o regeneration/replacement)
- Operated both CSR & burner w. 2 ppm_w S synfuel for 450 hrs (50 hrs w. n-C12)
- Stable CSR reformate w. ~70 mol% H_2 (dry basis)
- Product composition in good agreement with thermodynamic prediction

CSR exptl data at 1.5 kW_{th} and 1 atm vs. thermodynamic equilibrium

	Exptl Product Mol %, S/C=3.0, P = 1 atm	**Equilibrium Mol. %, S/C=3.0, P = 1 atm**
H_2	**69-71**	**68.5**
CO	**10.7-14.0**	**9**
CO_2	**14.0-19.3**	**17.6**
CH_4	**0.8-4.0**	**4.9**

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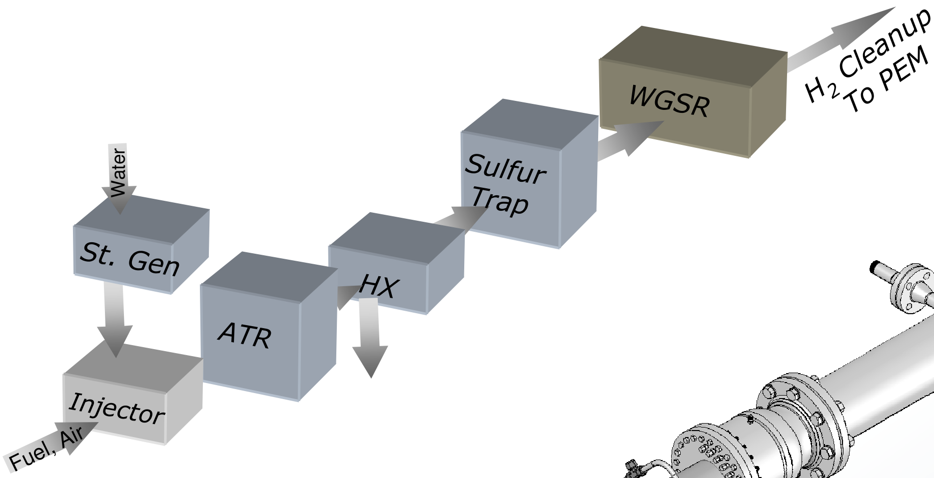
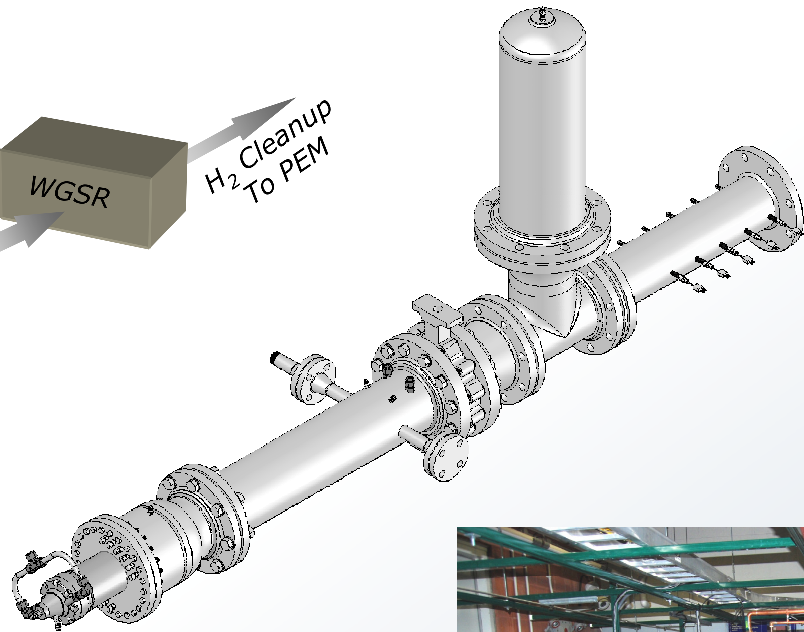
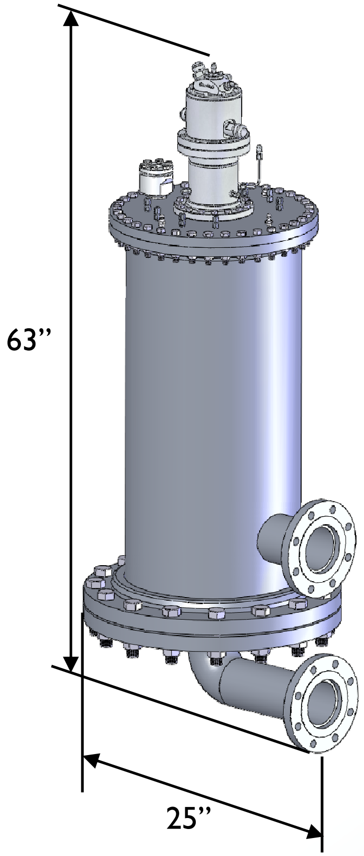
200 kW$_{th}$ Fuel Processor
(ATR + Sulfur Trap + WGSR – ONR)

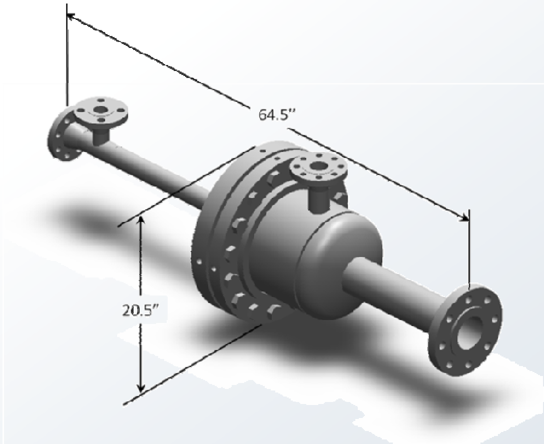




- Simple layout
- Compact footprint
- ATR Size: 3 liters
- Operating pressure: 7 atm
- Reforming efficiency: 70% - 80%
- 1 mkWe scale-up ongoing

Scale-up: 250 kW$_e$ to 5 MWth Fuel Processors





- 250 kW$_e$ Fuel Processing System Design & Hardware consisting of fuel/air/steam injector, ATR, steam generator hex, and downstream sulfur clean-up
- 5 MWth natural gas CPOX hardware

Summary

- Auto Thermal Reforming – *Diesel*:
  - Stable, long-term operation w. SOFC stacks
  - Compact package, w. high reforming efficiency (~85%) with JP-8
  - Water neutral operation verified via AGR and Condensation
  - Stable, long-term operation w. 400 ppm_w fuel sulfur
  - Higher HC's<100 ppm
- Steam reforming:
  - Catalytic ox. & endothermic design w. high heat flux – compact reactor
  - Stable, long-term operation w. distillate fuels (S-8)
  - Sulfur tolerance up to 25 ppm_w (no degradation over 50 hrs.)
- Catalytic Partial Oxidation (waterless) – *diesel*:
  - Stable, long-term operation in a compact package.
- Scale-up:
  - 200 kW_{th} to 5 MW_{th} demonstrated w. liquid & gaseous fuels

Acknowledgment

We are grateful to the DOE for their support,

And

The engineers and technicians at PCI.