Sulfur Tolerant Liquid Fuel Reformer

S. Elangovan, Joseph Hartvigsen, Piotr Czernichowski (Ceramatec)
Albin Czernichowski (ECP, France)

ceramatec
2425 South 900 West
Salt Lake City, UT 84119-1517

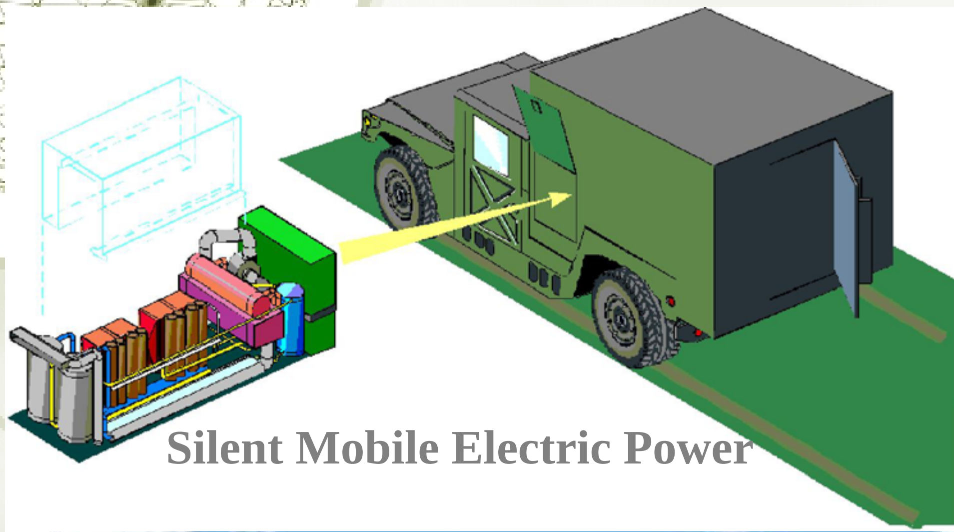
SECA Core Technology Program Workshop
Session: Balance of Plant

Lakewood, CO
October 27, 2005

Liquid Fuel Advantage

- Energy Density
  - JP-8 43 MJ/kg, 0.76 to 0.84 kg/liter
  - Diesel 42 MJ/kg, 0.86 kg/liter
  - Hydrogen at 680 bar (10,000 psi, 23100' head) Z=1.43
    - 4.35 MJ/liter (min. work of compression is 10-12% of LHV)
- Storability
  - Non-pressurized (tank cost & energy release issues)
  - No boil-off, e.g. LNG or LH2
- Availability
  - Highly developed infrastructure
  - Onboard as road engine fuel

Military, Commercial and Consumer APU Markets



Silent Mobile Electric Power

Class A Motor home
Silent APU

Class 8 Truck Hotel Power
Eliminate Road Engine Idling

Obstacles to Use of Liquid Fuels

ceramatec
ADVANCED MATERIALS & ELECTROCHEMICAL TECHNOLOGIES

- Sulfur
  - Poisons steam reforming catalysts
  - Corrosive effect on system BOP
- Aromatics, Alkenes, Alkynes, and Alicyclic hydrocarbons
  - Hydrogen lean mixtures, empirical formula $CH_{2-\delta}$
  - Prone to soot and coke formation
    - Deactivation of steam reforming catalysts
    - Operational problems to POx, CPOx, ATR, etc.
- Vaporization
  - Final Boiling Point near thermal decomposition T

The SOFC Advantage in Heavy Fuel Applications

- **High Operating Temperature**
  & **Oxygen Ion Conducting Electrolyte**
  => **Fuel Flexibility**

- CO as a fuel not a poison
- On anode reformation of hydrocarbon slip
- Better sulfur tolerance
- No thermodynamic penalty for nitrogen dilution
  - Ratio of p_{H2O} / p_{H2} unaffected by fuel diluents
  - Reversible Driving Potential:

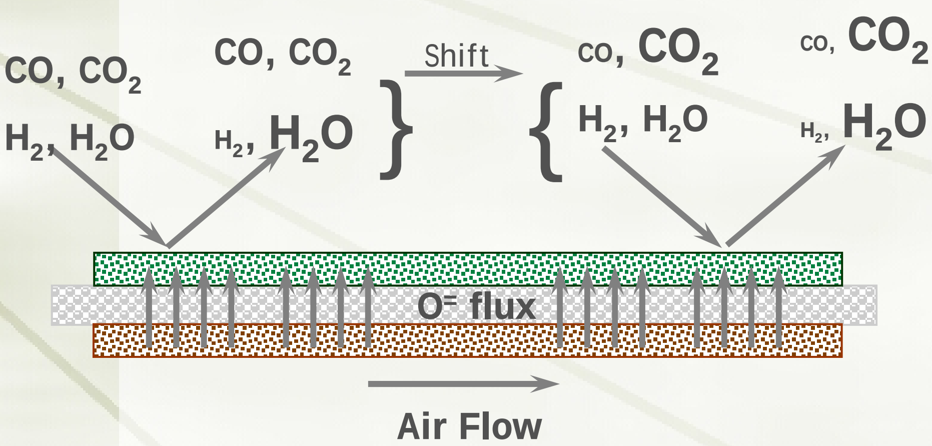
$$E_{rev} = E_N^0(T) + \frac{RT}{nF}\ln\left(\frac{p_{H2O}}{p_{H2}\sqrt{p_{O2}}}\right)$$

SOFC Utilization of CO, Light HC

Fuel Feed: H_2, H_2O, CO, CO_2, CH_4

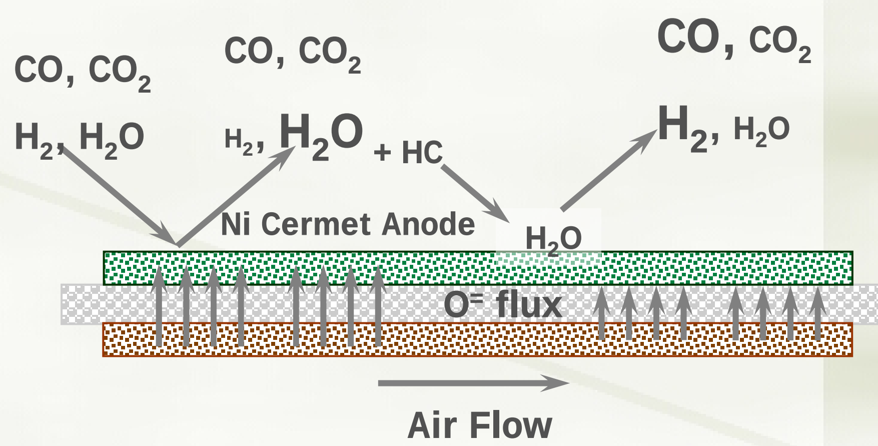
Shift Reaction

$$CO + H_2O \Longleftrightarrow CO_2 + H_2$$



Reforming Reaction

$$CH_4 + H_2O \xLeftrightarrow{\text{Ni Catalyst}} CO + 3H_2$$

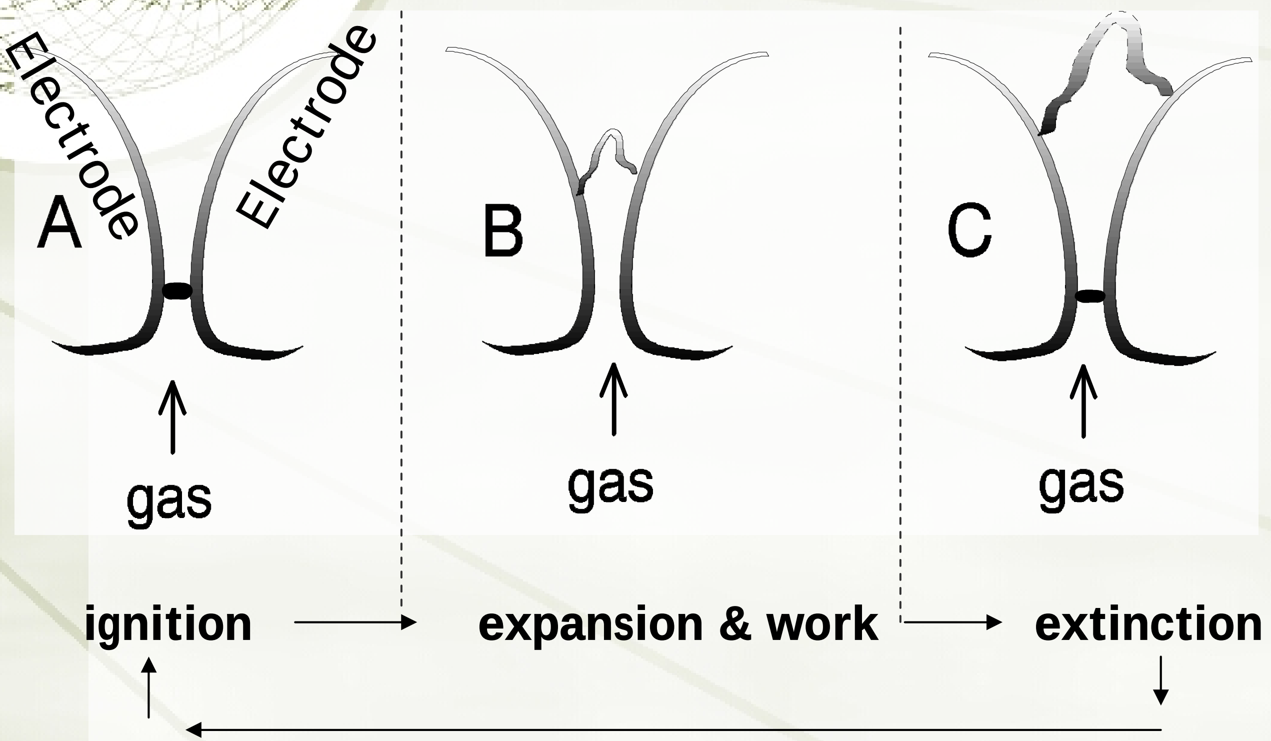


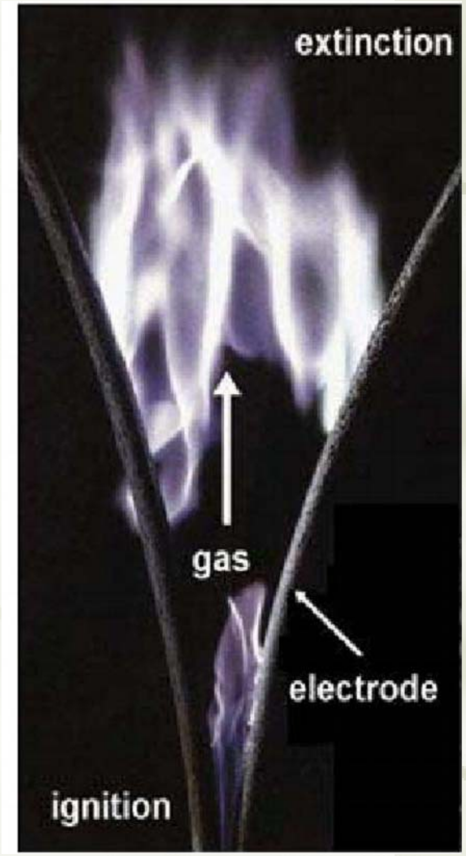
Reformer Description

Operating Principle

Features & Benefits

Cold Plasma GlidArc Operation





Cold Plasma Reformer Features

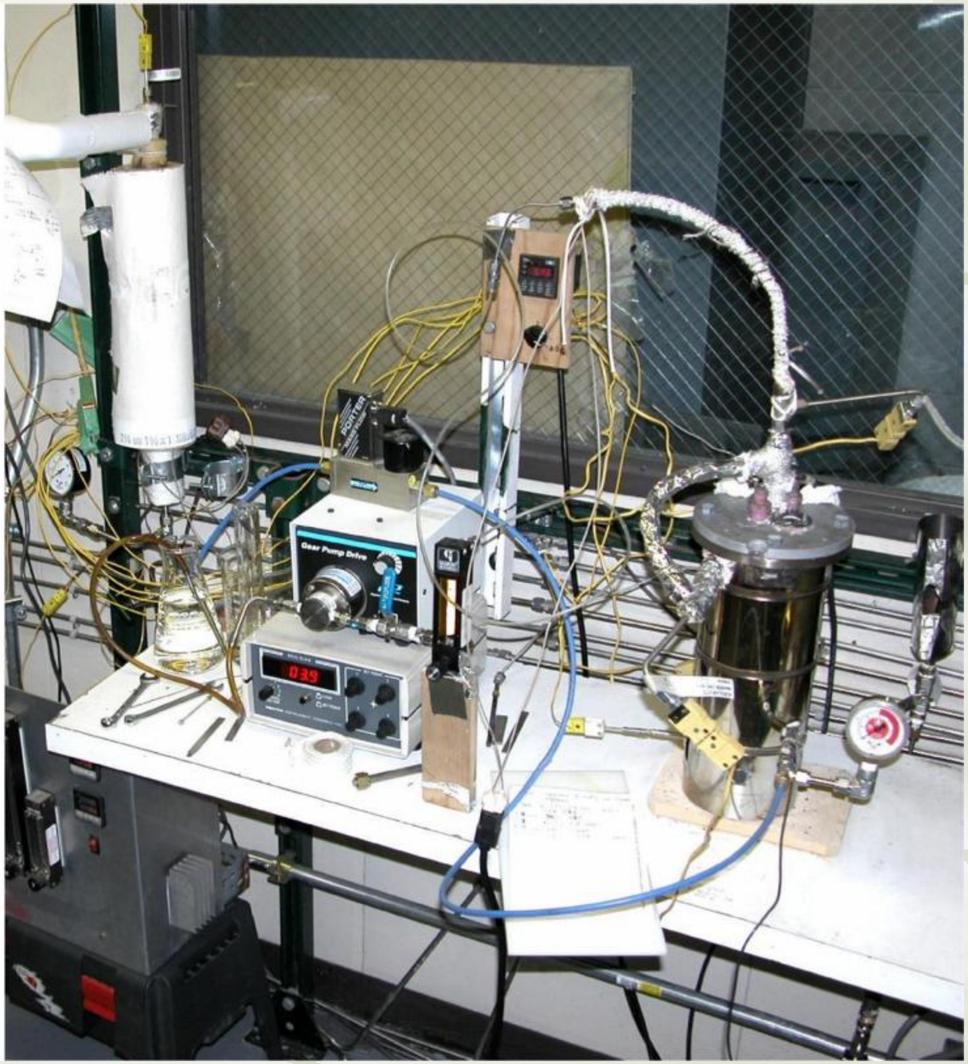
ceramatec
ADVANCED MATERIALS & ELECTROCHEMICAL TECHNOLOGIES

- Sulfur insensitive
  - No reformation catalyst
    - Unaffected by Sulfur
    - No deactivation over time
- Fuel flexibility
  - Light to heavy hydrocarbons
- Variable operating temperature (set by equilibrium thermodynamics)
  - 700 - 900^{o}C typical — matching SOFC operation window

Cold Plasma Reformer

- Very high reaction zone activity
  - Compact reformer size
  - Soot free operation
- Low power requirement for non-thermal plasma
  - 2% of fuel feed rate heating value
  - 4% of generated power (at 50% FC efficiency)
  - 8% of heat of reformation
  - 60 - 80^{o}C reformate sensible temperature rise

GlidArc Liquid Fuel Reformer
5 kW_t fuel rate, 0.6 liter, Atmospheric Pressure



JP-8 Reformation

Air Force SBIR Phase II

JP-8 Analysis

ceramatec
ADVANCED MATERIALS & ELECTROCHEMICAL TECHNOLOGIES

03/12/2004 12:31 FAX 8019721925 CERAMATEC INC 002

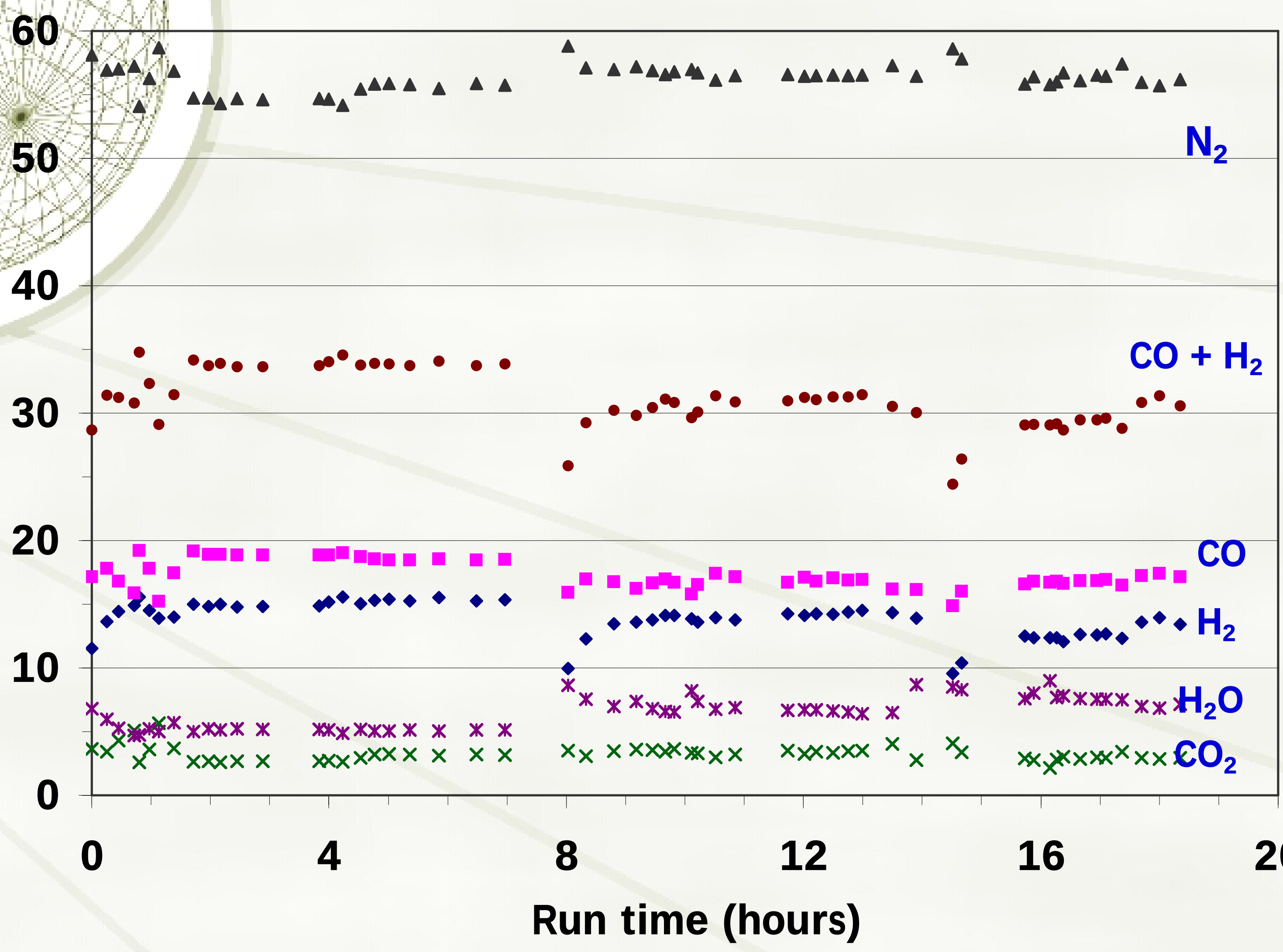
Chevron

CHEVRON PRODUCTS COMPANY
SLC REFINERY
TURBINE FUEL, AVIATION,JP-8
CERTIFICATE OF ANALYSIS

1	REPORT DATE:	07 October 2003
2A	CONTRACTOR:	CHEVRON U.S.A.
2B	CITY:	Salt Lake City
2C	STATE/COUNTRY:	UT, USA
3A	CONTRACT NO.:	
3B	CONTRACT LINE ITEM NUMBER:	
3C	DFSC ORDER NO.:	
4A	TANK NO:	TANK-40073
4B	BATCH NO.:	JET_2003_00078
4C	SAMPLE NO:	463307
5	PRODUCT:	JP8
6A	CRUDE OIL SOURCE:	
6B	CRUDE PROCESSIONG TECHNIQUE:	
7	SHIPPED TO:	Blender
8	QUANTITY REPRESENTED (gals):	

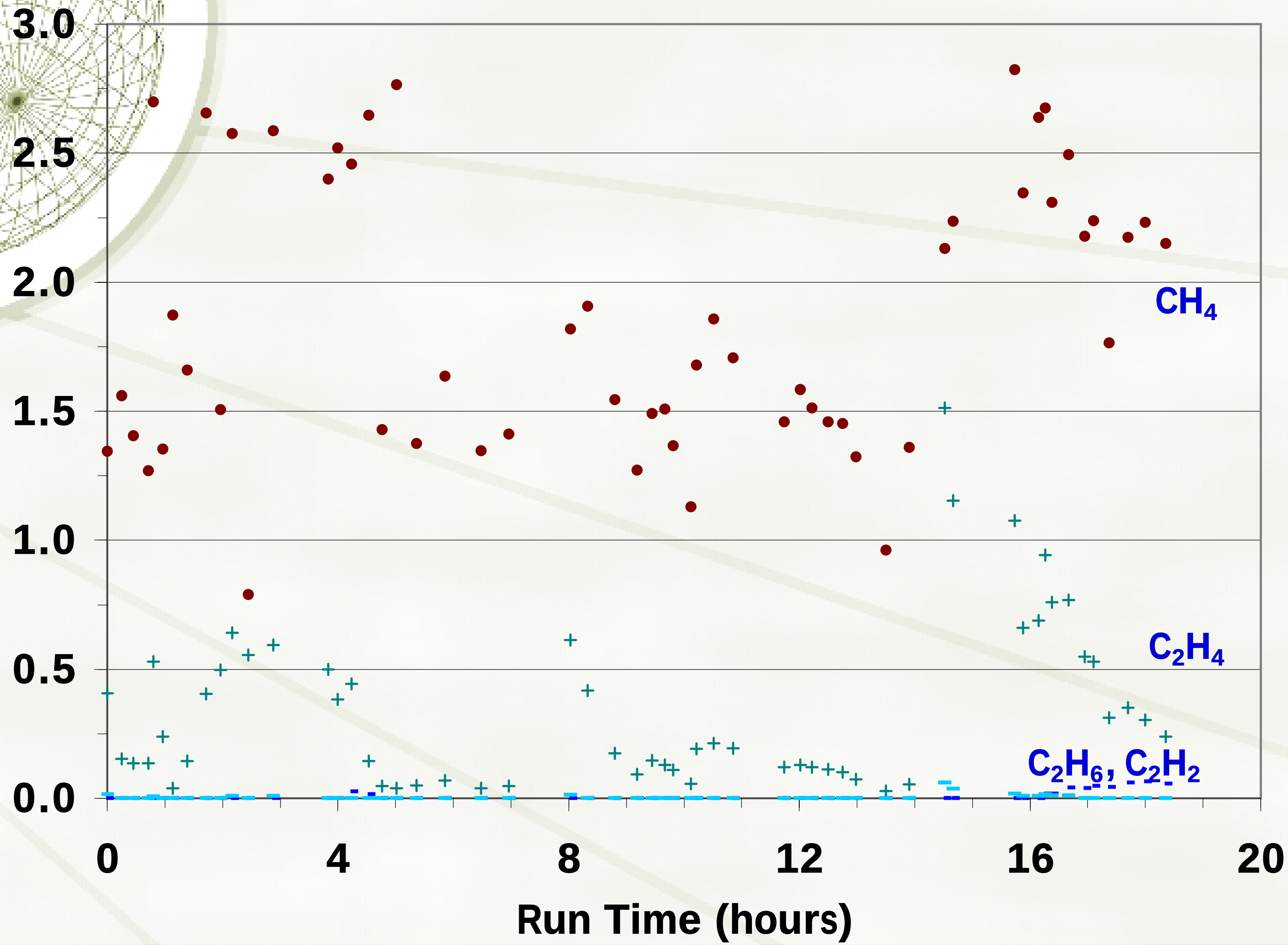
Code	Description	Unit of Measure	Result	Specification	Method
010A	Color		+21	REPORT	D156
020A	Appearance		B&C@70	B&C@70F	SM60-15
100C	Acid Number	mg KOH/g	0.002	MAX 0.015	D3242
110A	Aromatics	vol %	15.3	MAX 25.0	D1319
115	Olefins	vol %	0.8	MAX 5.0	D1319
120	Naphthalenes	vol %	1.24	MAX 3.0	D1840
130	Mercaptan Sulfur	weight %	0.0004	MAX 0.002	D3227
140	Doctor Test		NEG	NEG	SM-145-7
150F	Total Sulfur	weight %	0.0433	MAX 0.30	D4294
160A	Hydrogen Content	weight %	13.9	MIN 13.4	D3343
201	Initial Boiling Point	°C	150	REPORT	D86

Reformate Compositional Stability



Fuel: JP-8

Reformate Hydrocarbon Slip



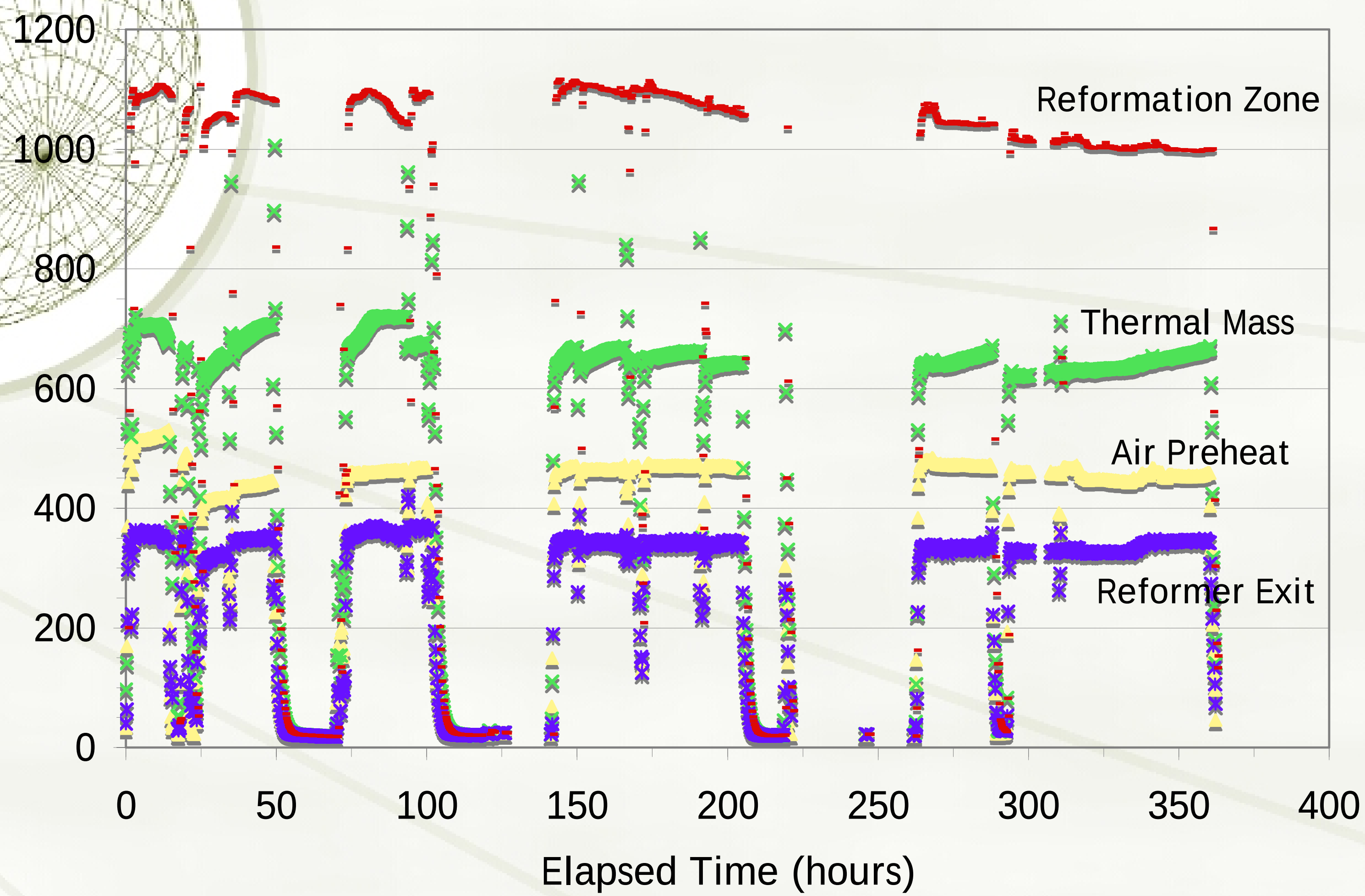
Fuel: JP-8

Commercial Diesel (non-desulfurized)

Air Force SBIR Phase II

Ceramatec IR&D

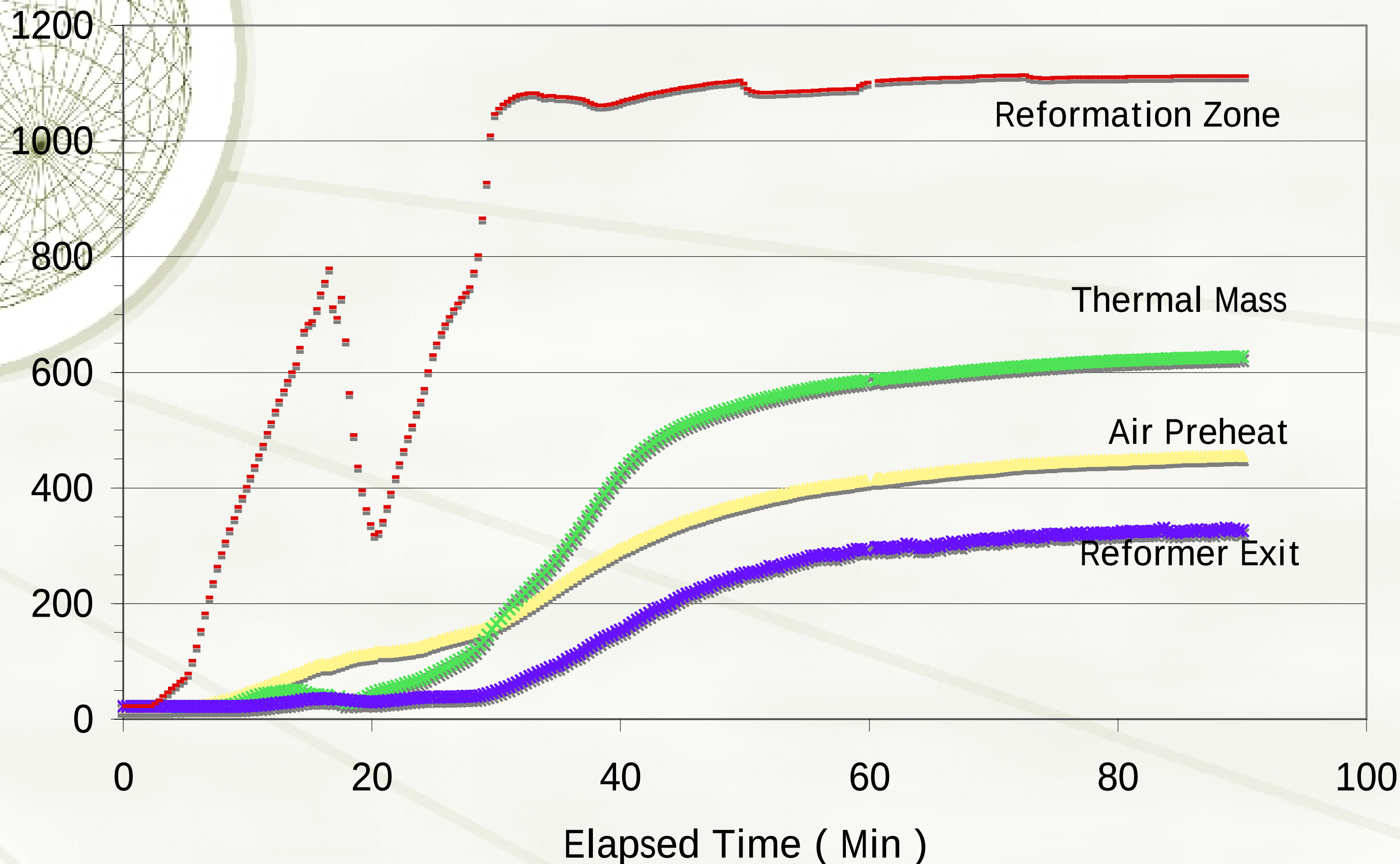
Long-term Operation



- Continuous operation
  - Reformation: 100 hours
  - Including hot stand by: 250 hours

Fuel: Commercial diesel

Reformer Start-up Time



- Manual Control
  - 30 minutes to temperature
  - 60 minutes to steady state

Fuel: Commercial diesel

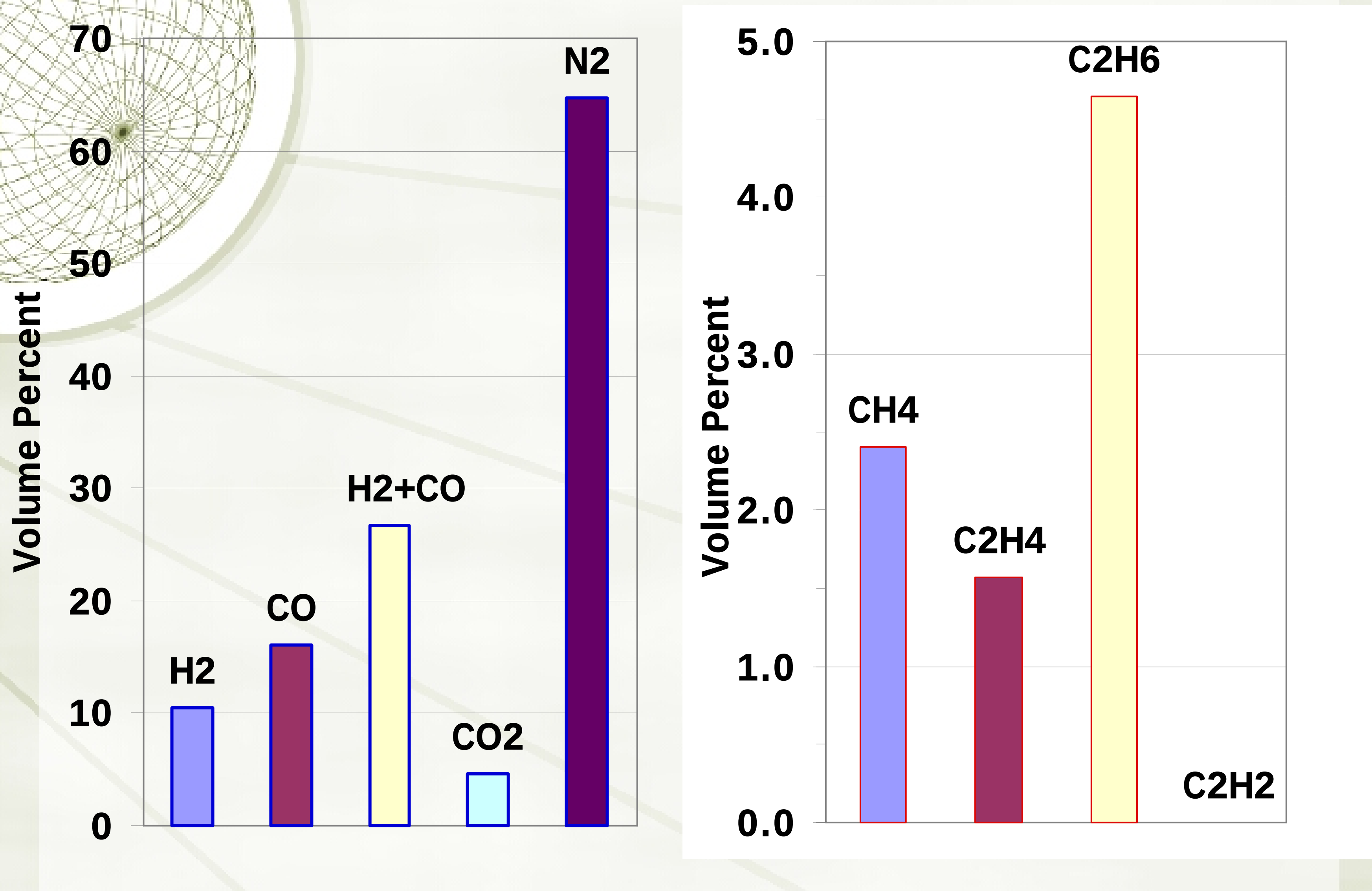
NATO F-76

Navy SBIR Phase I

F-76 Specification

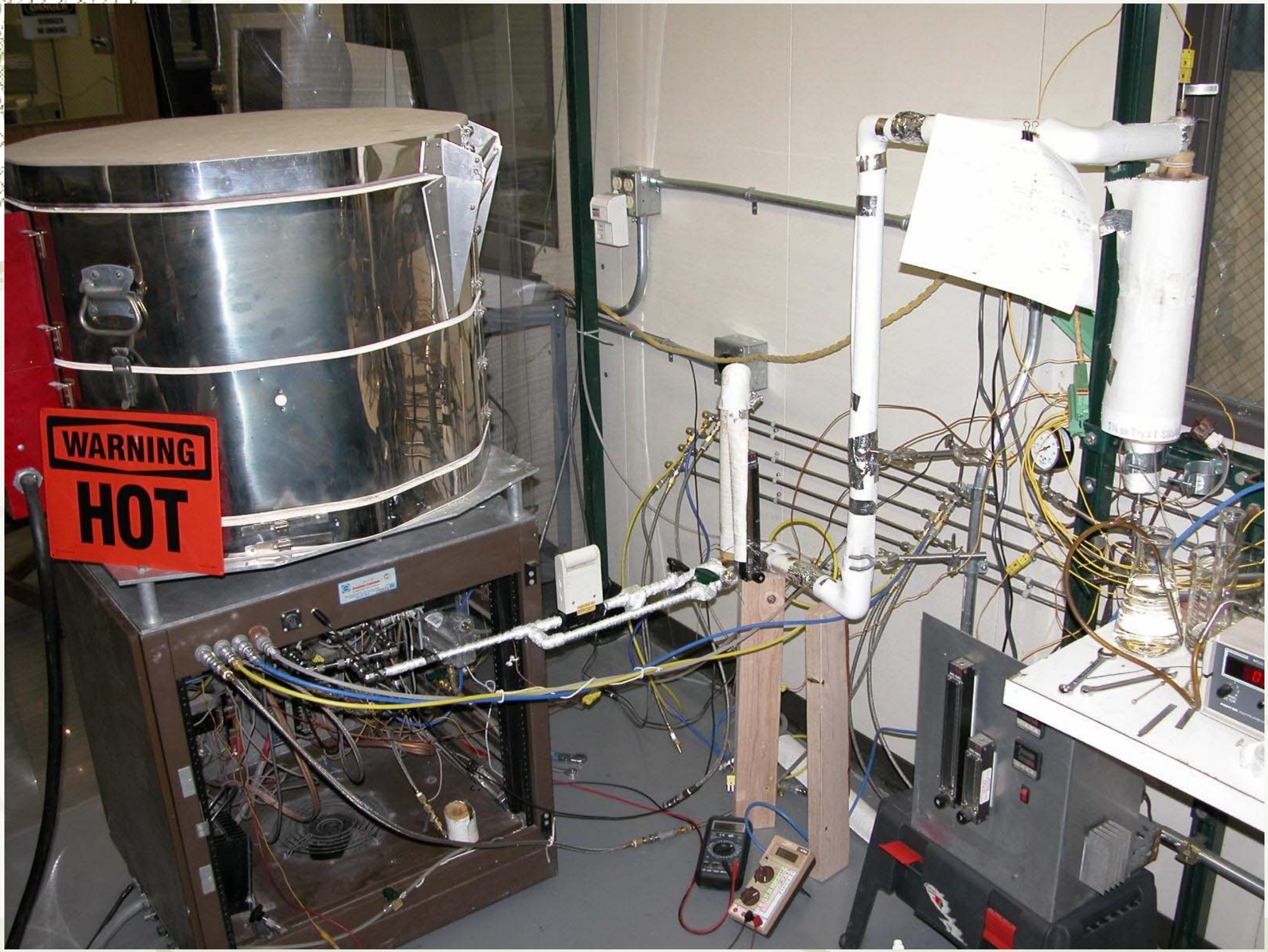
- MIL-PRF-16884K
  - Hydrogen content (wt% min) 12.5%
  - Sulfur content (wt% max) 1%

High Sulfur Fuel Reformate

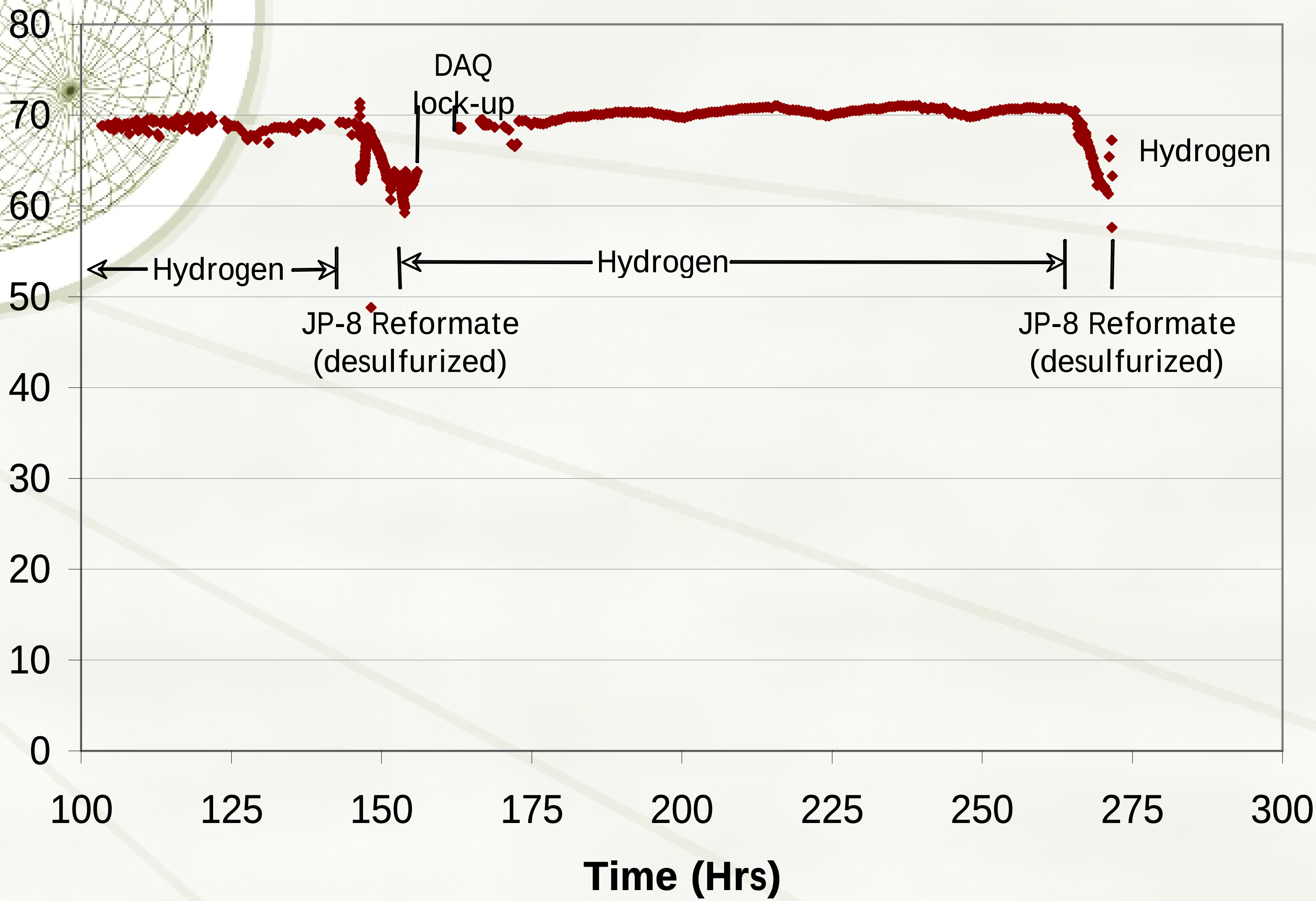


Fuel: F-76

SOFC Test of JP-8 Reformate Slip Stream



SOFC Stack on JP-8 Reformate

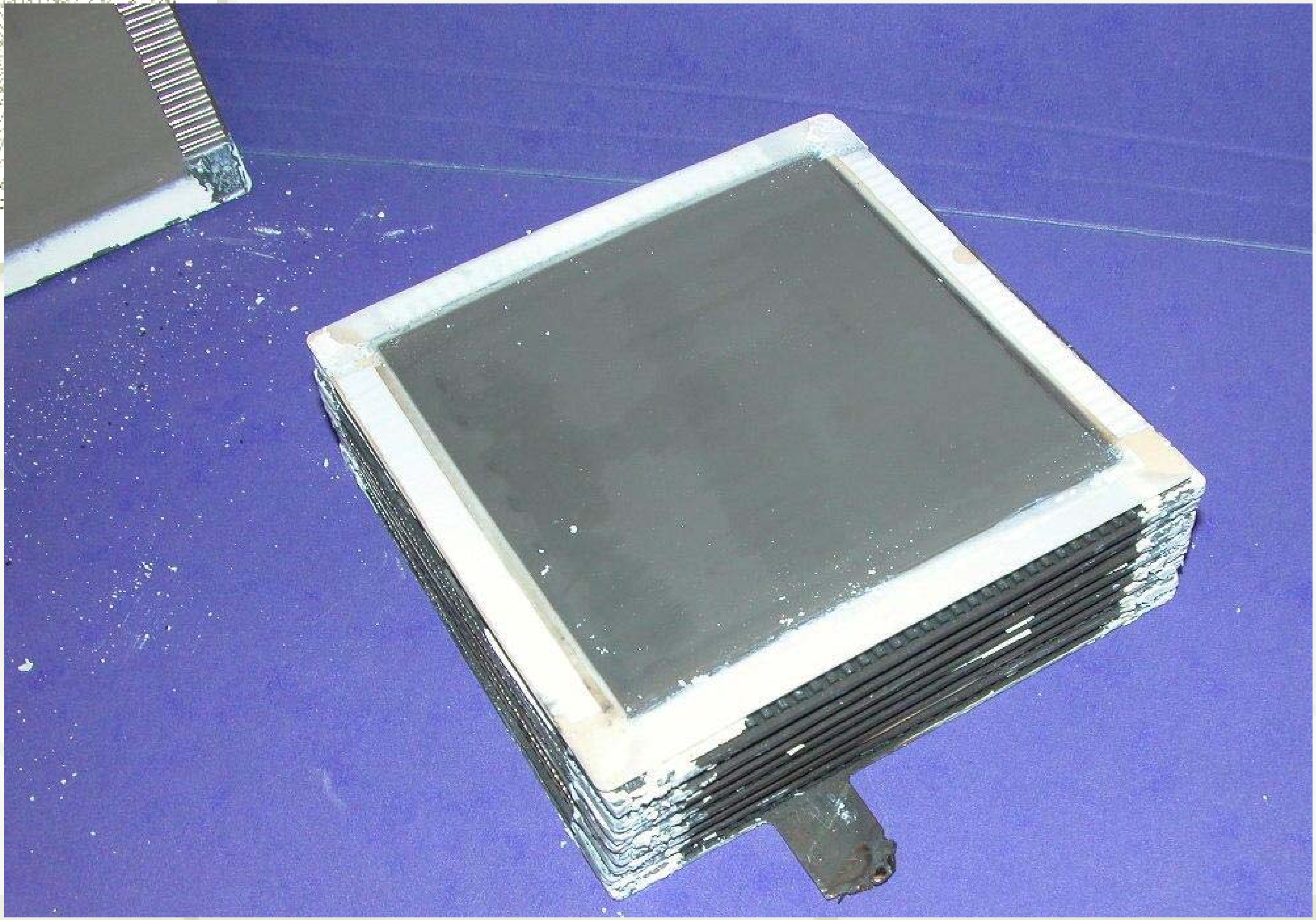


Stack Test Results

ceramatec
ADVANCED MATERIALS & ELECTROCHEMICAL TECHNOLOGIES

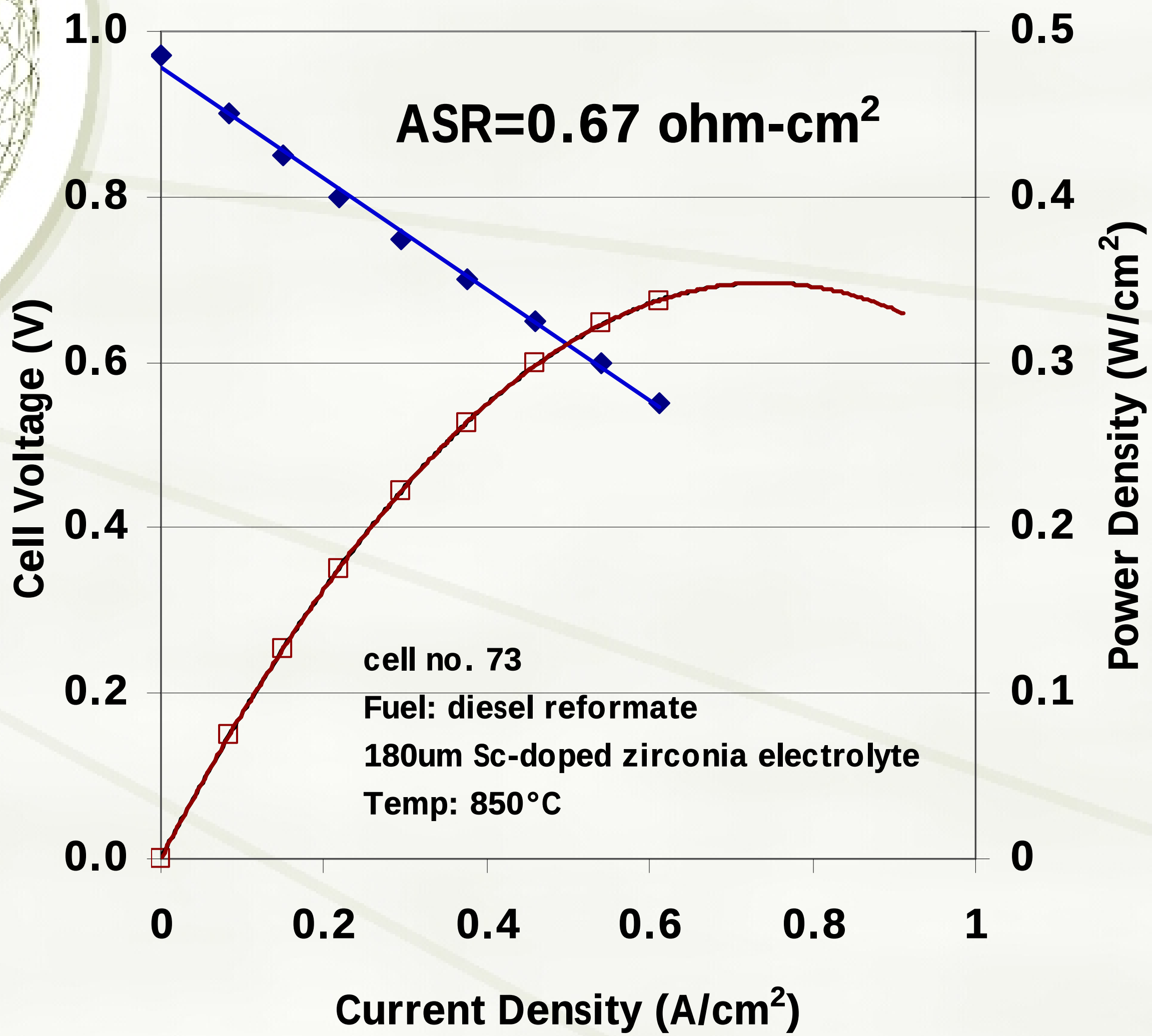
- Three tests conducted
  - Two 10-cell stacks
  - Pair of 11-cell stacks
- Performance comparable to hydrogen baseline
  - Power output difference correlates with reformate Nernst potential depression
  - Some cooling of stack due to presence of hydrocarbon in the reformate
- Soot free operation demonstrated
  - No soot found in fuel manifolds or electrodes

Post Test Appearance
Fuel Electrode



Button Cell Test on Diesel Reformate

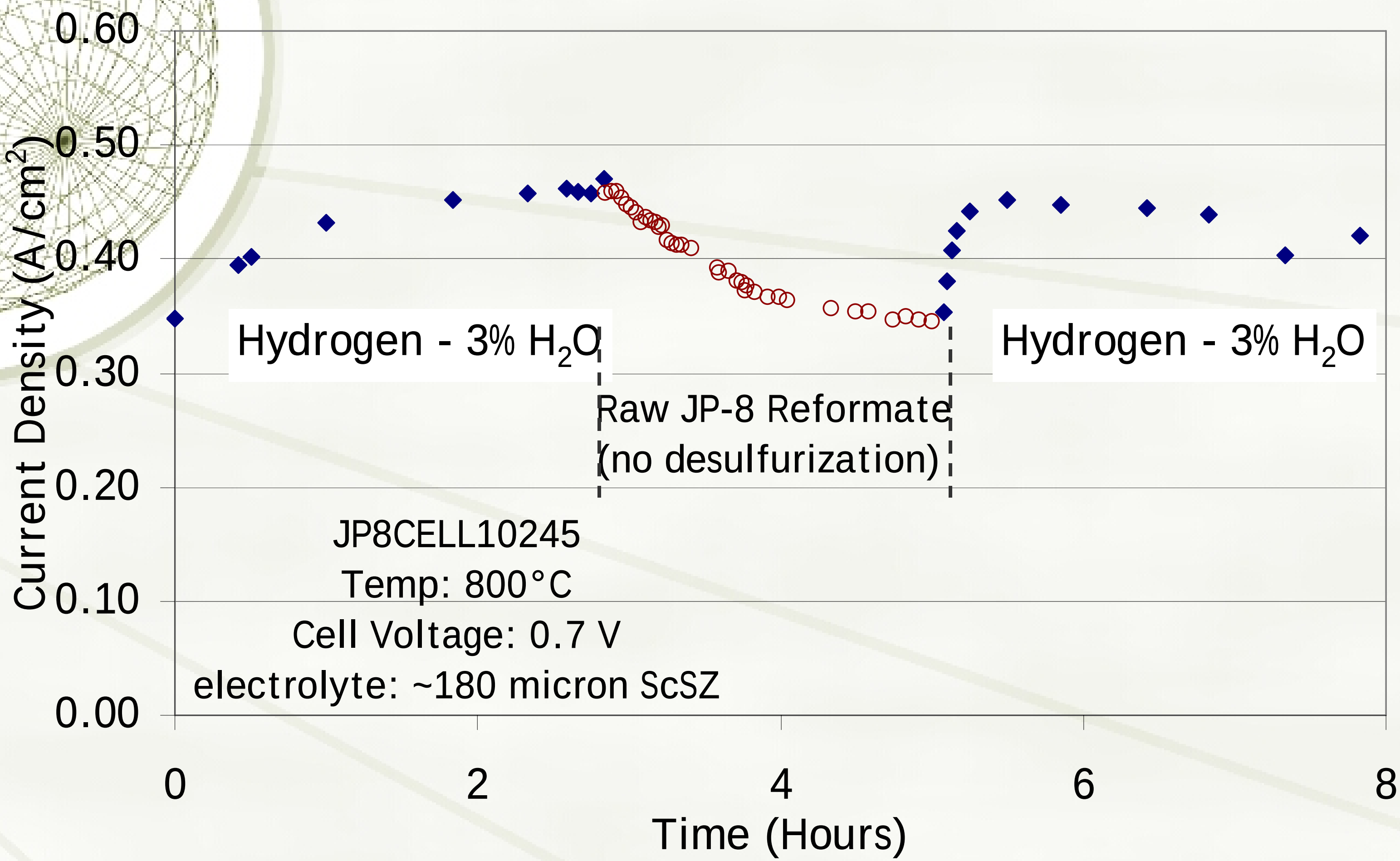
non-desulfurized raw reformate



- Cell ASR similar to H_2/H_2O fuel

Button Cell Test on JP-8 Reformate

Non-desulfurized raw reformate



- On JP-8 Reformate
  - Lower Nernst potential (~ 100 mV)
  - Presence of H_2S (~ 50 ppm)
  - Cell cooling from methane reformation (~2% methane)

Work in Progress

- Process Optimization
  - Effect of fuel equivalence ratio (ϕ)
- Size scale up

20 kW_t Reformer
Height: 12”
OD: 7”

5 kW_t Reformer
Height: 12”
OD: 4.5”

Present focus

Remaining Challenges

- Process optimization
  - Mapping reformate composition as a function of temperature, fuel/oxidant ratio, and residence time
- SOFC integration test
  - Reformer re-design in progress (Air Force)
- Start up time reduction
- Uninterrupted extended operation
- Turn down

Acknowledgements

- US Air Force
  - Hill Air Force Base, Air Logistics Center
    Joe Burns
  - Phase II SBIR Grant No. F42650-03-P-2750
- US Navy
  - NAVSEA, Philadelphia
    Brian Prew and Don Hoffman
  - Phase I SBIR Grant No. N655538-05-M-0145
- Ceramatec, Inc.
  - IR&D Funding