Renewable Energy for Minnesota

Progress in Fuel Cell Research at CPG

Cummins Power Generation

Who are we?
Cummins Power Generation (AKA Onan)

World Headquarters, Central Engineering, and Manufacturing for the Americas In Fridley Minnesota

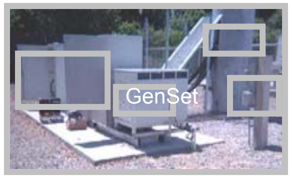
1,000,000 ft^2 1500 employees

Cummins Power Generation Products and Markets

Power Generation

Stationary Power Markets

Residential



Telecommunications

Standby / Interruptible

Distributed Generation

Mobile Power Markets

Portables

Marine

Recreational Vehicle

Commercial Mobile

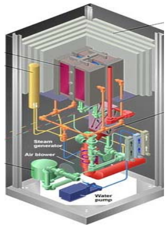
Rental

Technologies

Engine Gensets

Variable Speed and Hybrid Gensets

Controls, Switch Gear



Fuel Cell Program

Cummins v. Competition

	Diesel Engines	Gas Engines	Alternators	Controls & Switchgear	Gensets	Turbochargers	Filtration & Air-Handling Systems
Cummins	■	■	■	■	■	■	■
CAT	■	■			■		
Detroit Diesel/ MTU	■				■		
Kohler			to 200 kW	■	■		
Others				■	■		

Power of One: Single Source Supply

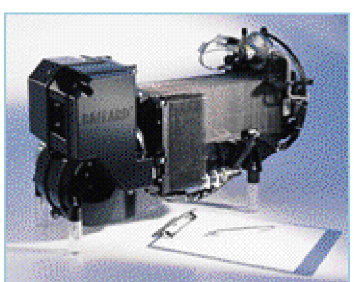
➢ **Gen-sets from 2.0kW to 2.8MW, parallelable to many Mega Watts.**

How is a Fuel Cell Different From a Battery?

Both cause an electrical potential through oxidation of materials

Batteries

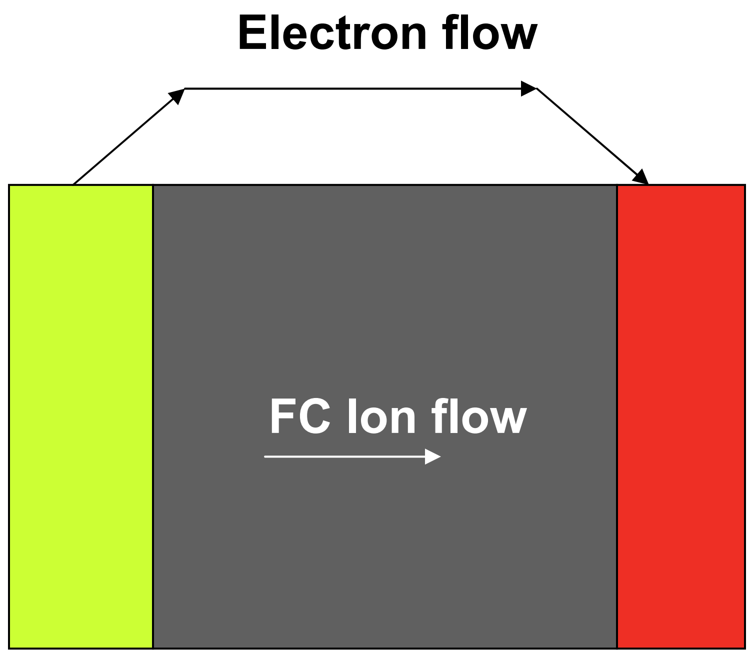
Internal materials transform during charging and discharging (power and energy limited by the cell size)



Fuel Cells

Internal materials act as catalysts and only the fuel oxidizes (power limited by cell size, energy by the fuel tank size)

Basic elements of a battery or fuel cell

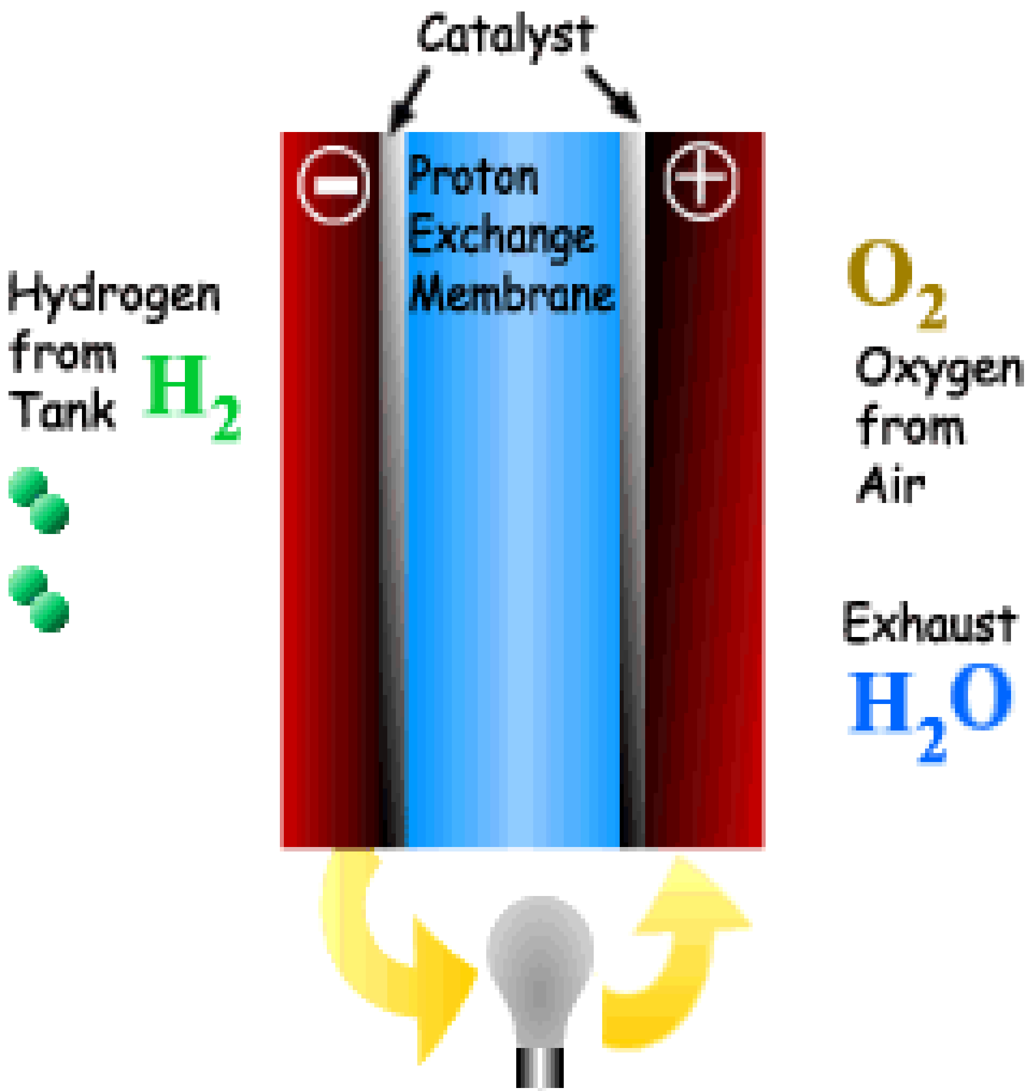


Anode	Electrolyte	Cathode
Fuel or reducing electrode	**Ion conductor**	**Oxidizing electrode**
	Not electrically conductive	
+ Positive		**- Negative**

Proton Exchange Membrane's The Hydrogen Economy Fuel Cell

Power Generation

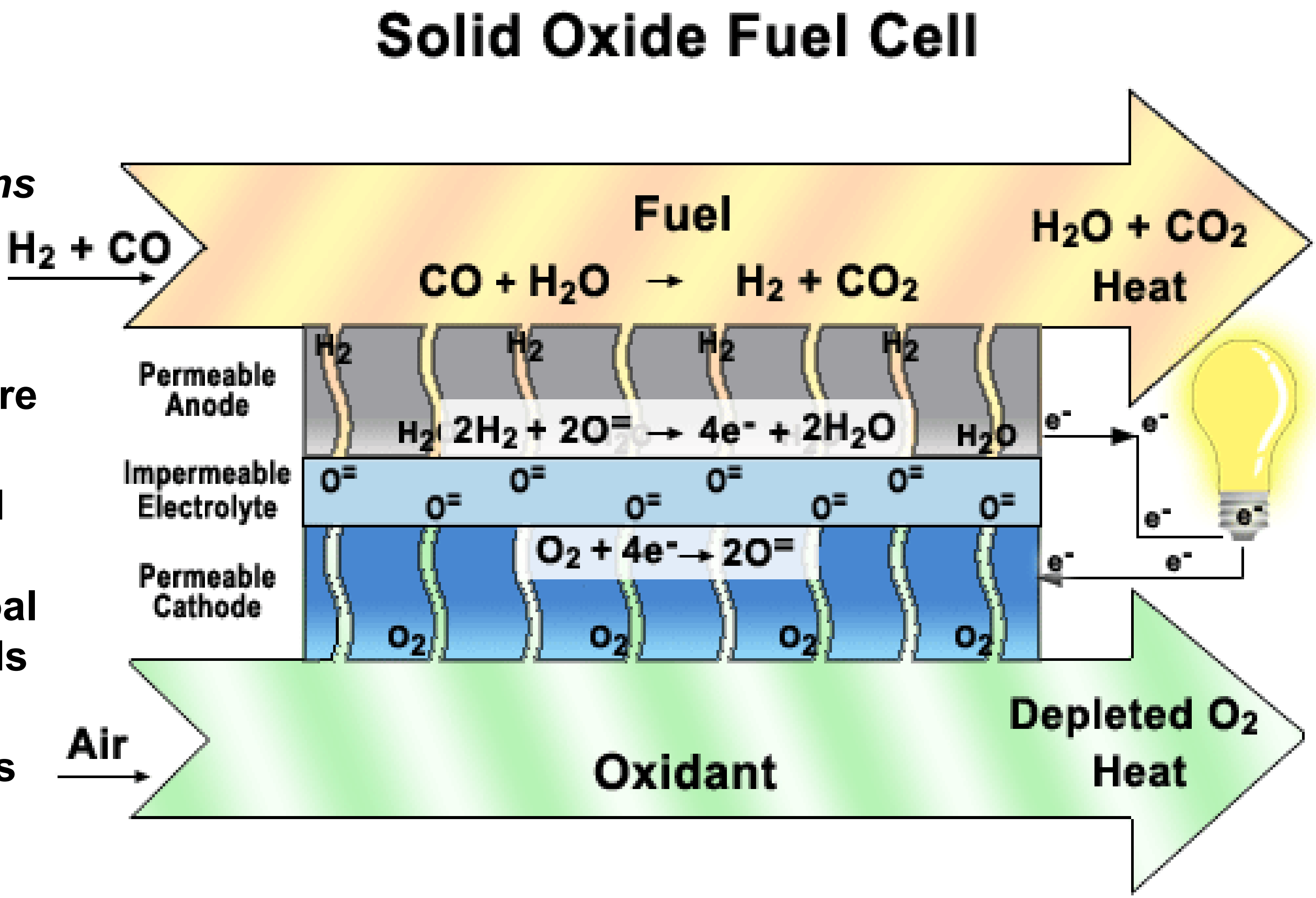
- Proton Exchange Fuel Cell
  - *Protons (Hydrogen Nuclei) Cross Electrolyte*
  - Solid Electrolyte
  - Requires ultra-pure Hydrogen.
  - Chemical to Electrical conversion efficiencies
    - ~50%
  - System efficiencies
    - 35% - 45%



Solid Oxide Fuel Cells
The Omnivorous Fuel Cell

Solid Oxide Fuel Cell (SOFC)

- *Oxygen Ions Cross the Electrolyte*
- Operating Temperature 700-800 °C
- Well suited to run on gasified coal or Bio-Fuels
- System Efficiencies ~40-50%



Why Solid Oxide Fuel Cells (SOFC's)?

- Simplified fuel reformation for HC fuels (CO is fuel constituent, some Sulfur tolerance)
- No water management in stacks
- Potential for low cost / no precious metals
- No external cooling required
- High quality waste heat stream
- High efficiency

Challenges

- Thermal management (start up, shut down, transients) – startup time
- Degradation
- Seals
- Cost, cost, cost

DOE Solid State Energy Conversion Alliance (SECA) Fuel Cell Program

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- SECA helps bridge cost
- of moving from Lab to
- Commercialization Process

SECA drives research needed to get cost to a commercially competitive level -- $400 / kWe

SECA funding enables the process

Power Generation

SECA

(Solid State Energy Conversion Alliance)
10 kWe SOFC Power System Commercialization

Objective:

- Develop a SOFC system including
- SOFC stack, reformer, heat exchanger
- Balance of Plant
- Controls and Power Electronics
- Packaging and integration
- Factory cost of $400/ kWe net by end of Phase III
- Commercialized at earliest possible date

Target Markets

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Objective:

Commercialization

Recreational Vehicle

Truck APU

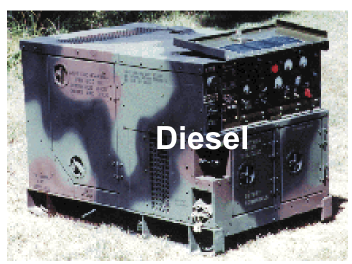
Commercial Mobile

Marine

Telecommunications

Natural Gas or Propane

Military



Team Arrangements

Power Generation

- System integration
- Electronic controls
- Power electronics
- Fuel systems
- Air handling systems
- Heat transfer
- Reformer technology
- Noise and vibration
- Manufacturing
- Marketing, sales, distribution

Strategic Partners

- Planar SOFC technology
- Planar stack manufacturing
- Reformer technology
- Reformer manufacturing
- Material sciences

What are the advantages?

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- Advantages of **fuel cells**
  - –Can have greater conversion efficiency.
    - •Particularly for the conversion to electrical energy.
      - –SOFC can provide 50% open cycle and potentially 70% with bottoming cycle vs. 40% for heat engines open cycle.
    - •One of the leading arguments for fuel cells. Makes more costly renewable energy, affordable.

Efficiency Vs. Technology

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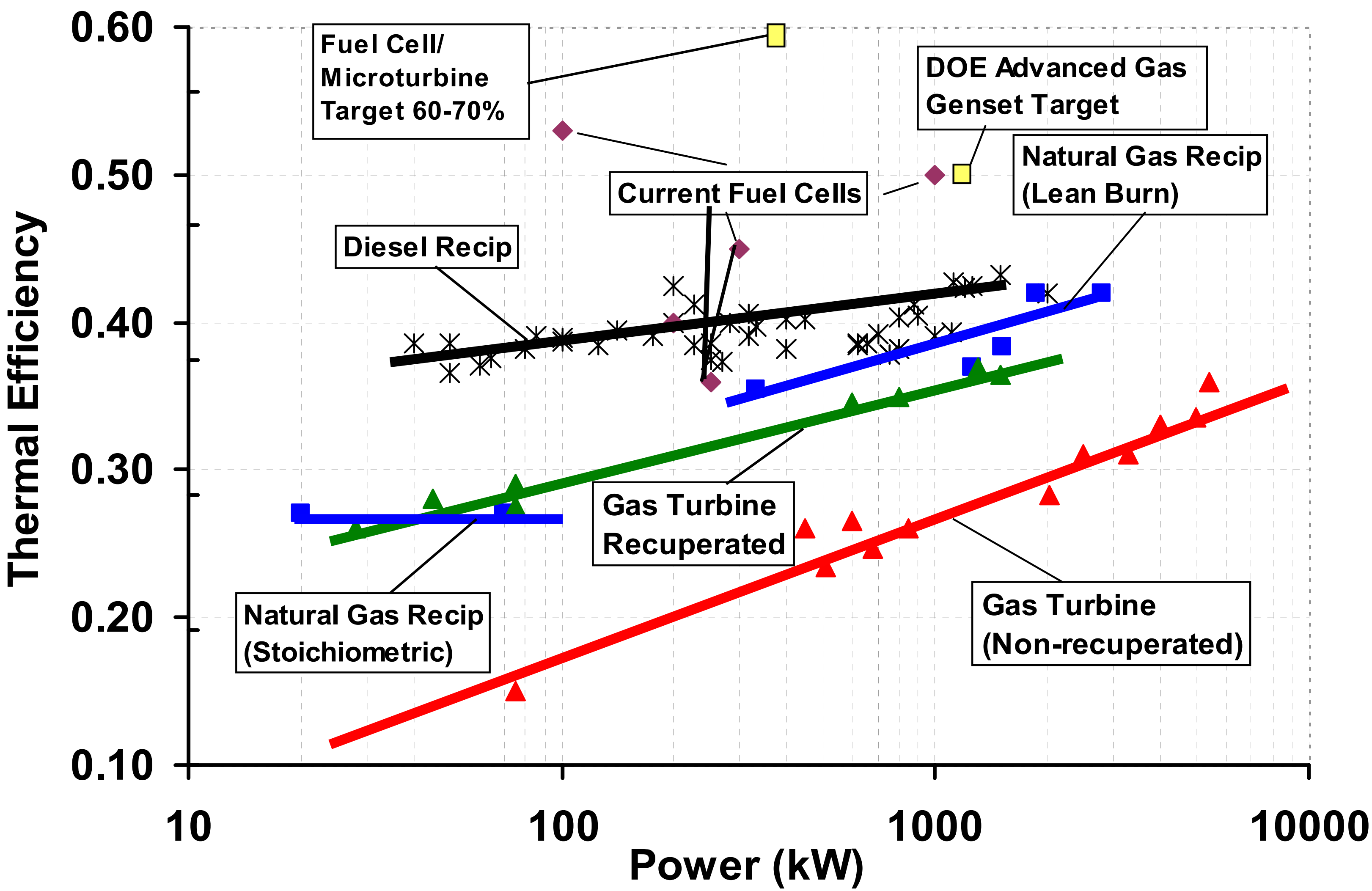
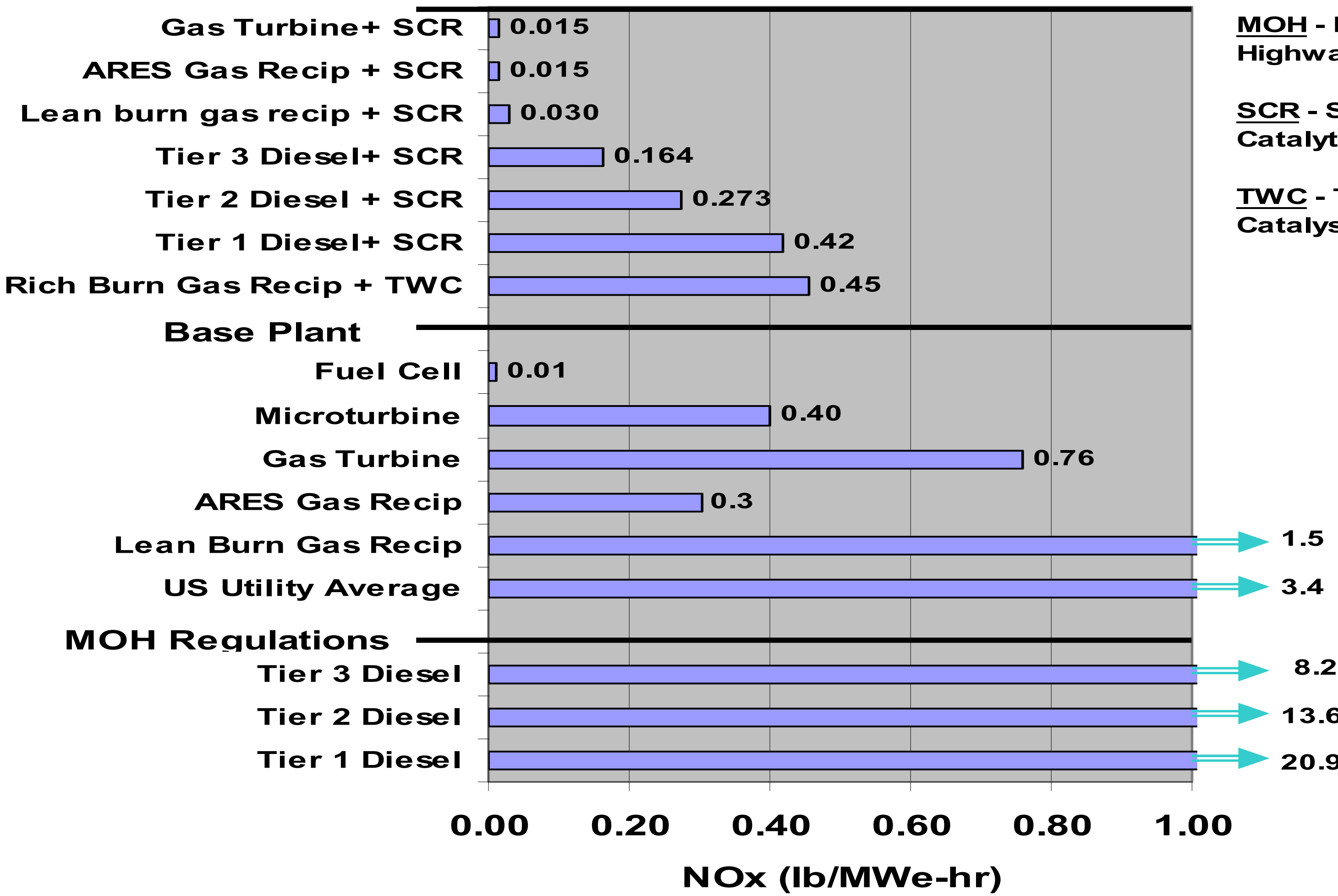


➢ Higher efficiency plus high fuel costs favor evolving technology, fuel cells

What are the advantages?

- Advantages of **fuel cells**
  - **Can have near zero harmful emissions on carbon based fuels (SOFC's).**
    - Heat engines running on Hydrogen also have near zero emissions.
    - No NOx, if you are careful.
  - Fuel Cells are quiet with no vibration.
  - Fuel Cells can have a reduced IR signature.
    - The military likes em.

Generating Equipment Exhaust Emissions



MOH - Mobile Off-Highway

SCR - Selective Catalytic Reduction

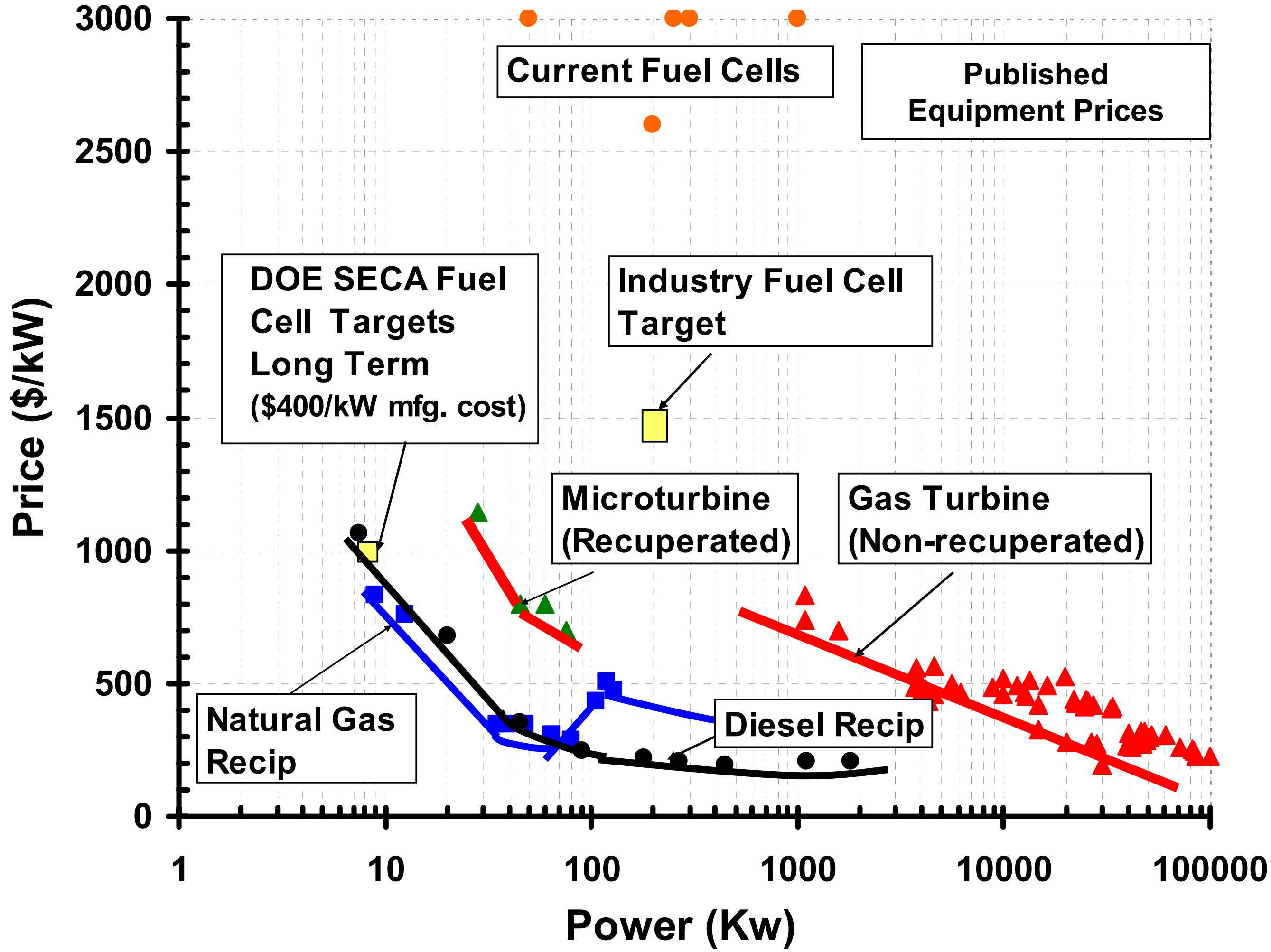
TWC - Three-Way Catalyst

- All technologies are evolving into a tight band
- Ultra low FC emissions may drive BACT regulations that favor fuel cells in non containment areas

What are the disadvantages?

- Disadvantages of **fuel cells**
  - **Presently more costly.**
    - Not a mature technology.
    - Ceramics are relatively fragile.
    - Can be difficult to seal.
  - **Start up issues.**
    - SOFC's will always take tens of minutes to start.
    - Transient response, Fuel must lead load.

Equipment Cost/KW vs. Power



- High Eq. costs drive total ownership costs, particularly in less than base load applications

Fuel Cells and Cummins

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- Solid State Energy Conversion Alliance (SECA)
  - Public (DOE), Private partnership to develop low cost SOFC's.
    - Cummins Power Generation is one of the industry teams.
  - DOE Target System Cost of $400 / kW by 2010

Phase	I	II	III
Cost	*	*	$400/kW
Efficiency			
Mobile	25–45%	30–50%	30–50%
Stationary	35–55%	40–60%	40–60%
Steady-State			
Test Hours	1,500	1,500	1,500
Availability	80%	85%	95%
Power Degradation per 500 hours	$\leq$2%	$\leq$1%	$\leq$0.1%
Transient Test			
Cycles	10	50	100
Power Degradation after Cycle Test	$\leq$1%	$\leq$0.5%	$\leq$0.1%
Power Density	0.3W/cm^2	0.6W/cm^2	>0.6W/cm^2
Temperature	800 °C	~700 °C	700 °C

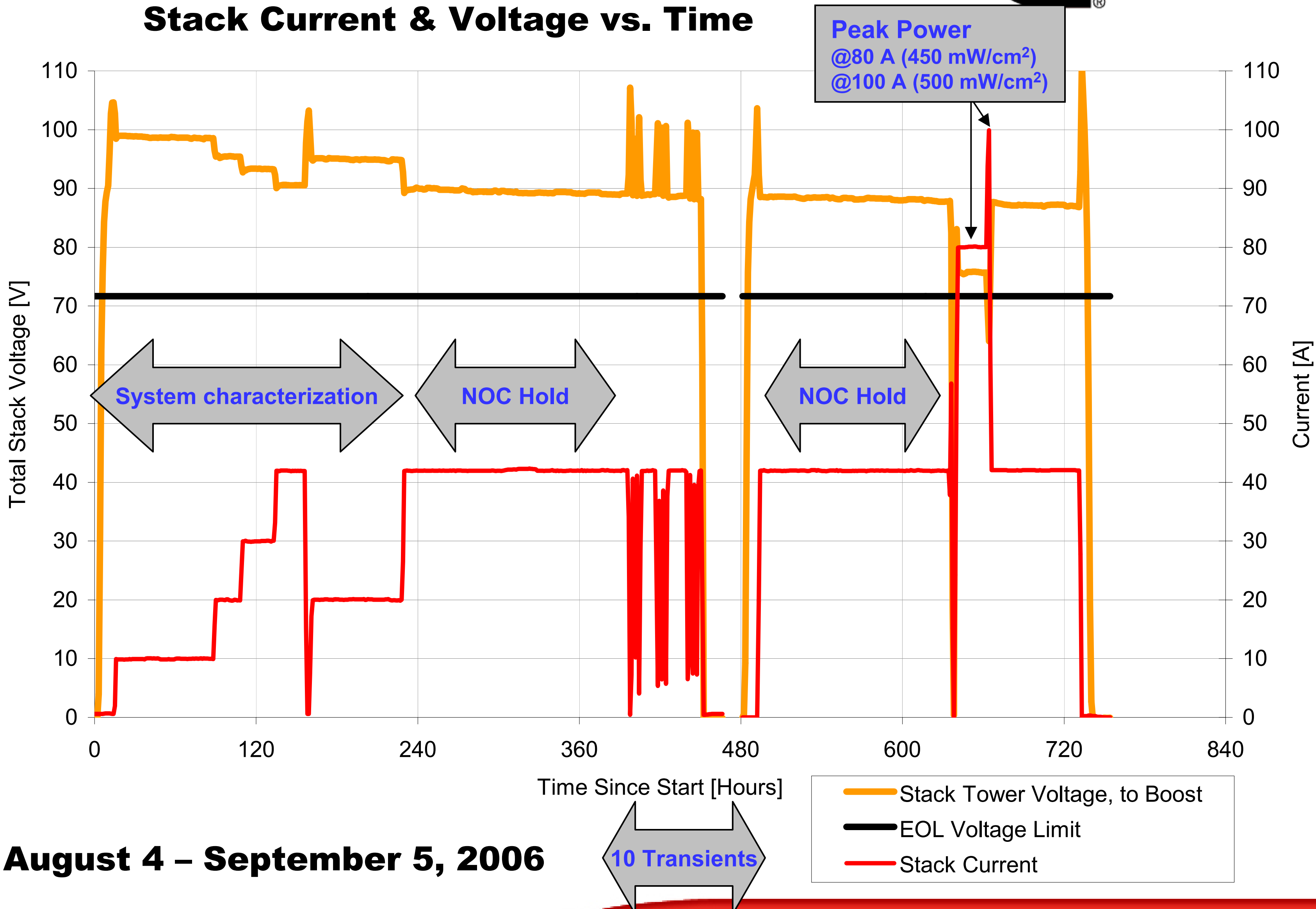
Phase 1 Reality

	Phase 1 Program Requirements	Phase 1 Reality
System Size (net)	3 – 10 kW	~ 3.3 $kW_{DC\ NET}$ (NOC) ~ 5.4 kW $_{DC\ NET}$ (Peak)
Cost ($/kW @ 50k/a.)	$\leq$ 800	~ 750 – 775
Efficiency (net electrical LHV)	$\geq$ 25% mobile	~ 35 - 44% DC Net
Steady State Degradation (/ 500 hrs.)	< 2 %	~ 1-2 %
Transient Degradation (/ 10 cycles)	< 1 %	< 1%
Availability	$\geq$ 80%	> 90%

- Notes:
  - Peak efficiency is not a specific test - it is normal operation
  - $/kW calculation is based on peak power which will be done at end of test
  - All operation on pipeline natural gas with facility desulphurizer

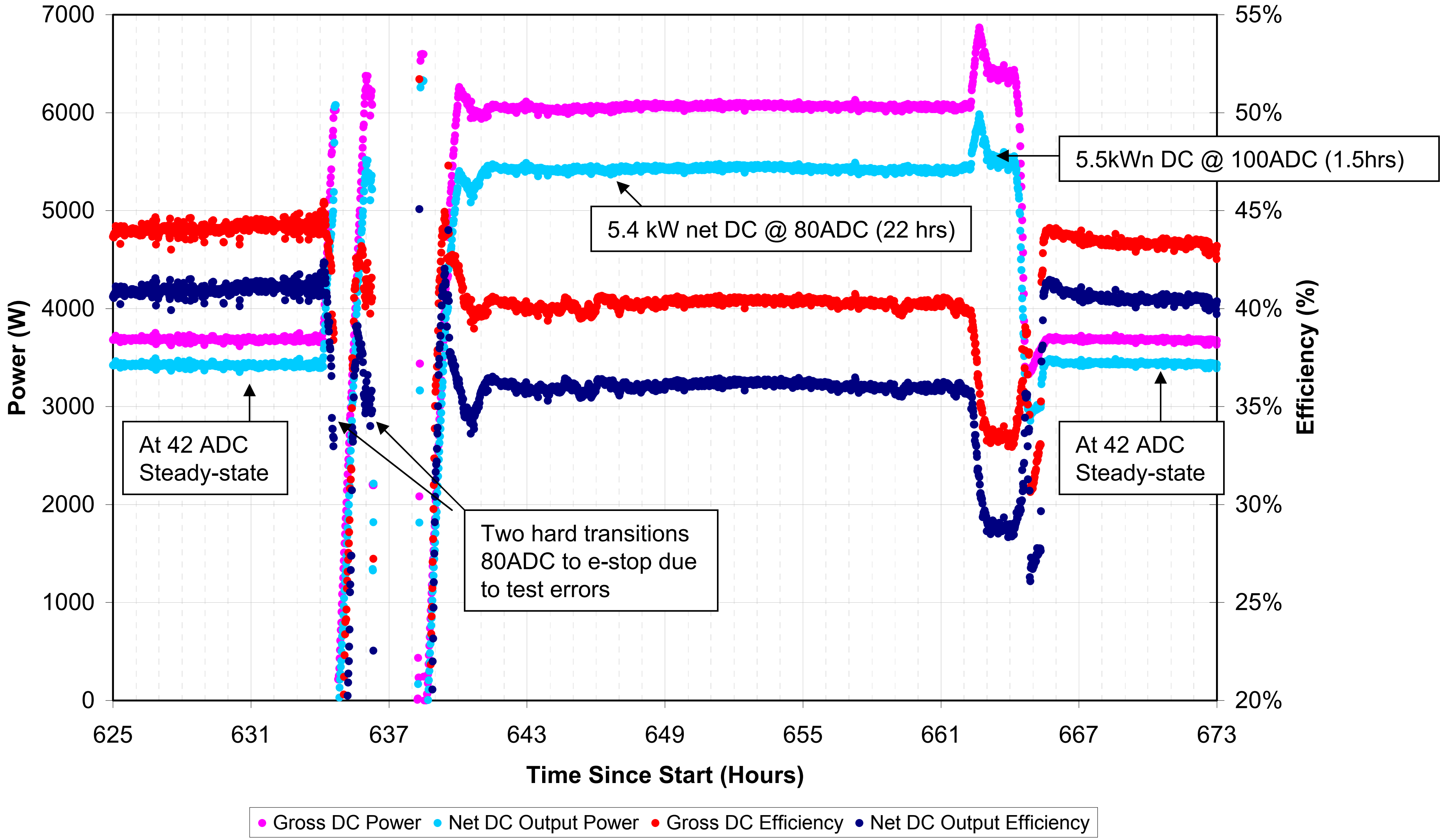
Initial Phase 1 System Testing:

Stack Current & Voltage vs. Time



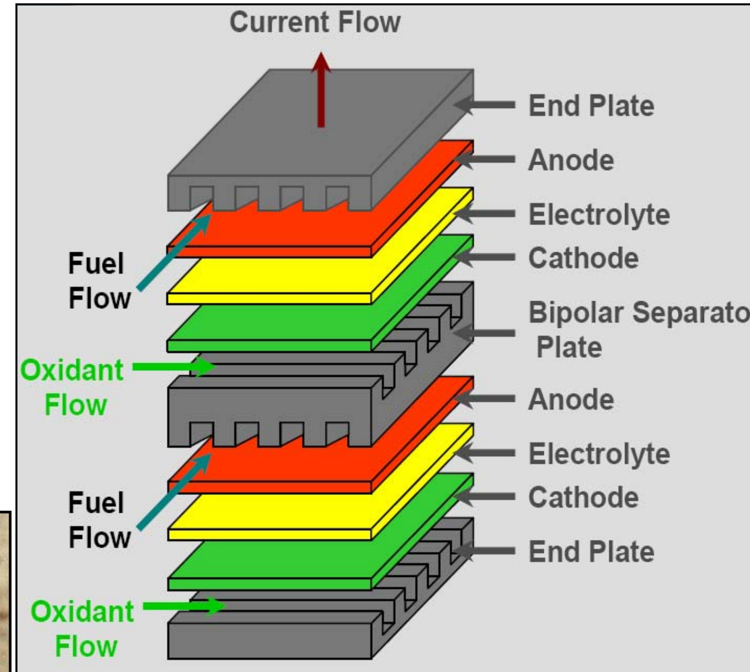
August 4 – September 5, 2006

Initial Phase 1 System Testing:
Peak Power

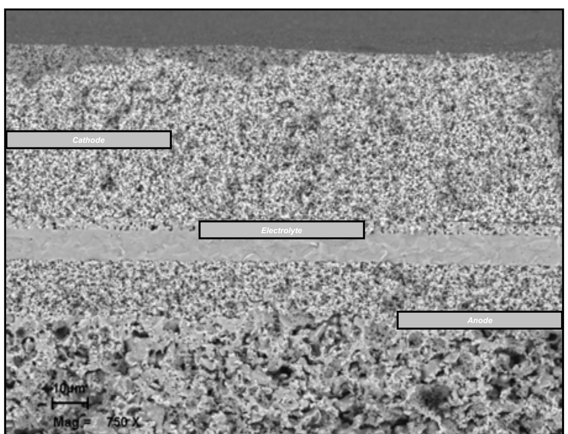


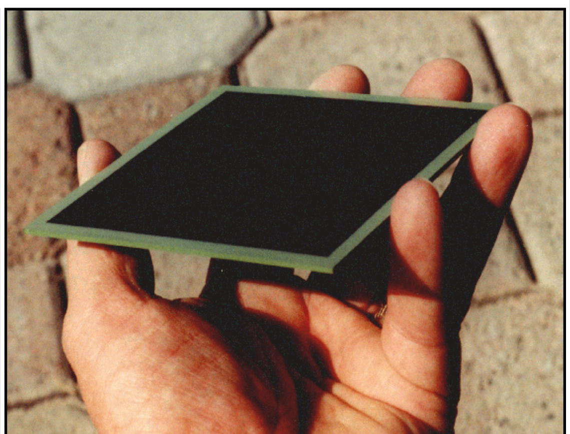
SOFC Stacks

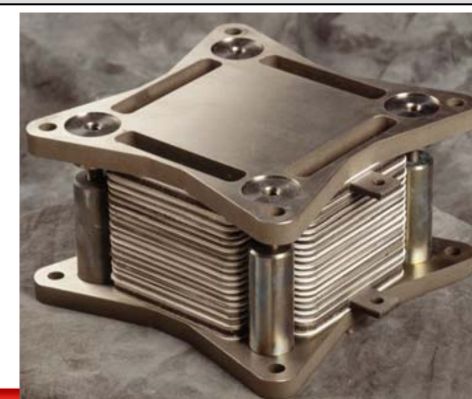
- SOFC Planar Construction
  - Solid electrolyte, supported by Anode material.
  - Cell interconnects made of stainless steel.



SOFC Cells



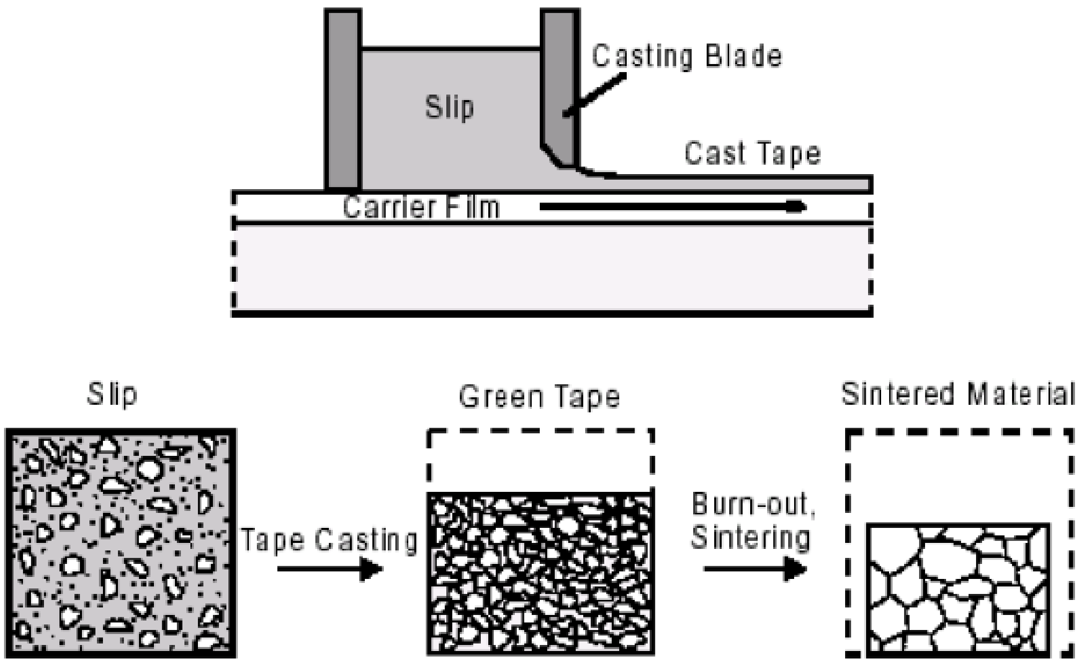




- *Anode* – nickel-zirconia cermet, ~ 1 mm thick
- *Electrolyte* – yttria-stabilized zirconia (YSZ), ~ 5 µm thick
- *Cathode* – conducting ceramic, ~ 50 µm thick

All Courtesy of Versa Power

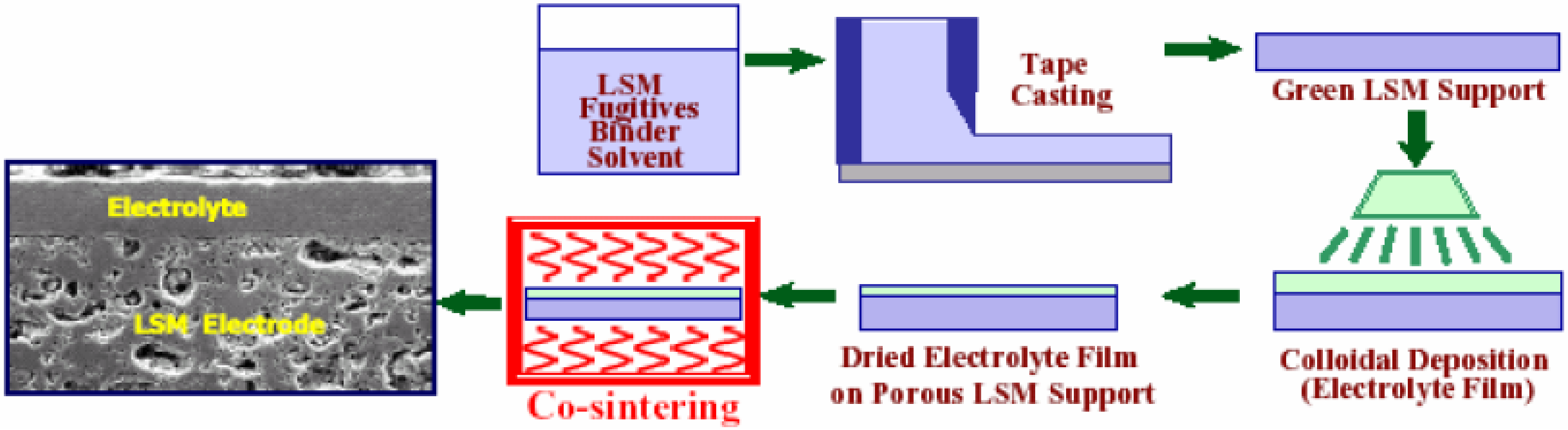
Ceramics manufacturing



The top schematic drawing illustrates tape casting. The bottom sketch shows the different stages during the processing: the slip consisting of water, ceramic particles and binder; the cast, dried green sheet; and, finally, the microstructure of the sintered material.

Low cost, high volume ceramics manufacturing

Multilayer ceramic manufacturing process, similar to ceramic circuit boards.



The System

- **Fuel Cell Stacks center piece of a larger system.**
  - **Fuel Cells by themselves are clean, balance of plant may not be.**
  - **Balance of Plant (BOP)**
    - **Thermal, fluid management**
      - Control flows to match current demand, and fuel utilization requirements.
      - Control stack average temperature.
      - Control stack temperature gradients.
    - **Combustor cleans up exhaust**
      - MUST BE CAREFUL WITH DESIGN OF COMBUSTOR.
  - **Fuel processor**
    - Other than Natural Gas, SOFC needs some fuel processing
    - Greatly simplified versus a PEM, however.

Mobile SOFC Balance of Plant

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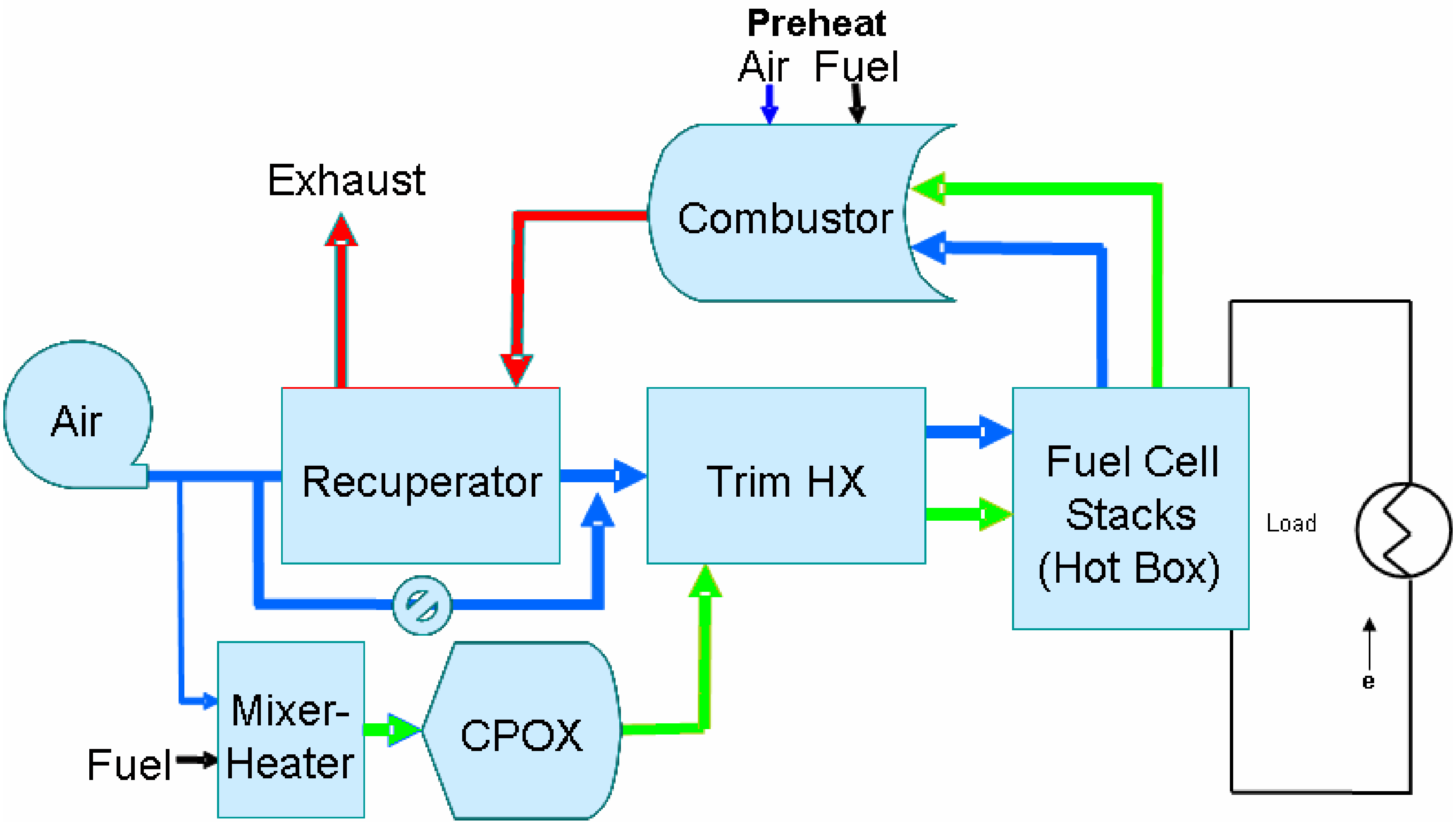
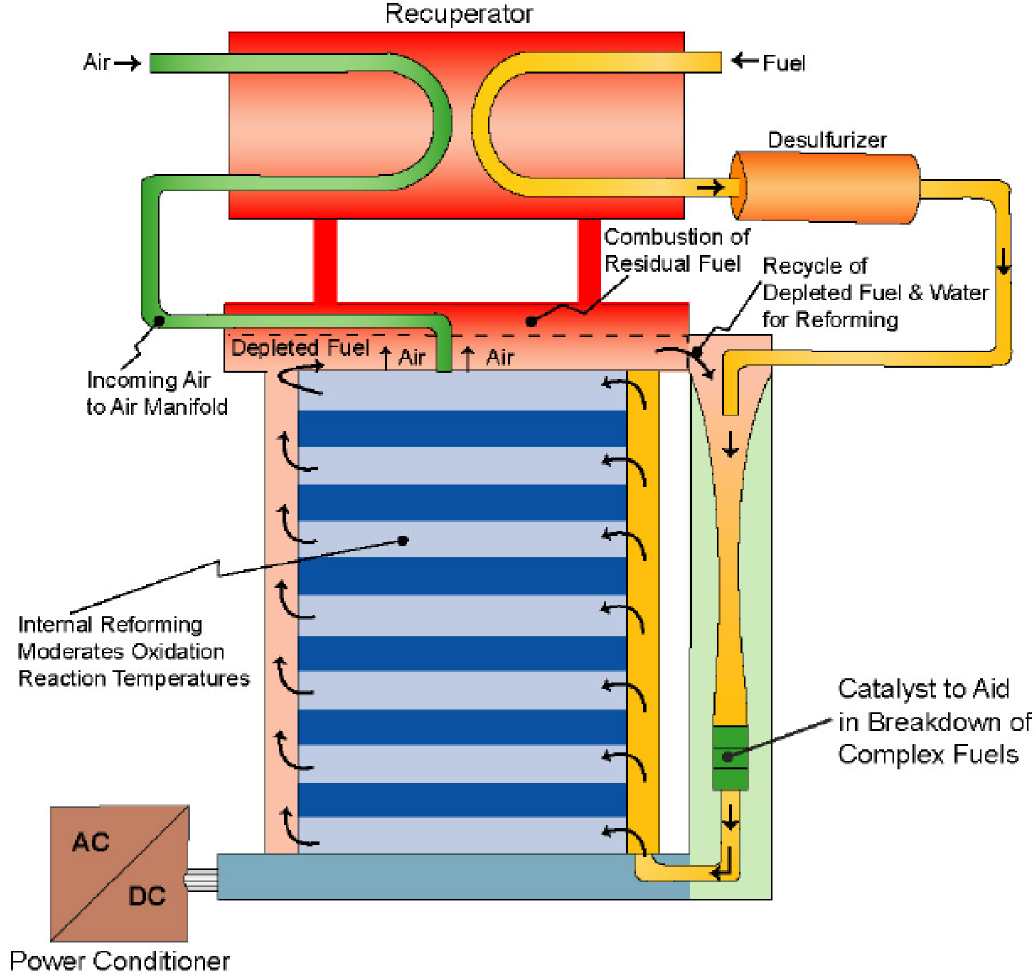


Stationary SOFC BOP

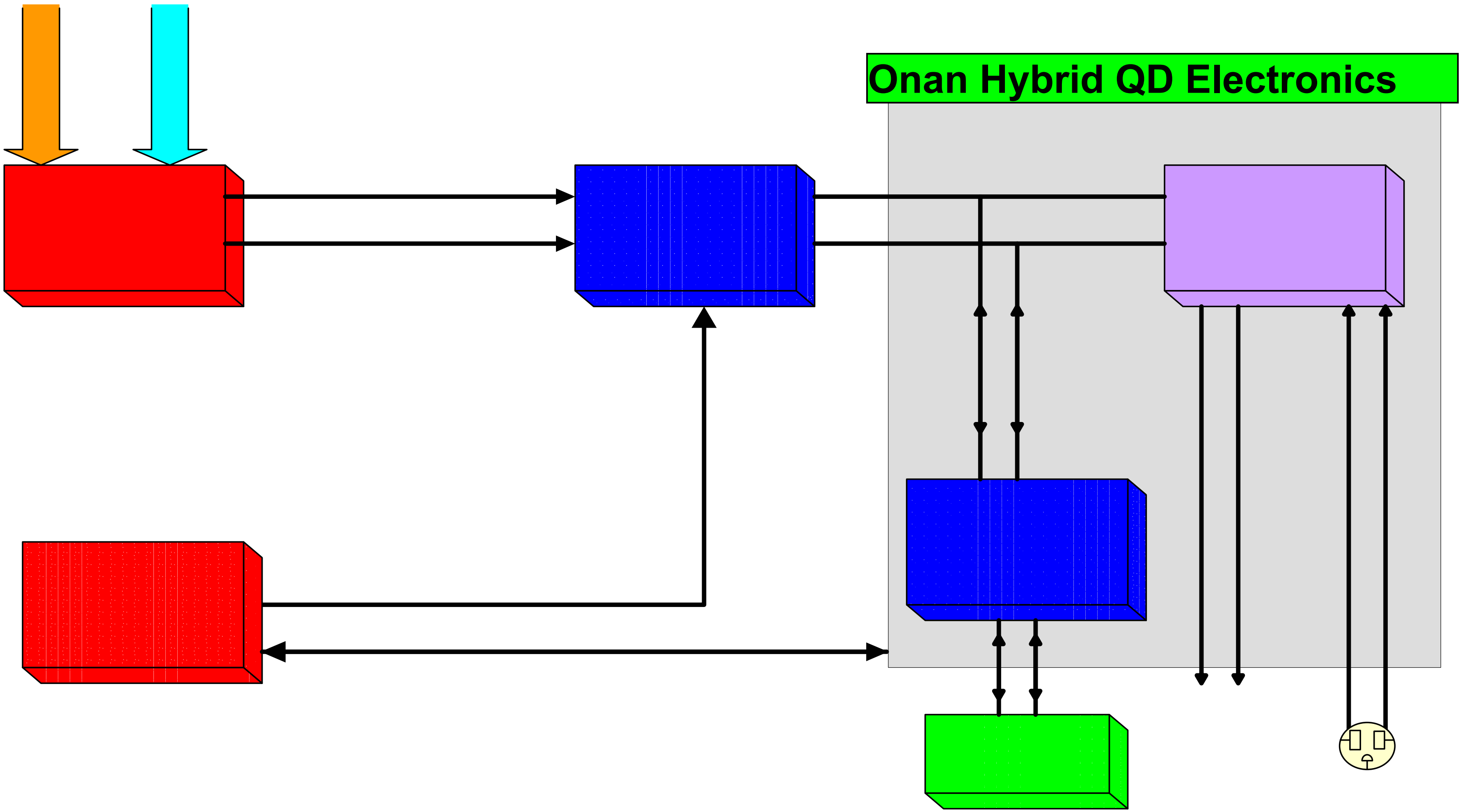


Fuel Cell System

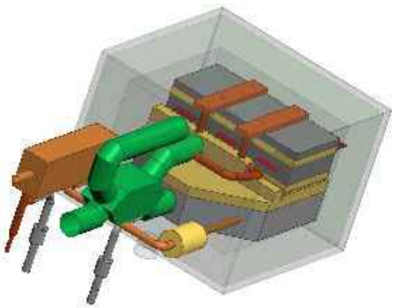
The System PE

- Power Electronics
  - Load management
    - Fuel Must Lead ON Load, and Must Lag OFF Load
  - Supply a buffer between required load power and fuel cell dynamics (Fuel processor limits transient performance).
    - Control stack loading to a safe rate.
    - Maintain supplemental energy storage.
      - Battery based hybrid system
    - Generate stable AC power to user.

Fuel Cell Power Electronics



Affordable Hybrid Fuel Cell System



Fuel Cell Module

Packaged System

- Ceramic solid-oxide technology
  - Clean, efficient, silent power
  - 10 kW power system
  - Improved emissions
  - Improved efficiency
  - Maintenance benefits over engine gensets
  - Longer life
  - Lower costs over longer term
- Key Markets
  - RV
  - Commercial mobile
  - Telecommunications standby
  - Distributed Generation
  - Residential

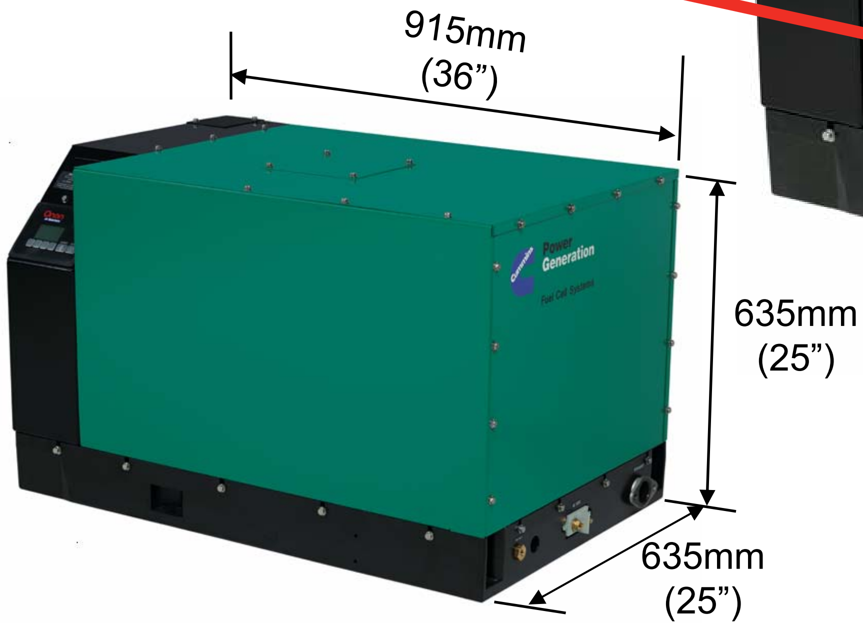
Fuel Cell System Mock-Up

Operator controls

Power Module

Fuel cell boost

BOP Section



Fuel Cell System Components

Display Panel

Inverter / Charger

Power Unit

Transfer Switch

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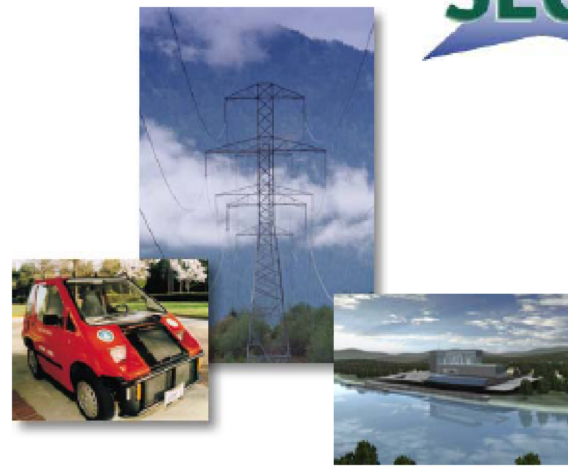
SECA

SECA Applications



2005

- **APU Prototypes (Beta)**
  - Long Haul Trucks)
  - RV's
  - Military
  - Premium Power

2010

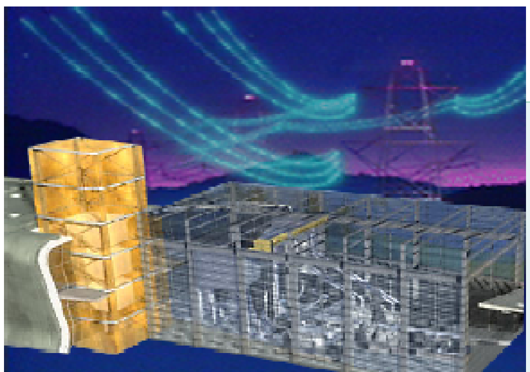
- **$400/kW**
- **Commercial Products**
  - Transportation APUs
  - Residential & Industrial CHP

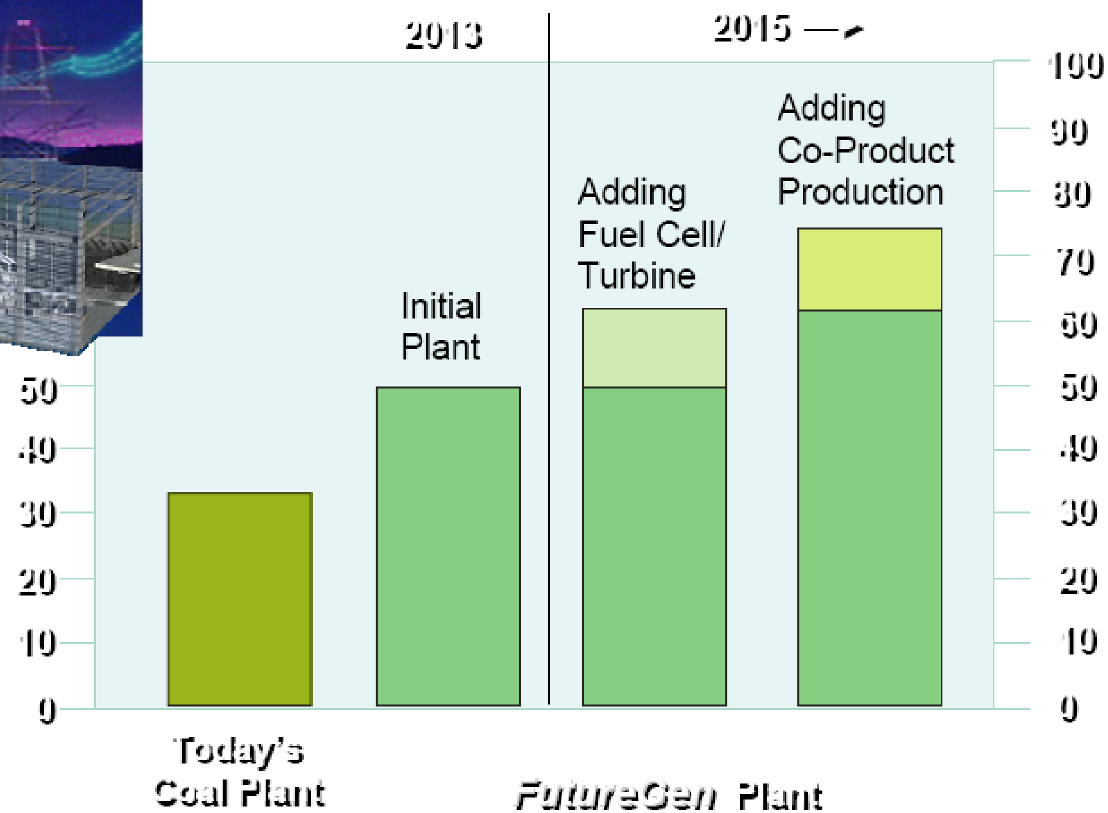
2015

- **$400/kW**
- **Hybrid Systems**
  - 60-70% efficient
- **Vision 21 Power Modules**

FutureGen

The World's Most Energy-Efficient Power Plant

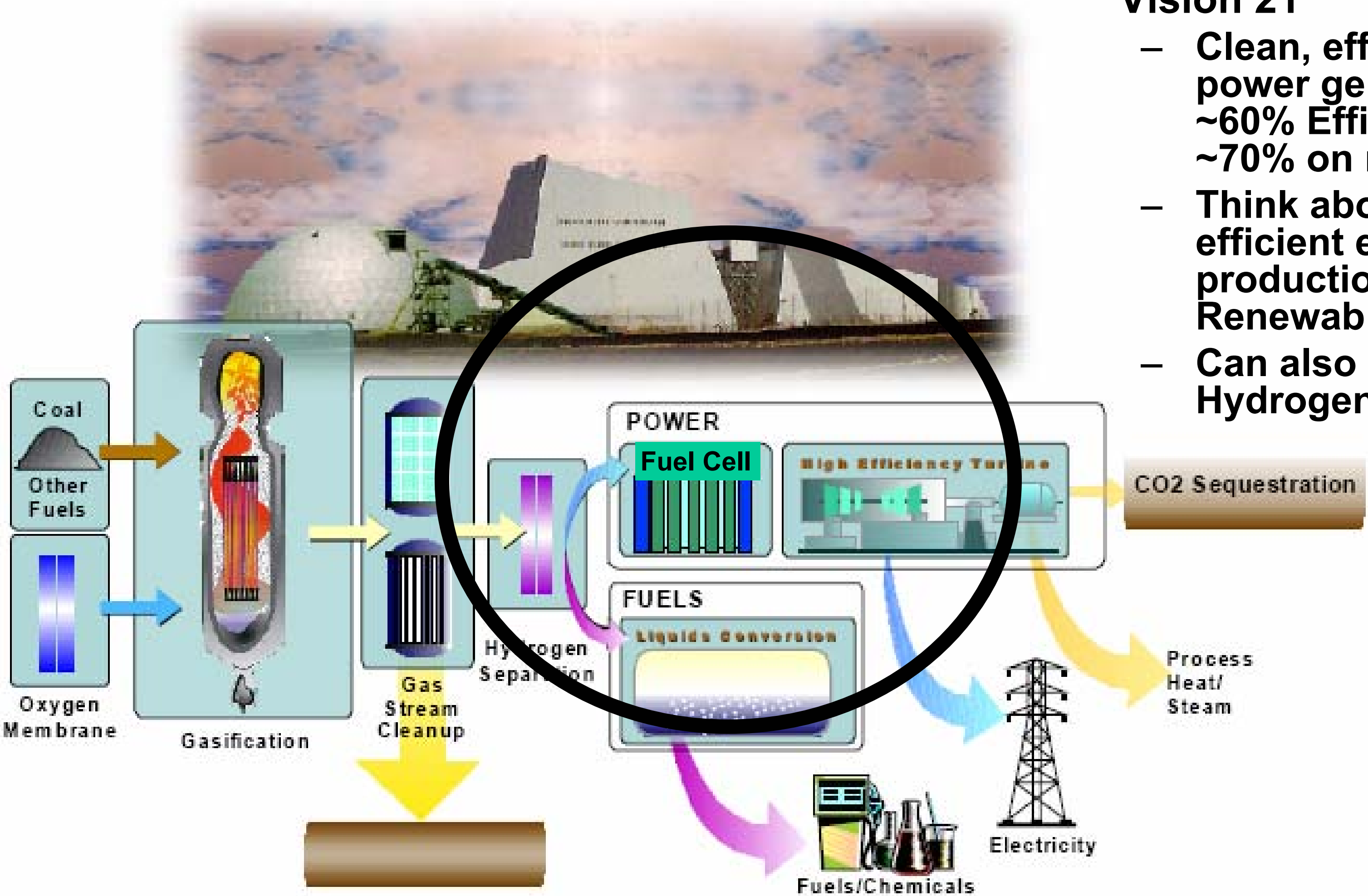




Boosting power plant efficiencies is first step toward reducing greenhouse gases

Ultimate Goal of SECA Clean Coal and/or Clean Renewables

- SECA is a vital part of the DOE's ultimate goal, called Vision 21
  - Clean, efficient electric power generation with ~60% Efficiency on coal ~70% on natural gas 2015.
  - Think about it, ~60% efficient electric power production on Coal or Renewable Bio-Fuels!
  - Can also include Hydrogen separation.



100 - 450 MW Central Power Stations -Near Zero Emission

Mature SECA Fuel Cell Systems Cost and Performance Goals

	Fuel Cell System	Fuel Cell Turbine Hybrid System
Capital Costs	<$400/kW	<$400/kW (includes turbine)
Maintenance Interval	3000 hrs.	3000 hrs.
Full Load Electrical Efficiency (LHV)	50% APU 60% stationary	60-70% adaptable to coal gas
Design Life	5000 hrs. APU 40,000 hrs. stationary	40,000 hrs.
Emissions of criteria pollutants	Near zero	Near zero