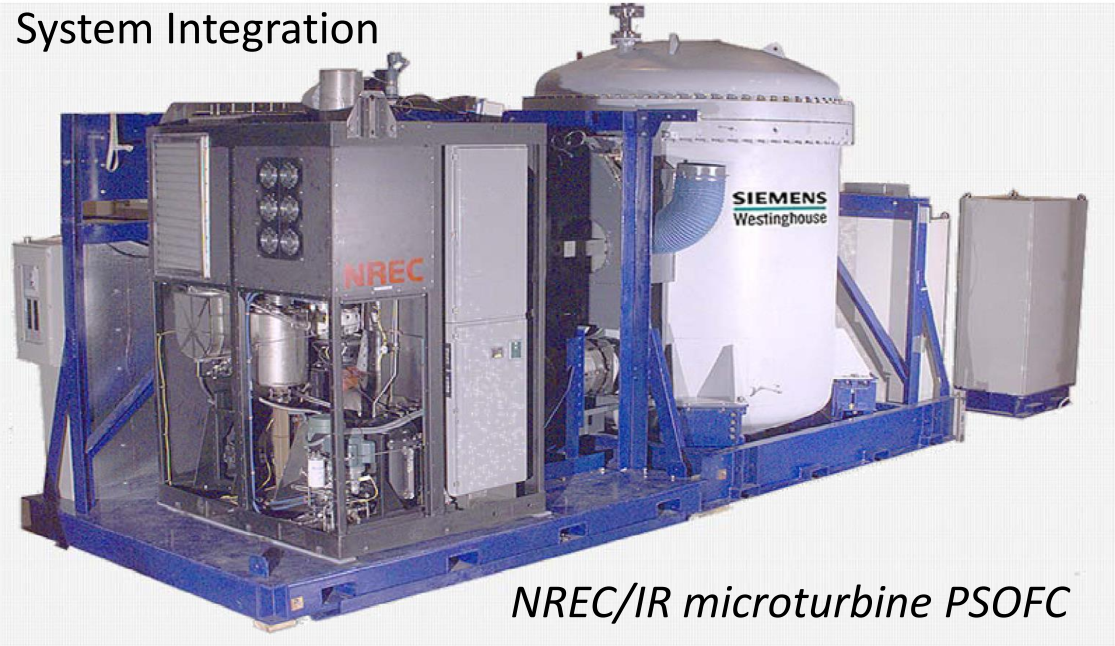
ARPA-E HYBRID SYSTEMS WORKSHOP

JANUARY 26-27, 2017

By Jim Kesseli kesseli@BraytonEnergy.com

Brayton Energy: Fuel Cell History

System Integration



NREC/IR microturbine PSOFC

Gas Turbine Design and Manufacturing

Compact Heat Exchanger Design and Manufacturing

Brayton Energy Advanced Hybrid Fuel Cell Project with Siemens & Arctic Research/NETL/CTC (2004-2007)

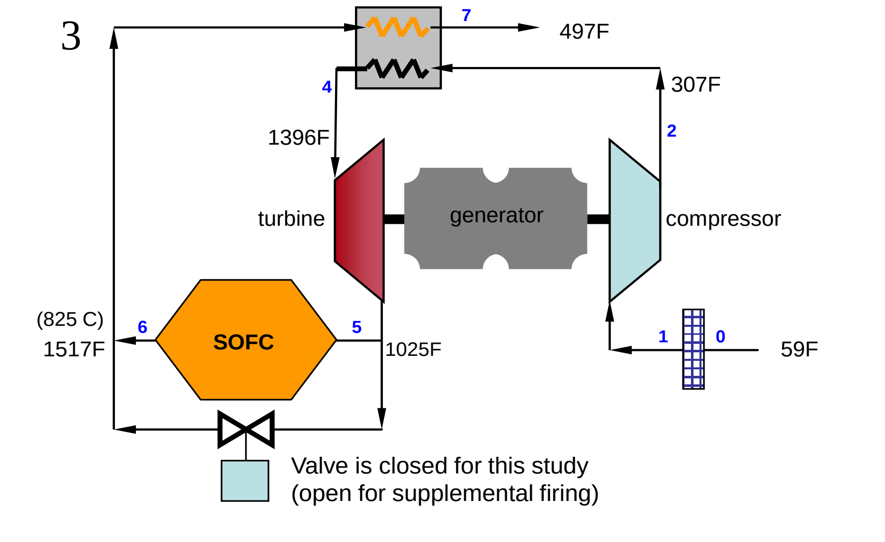
1. Detailed system performance modeling, optimization, and LCOE
   - Systematic Trades studies focused on lowering the cost of fuel cell systems.
   - 6 cycles analyzed 2 MSFC 4 SOFC

•***SOFC Hybrids showed the most potential***

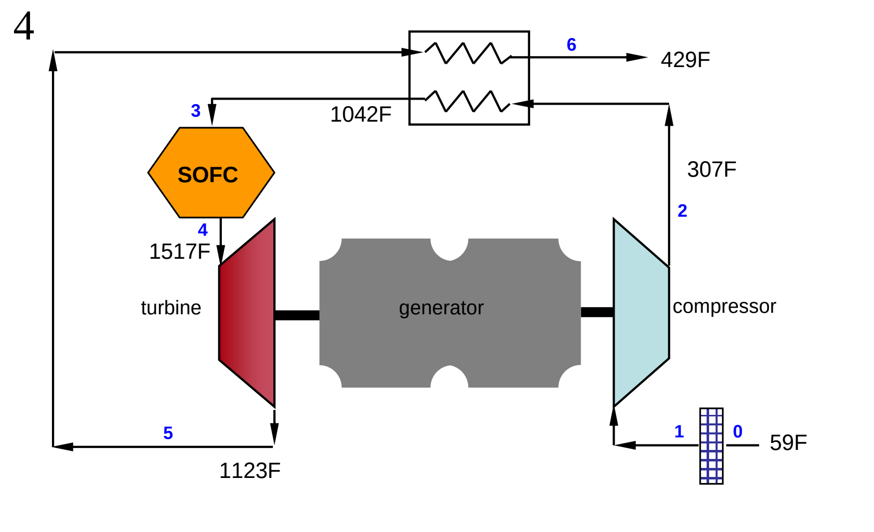
(lowest LCOE, highest efficiency)

2. Design of compact 850C heat exchangers

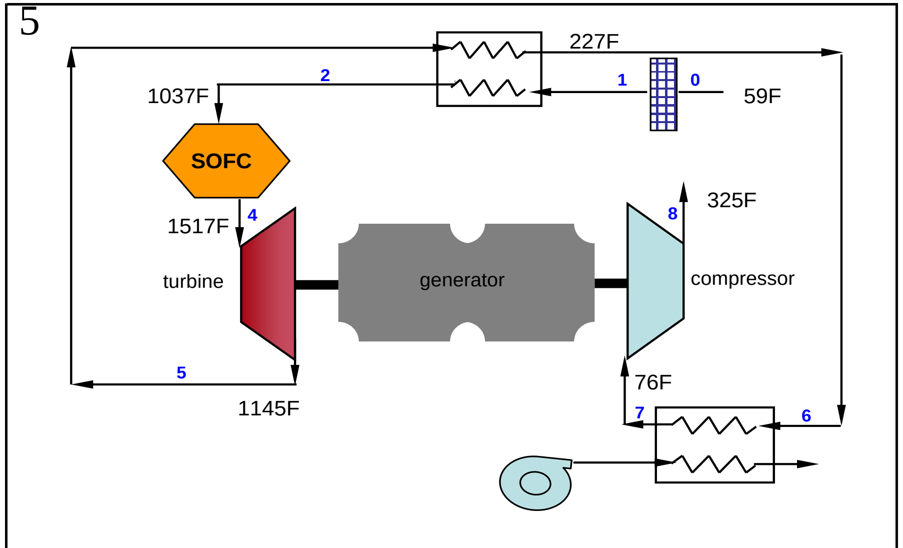
Four SOFC Hybrids Analyzed for Siemens-Westinghouse Arctic Energy Lab at U. Alaska



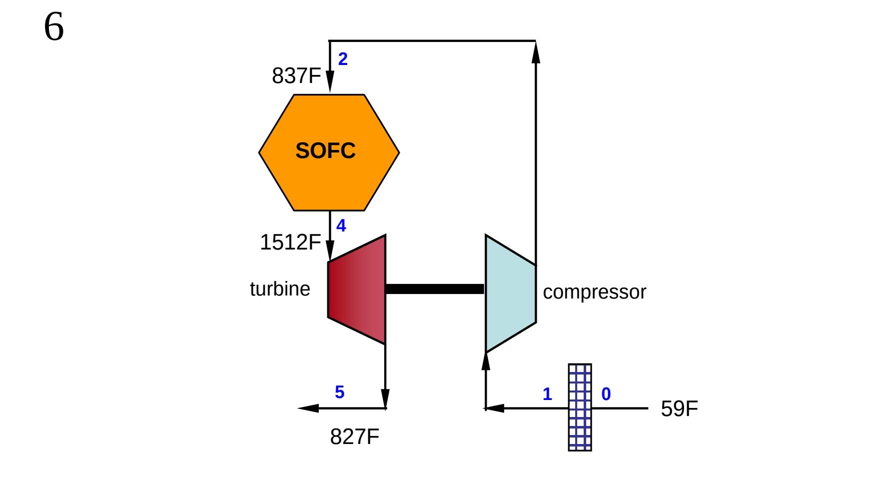
Unpressurized SOFC / Indirect-Fired Turbine



Pressurized SOFC



Unpressurized SOFC / Subatmospheric Turbine



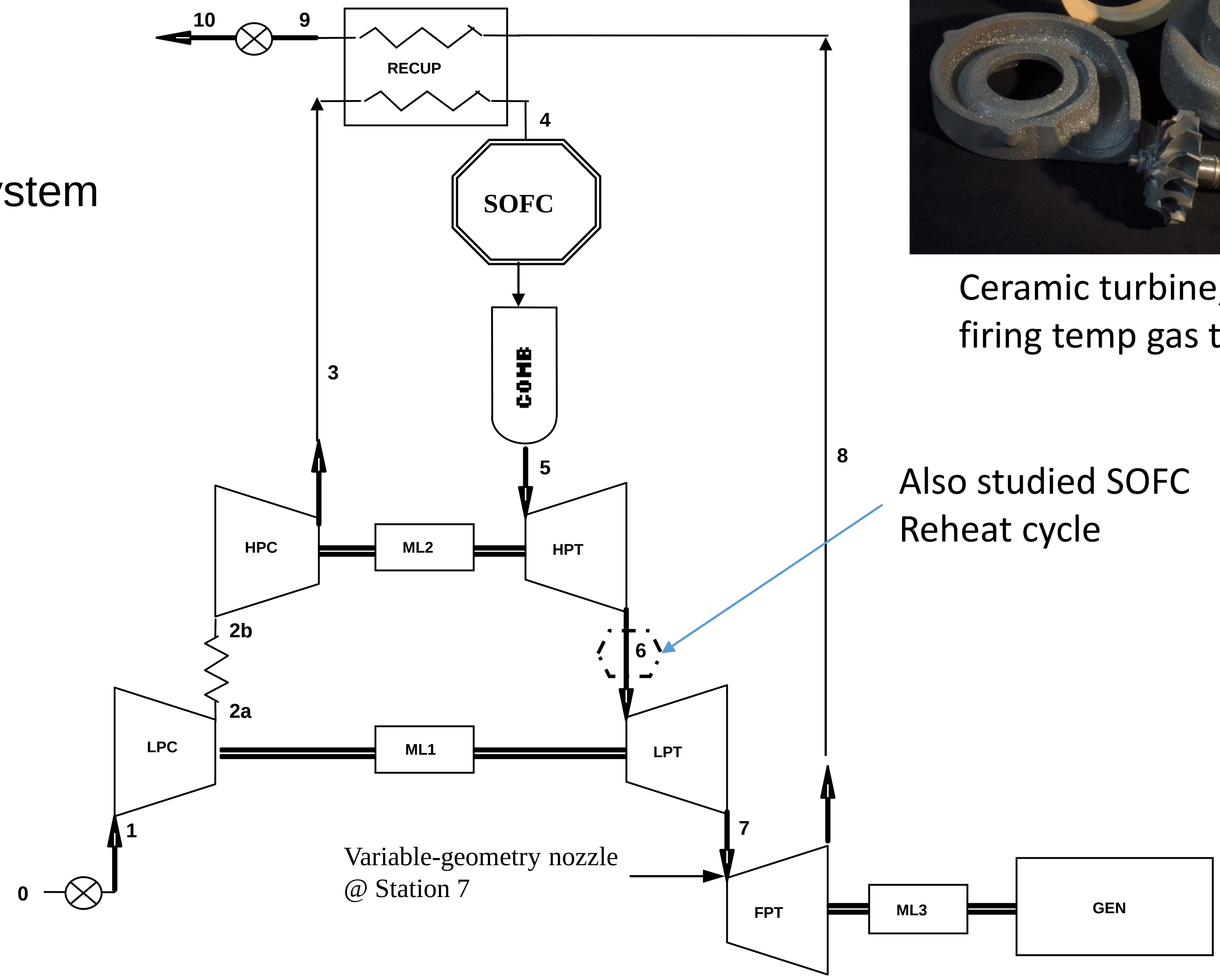
Turbocharged SOFC

Schematic for Proposed Intercooled Recuperated (ICR) Cycle Hybrid co-fired PSOFC

Three degree of freedom system

1. Fuel throttle
2. VAN
3. PT speed

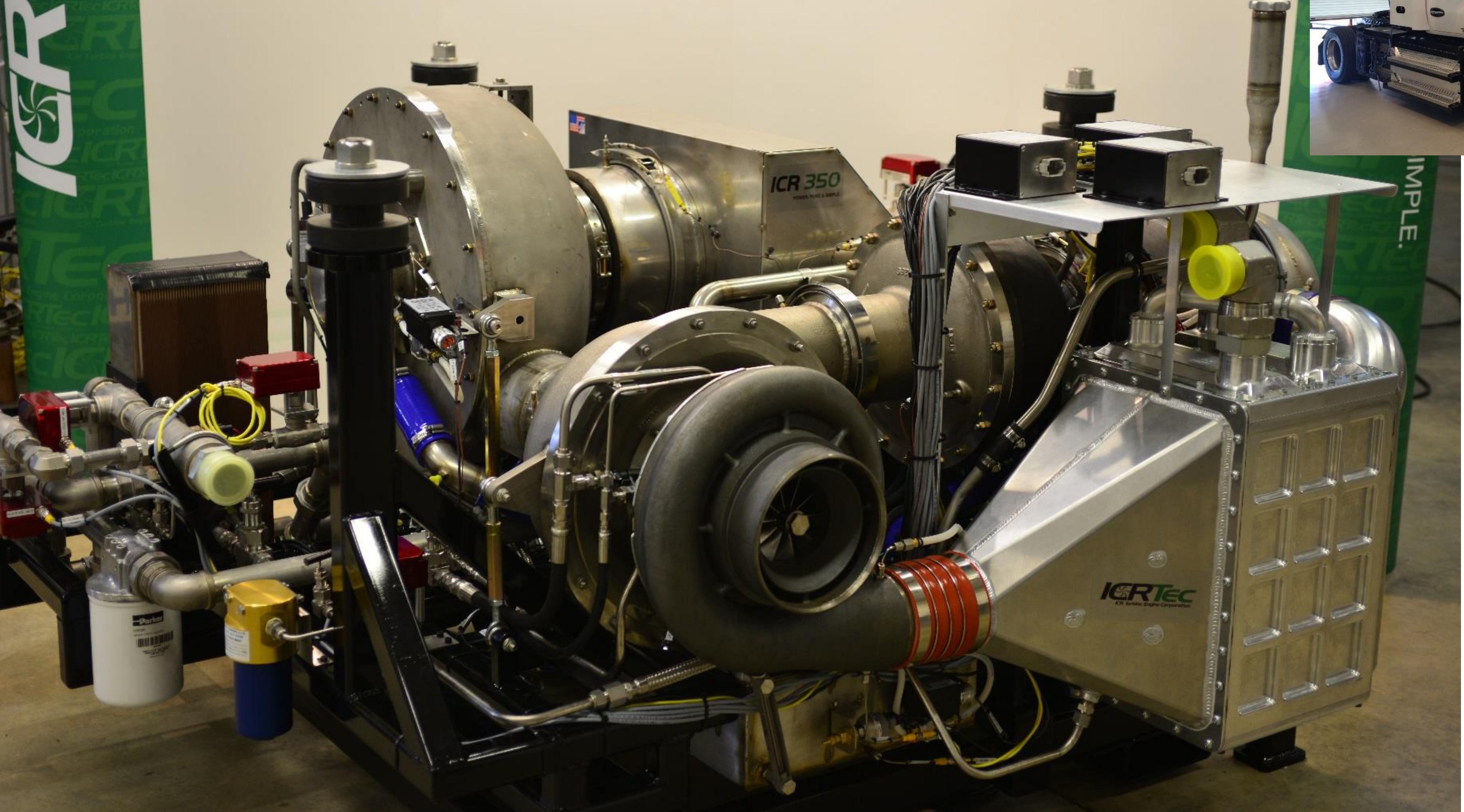
- Operate without combustor firing, for best efficiency, low power.
- Co-fire combustor to magnify power, load follow, and improved economics



Also studied SOFC Reheat cycle

Ceramic turbine, high firing temp gas turbine

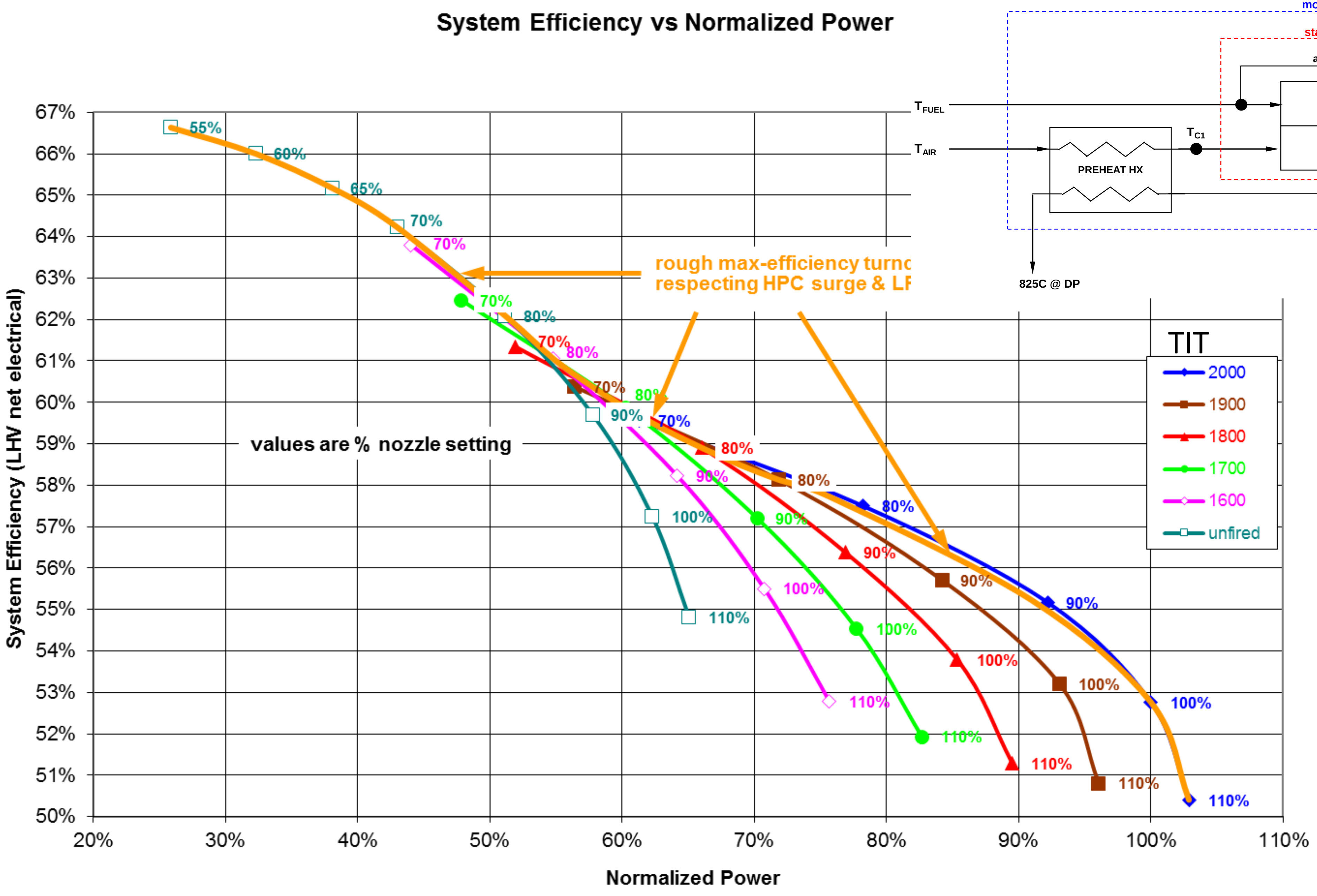
ICR350 – Vehicular and stationary gas turbine

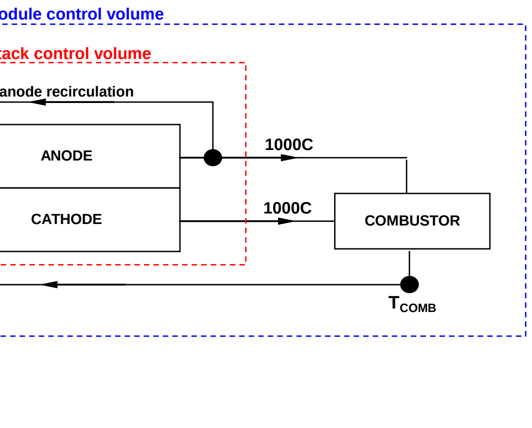


Peak electrical efficiency 42%, fired at 1100 C, 2000F

This ICR engine formed the basis for hybrid SOFC modeling.

SOFC Idealized Thermal Model



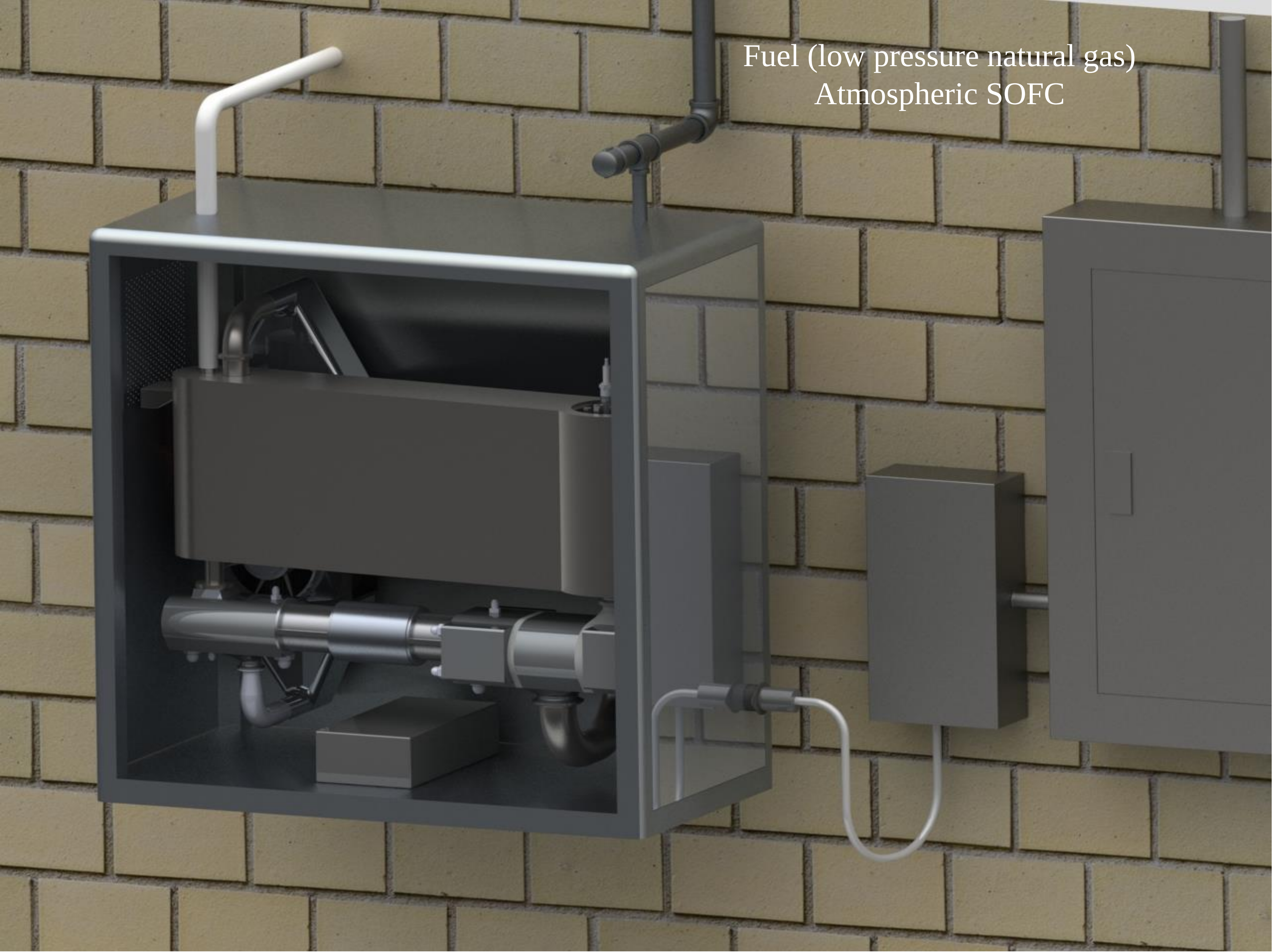


Summary of Fired/Unfired Operating Parameters

	fired	unfired	
TIT	2000F	1567F	
Nozzle Setting	100%	70%	
Airflow (kg/s)	0.83	0.31	
PR_{STACK}	14.3	5.2	
Engine Power (kWe)	248.3	46.8	(531%)
SOFC Power (kWe)	197.6	149.1	(133%)
SOFC Effy (LHV)	36.8%	48.9%	
System Power (kWe)	445.9	195.9	(228%)
System Effy (LHV)	52.8%	64.2%	
Cell Voltage (V)	0.500	0.664	

Normalized costs:	Hybrid PSOFC at 700ma/cm2	Std atm. SOFC at 400ma/cm2
SOFC $/kW	3429	6000
ICR GT $/kW	500	
Net $/kWe	**1798**	
Power density, ma/cm2	700	400

note: SOFC power & efficiency are net electric after 90% inverter



GENSET: 4 to 10 kWe Hybrid SOFC

- Residential net metering power
- $\eta e \sim 66\%$
- $\eta_{chp} = 84\%$ (1 kW-thermal)

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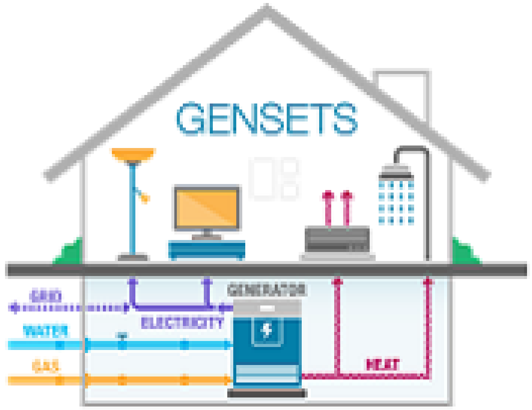
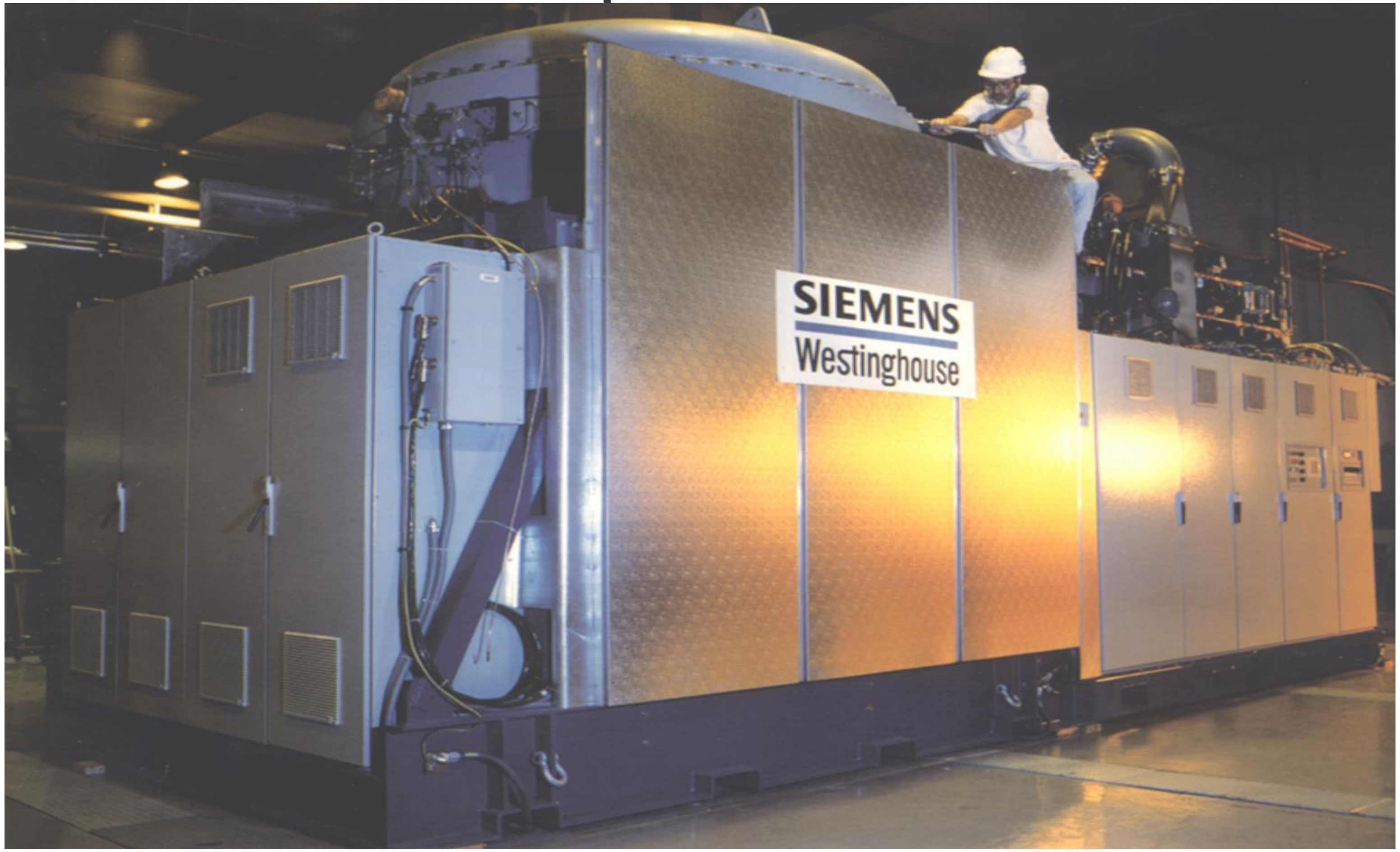


Siemens Westinghouse SOFC Hybrid (220 Kwe)



Courtesy Siemens Stationary Fuel Cells

Siemens Westinghouse SOFC Hybrid System

Successes

- World's first demonstration of a Fuel Cell/Micro Turbine Generator hybrid power system
- Successfully demonstrated startup-stable operation, and orderly shutdown
- ~3,000 hrs operation
- Electrical efficiency ~53% LHV (Potential for higher system efficiency)
- Reduced emissions (NOx and SOx)

Challenges

- Complex Balance-of-plant
- Turbine airflow match/mismatch with Fuel Cell requirements
- Low turbine inlet temperature
- Higher capital cost
- Operational complexity (higher risk to damage the fuel cell stack)

Dynamics of Hybrid Fuel Cell Systems

for: ARPA-E Workshop, Washington DC

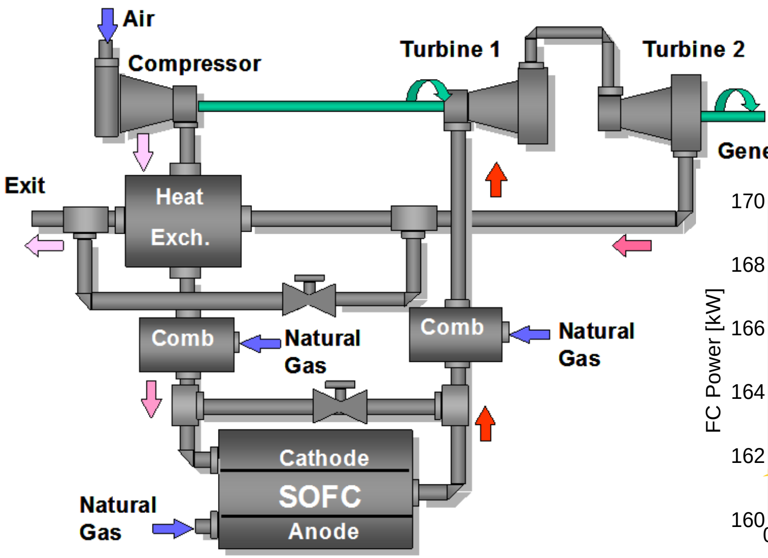
ADVANCED POWER & ENERGY PROGRAM
UNIVERSITY of CALIFORNIA • IRVINE

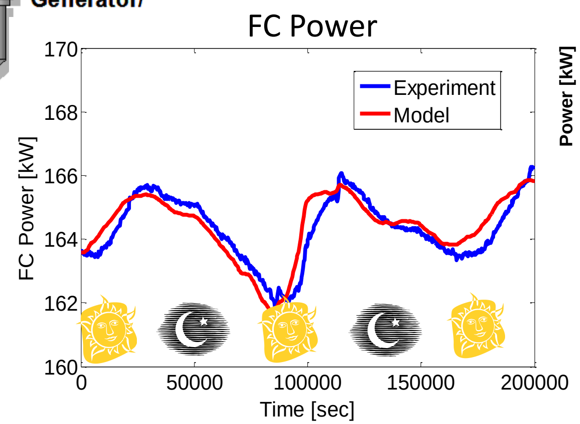
NFCRC
National Fuel Cell Research Center
UCIrvine | UNIVERSITY OF CALIFORNIA

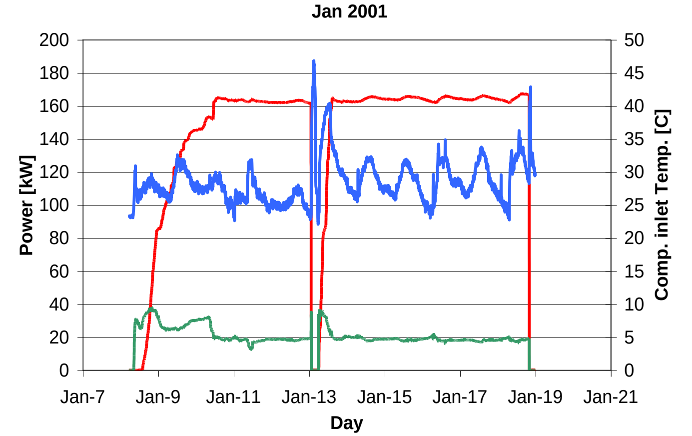
Jack Brouwer, Ph.D.
Associate Director

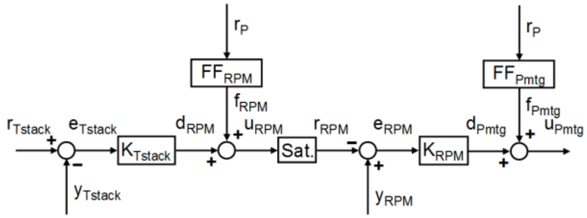
2017

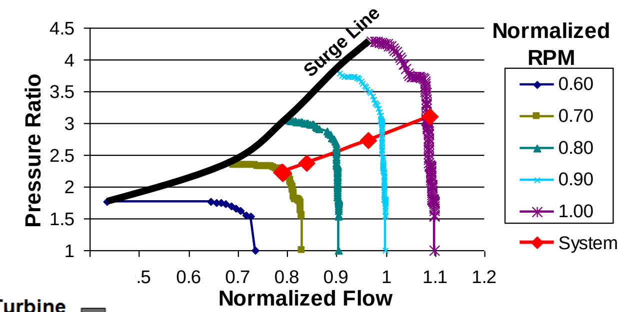
Integrated Fuel Cell System Dynamics

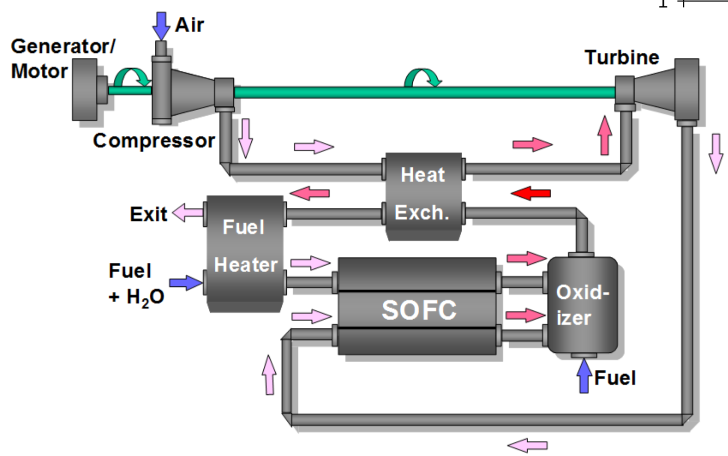




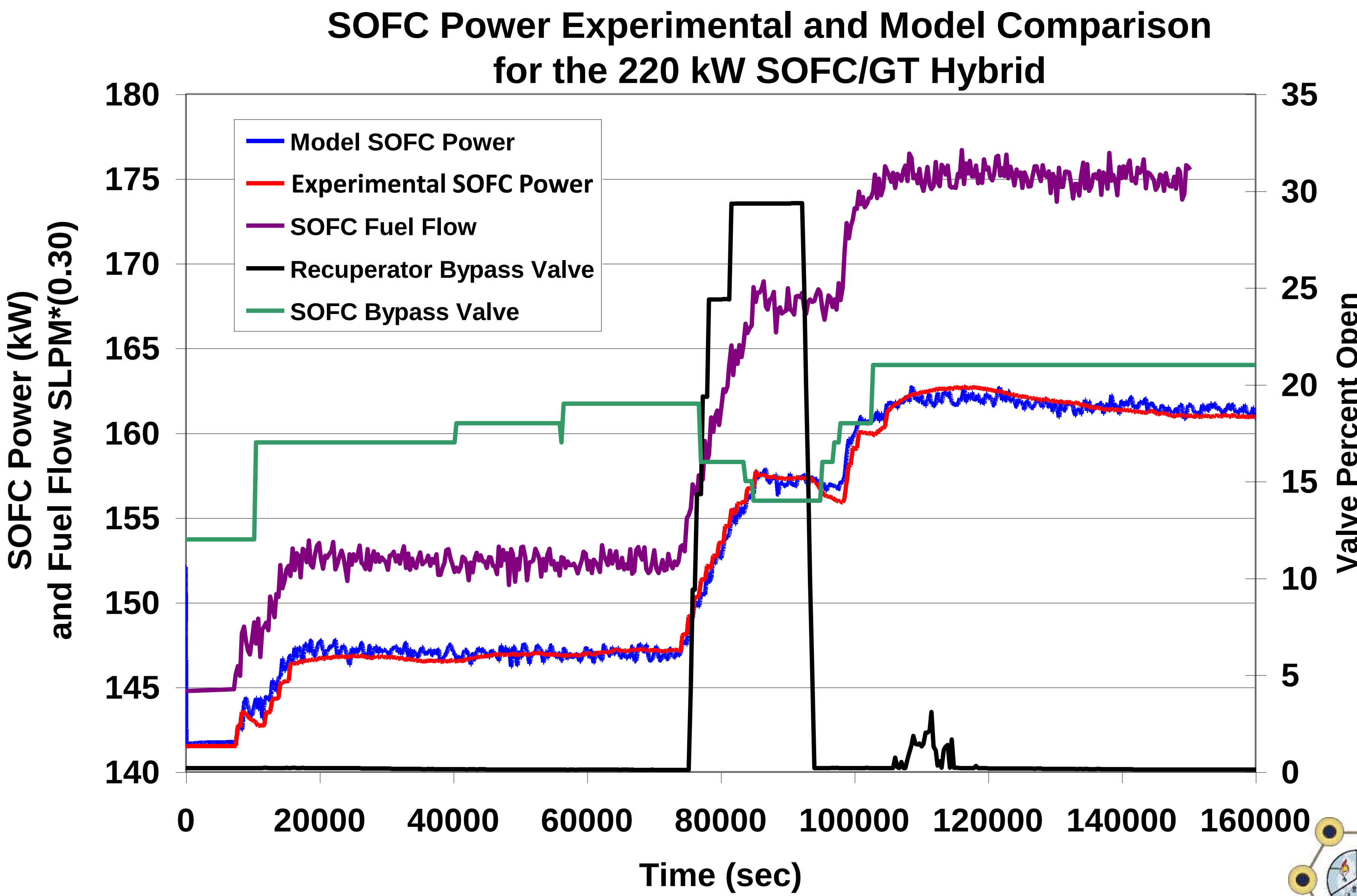






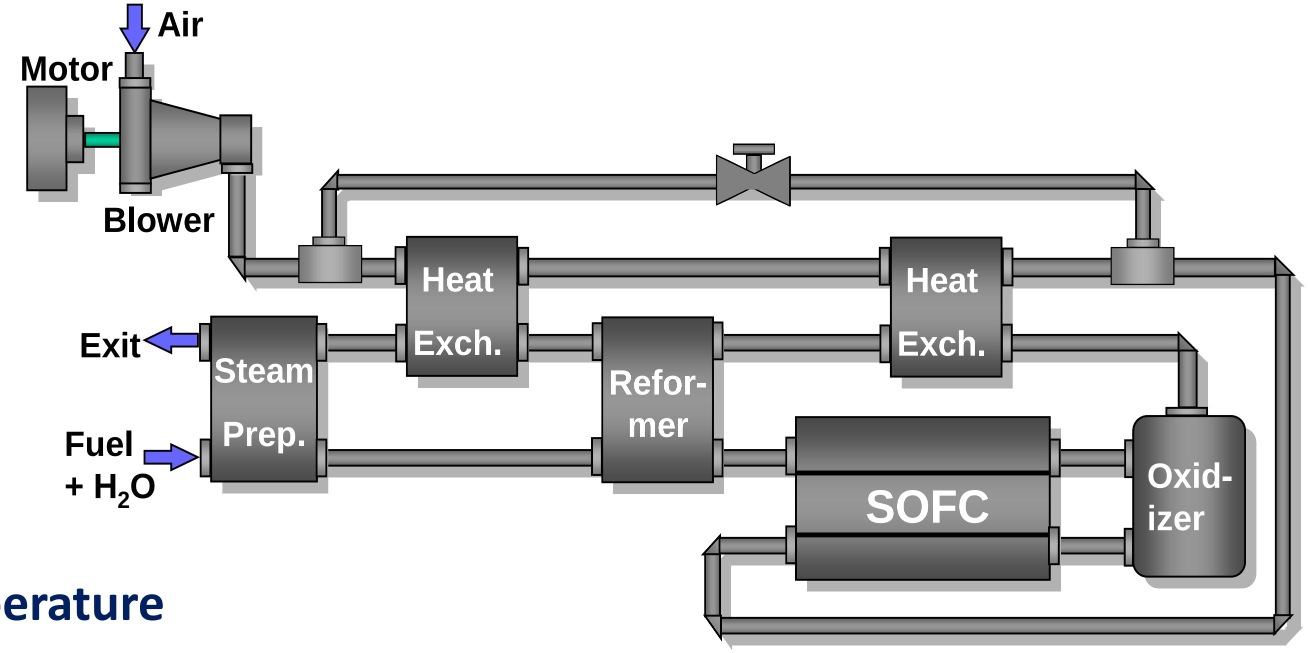


Dynamic Simulation: 220kW SOFC/GT System



How Can We Do It?

Integrated Stand-Alone SOFC system



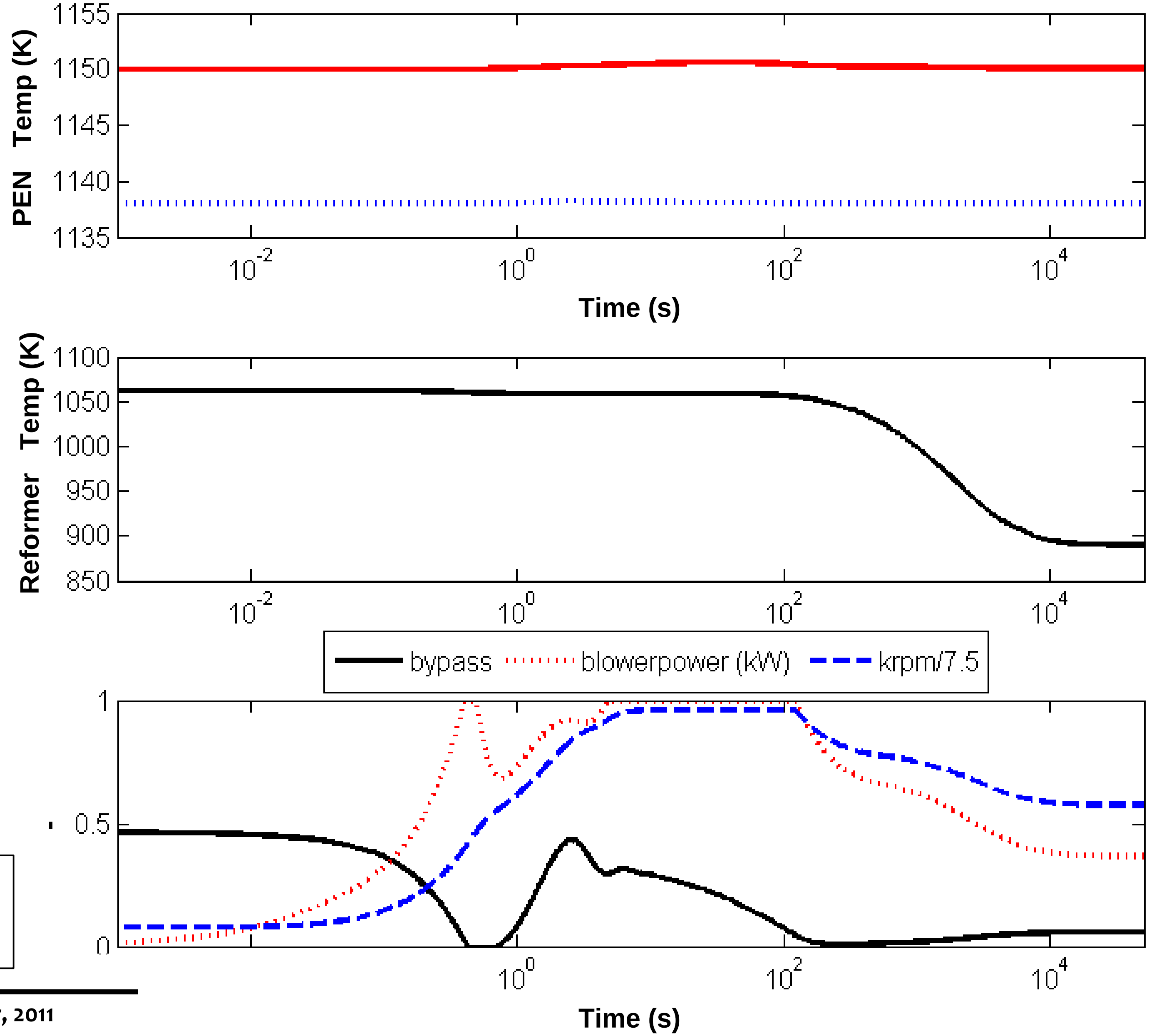
- **Manipulate:**
  - Fuel flow
  - Blower power
  - Bypass valve
- **Control:**
  - System power
  - Peak SOFC temperature
  - SOFC temperature profile
- **Perturbation:**
  - 25 to 70 amp current increase with PEN temperature feedback

Mueller, F., Jabbari, F., Brouwer, J., Journal of Power Sources, Vol. 187, Iss. 2, pp. 452-460, 2009

How Can We Do It?

Integrated SOFC system

25 to 70 amp current increase perturbation

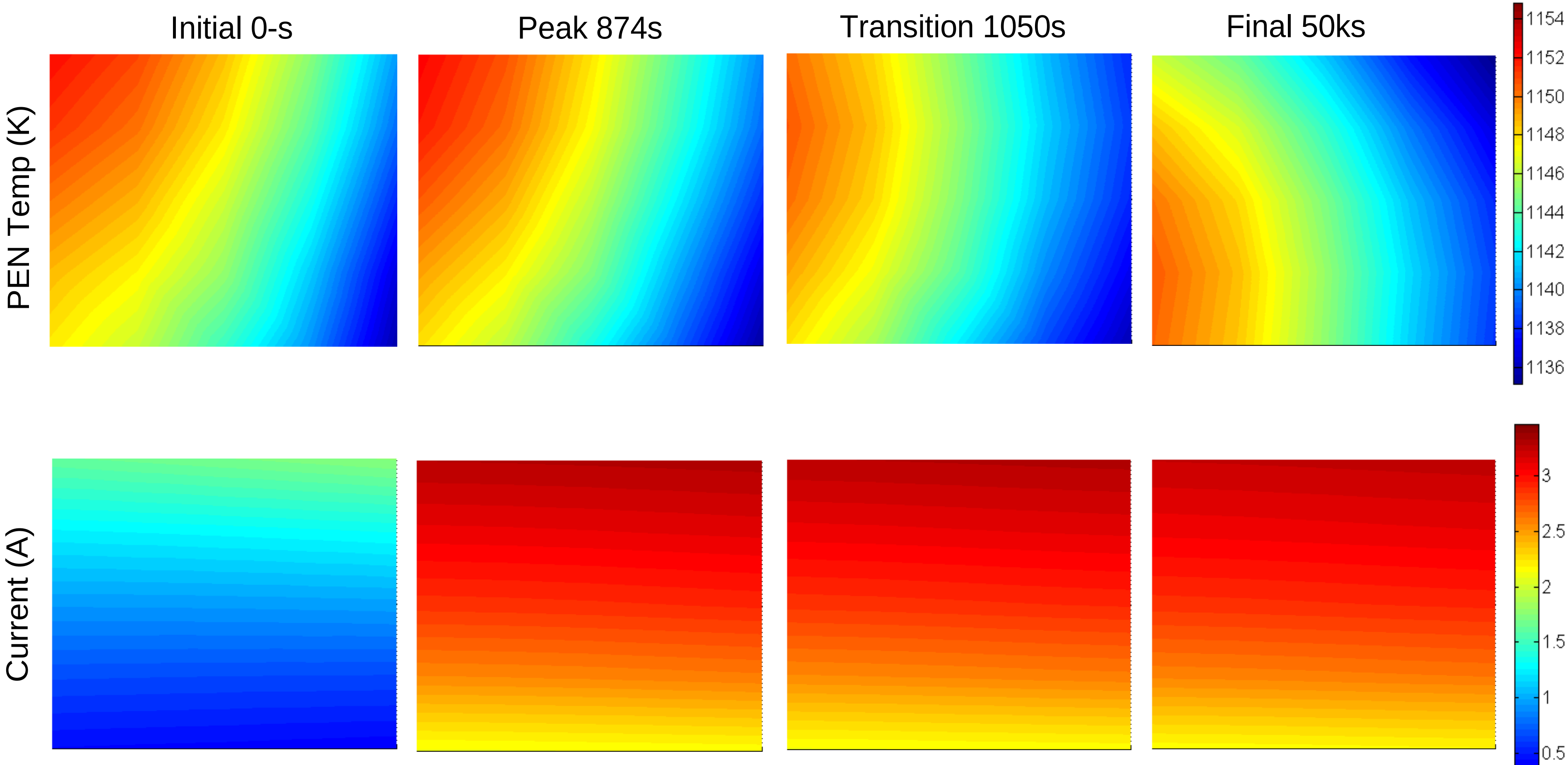


Control actions:

Mueller, F., Jabbari, F., Brouwer, J., Journal of Power Sources, Vol. 187, Iss. 2, pp. 452-460, 2009

How Can We Do It?

Integrated SOFC system - 25 to 70 amp current increase with PEN temperature feedback

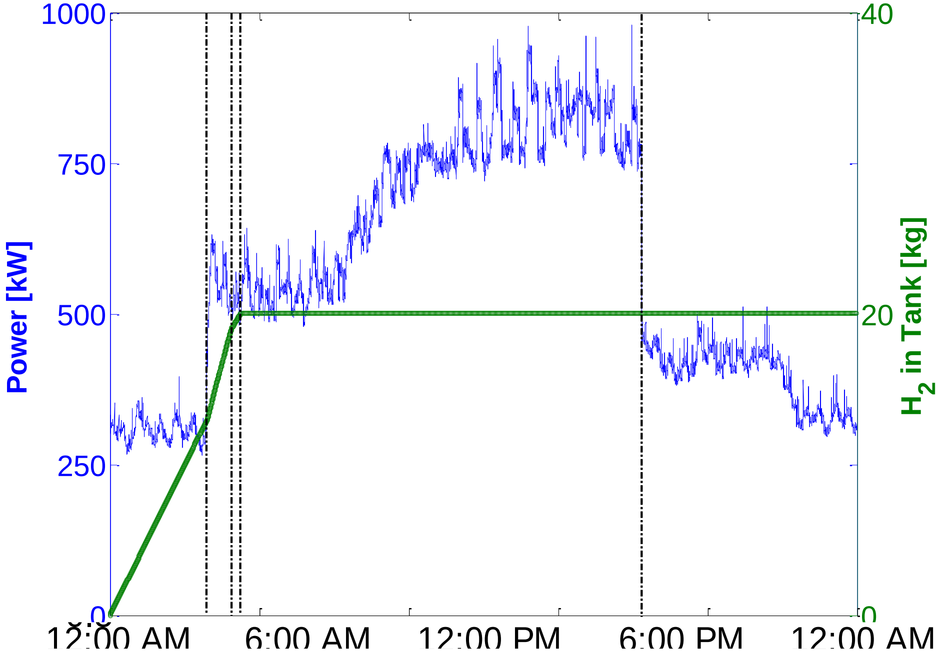


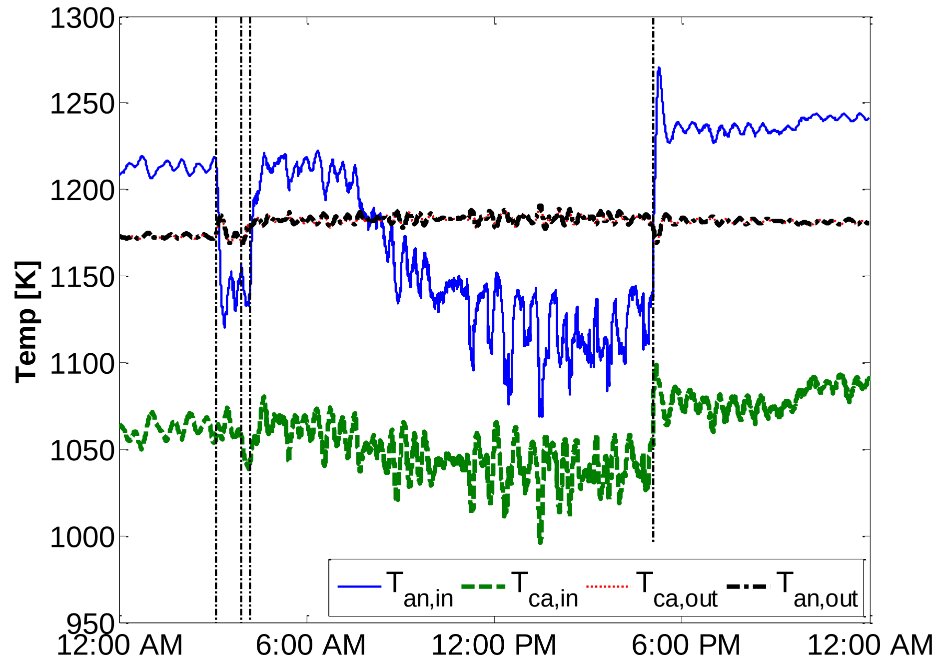
Mueller, F., Jabbari, F., Brouwer, J., Journal of Power Sources, Vol. 187, Iss. 2, pp. 452-460, 2009

Dynamic Poly-Generation Analyses

Can a Tri-Generation System Respond to Fueling, Full Tank?

- **Diurnal dynamic operation of SOFC**
- **Hydrogen tank fills forcing end of tri-generation**
- **Control of system temperatures during transient is possible**

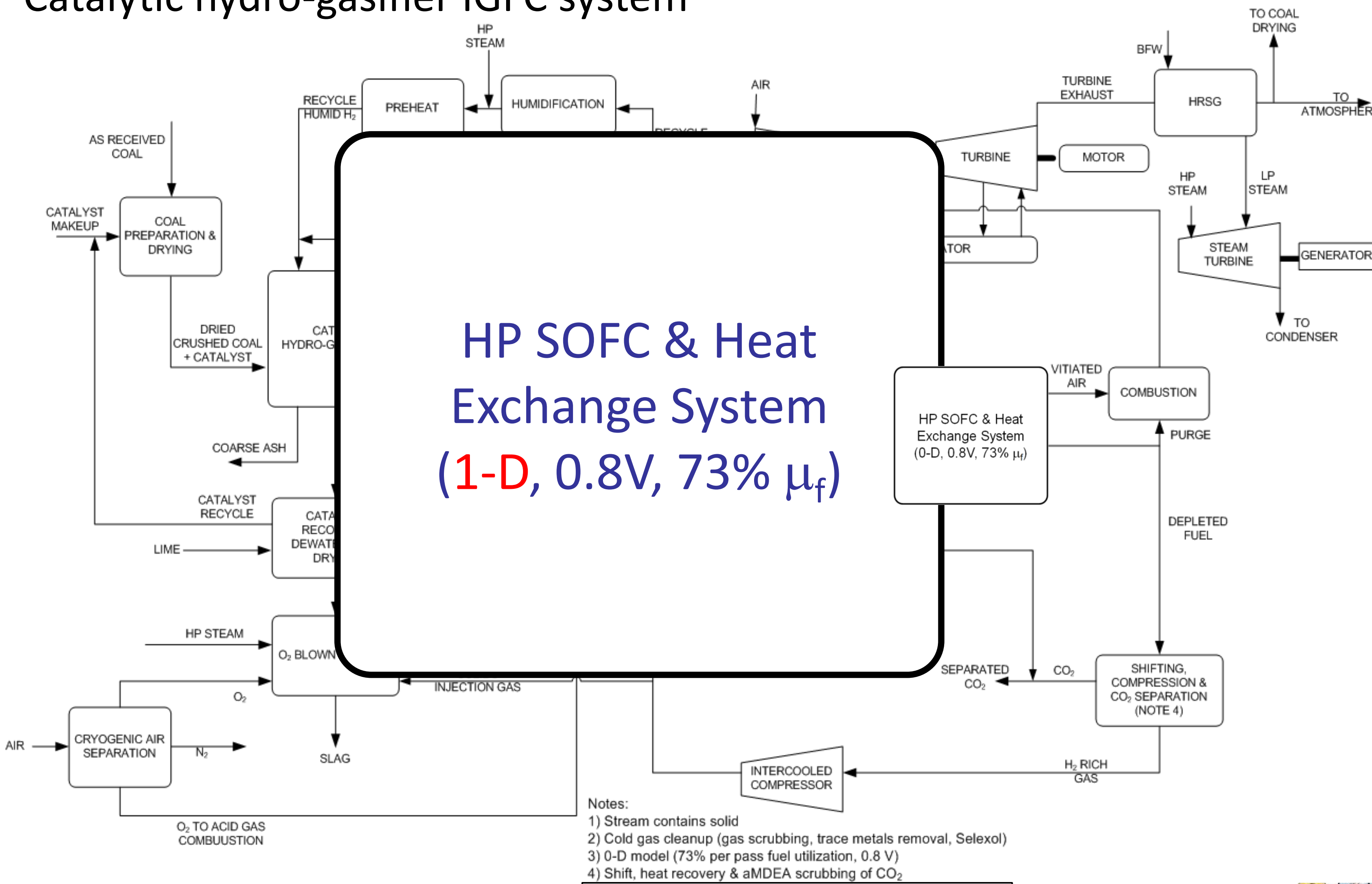




Shaffer, B.P, and Brouwer, J. J. Fuel Cell Sci. Technol., Vol 9, p. 041012 ff., 2012

1-D Model Integration into Systems Analysis

Catalytic hydro-gasifier IGFC system



Li, et al., Journal of Power Sources, Vol. 195, Iss. 17, pp. 5707-5718, 2010.

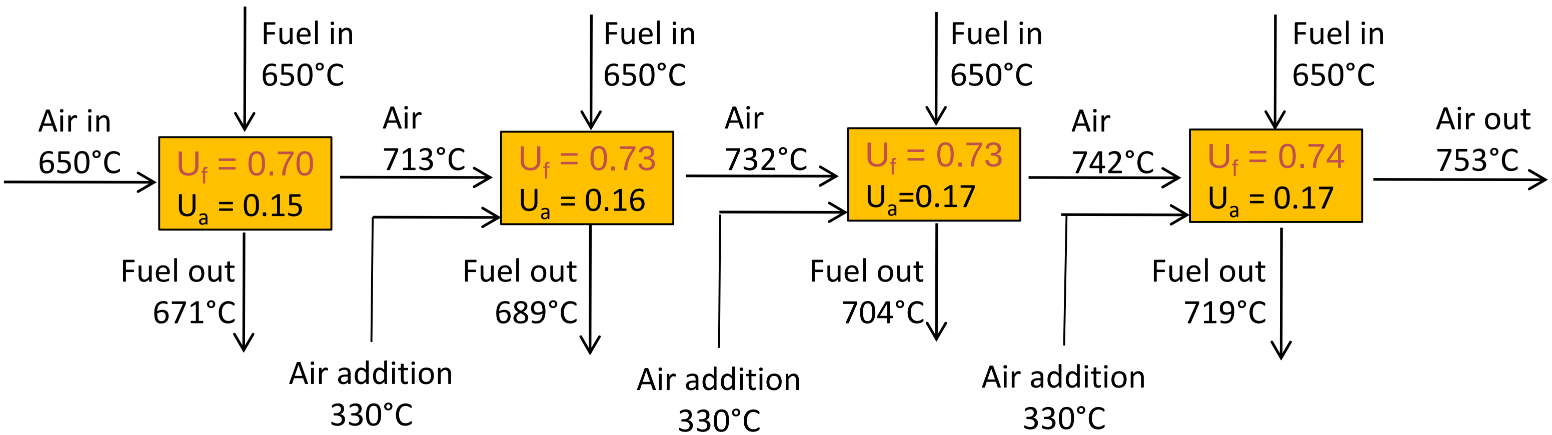
IGFC Performance Comparison

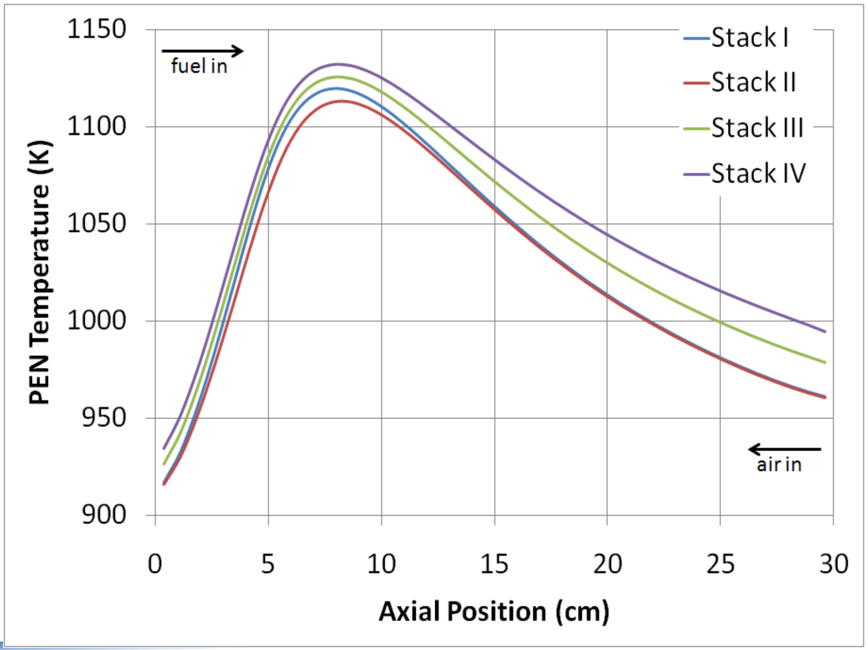
Item	0-D Model	1-D Single Stage Counter-flow SOFC
Coal energy input	1,397 GJ/h (HHV)	1,397 GJ/h (HHV)
SOFC operation pressure	10 atm	10 atm
Gross power output		
SOFC electrical power	247.8 MW	247.3 MW
Cathode exhaust expander	63.4 MW	178.6 MW ↑
Steam turbine	2.6 MW	1.9 MW
Syngas reactor/expander topping cycle	9.3 MW	7.6 MW
Total gross power generated	323.3 MW	435.6 MW ↑
Auxiliary power consumption (incomplete list)		
ASU	2,186 kW	2,186 kW
SOFC air compressor/blower	66,906 kW	242,499 kW ↑↑↑
Recycled H_2 compressor	8,235 kW	8,283 kW
Total internal power consumption and losses	84.7 MW	260.5 MW ↑↑↑
Net electric power	238.6 MW	175.1 MW ↓↓↓
Overall thermal efficiency	61.5% (HHV)	45.1% (HHV) ↓↓↓

Li, M., Rao, A.D., Brouwer, J., and Samuelsen, Journal of Power Sources, Vol.195, Iss. 17, pp. 5707-5718, 2010.

Strategy for Mitigating High DT Challenge

- **Cascade SOFC stacks**





Overall
U_f = 0.727
U_a = 0.455

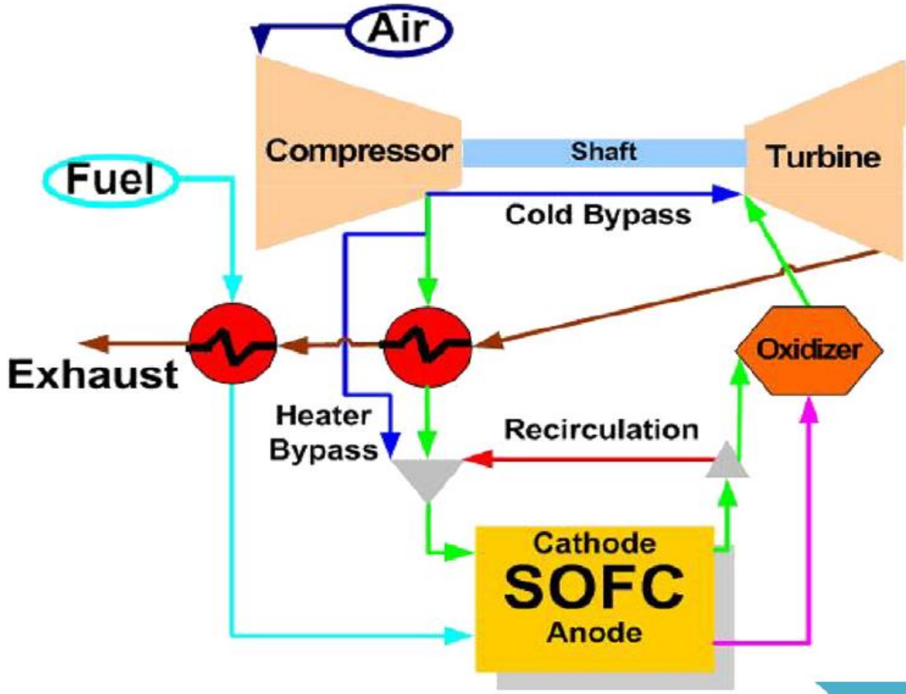
Li, M., Rao, A.D., Brouwer, J., and Samuelsen, Journal of Power Sources, Vol.195, Iss. 17, pp. 5707-5718, 2010.

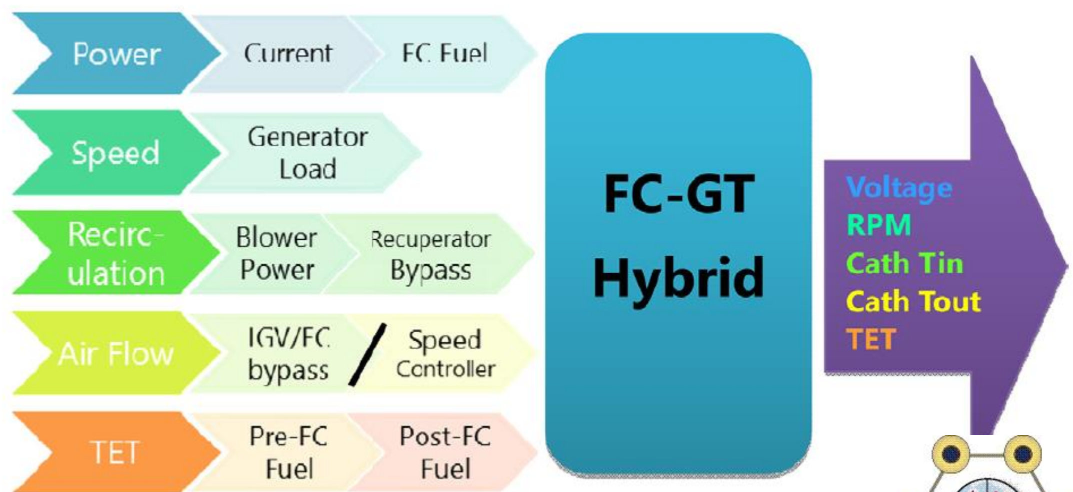
IGFC Performance Comparison

Item	0-D Model	1-D Cascading Counter-flow SOFCs
Coal energy input	1,397 GJ/h (HHV)	1,397 GJ/h (HHV)
SOFC operation pressure	10 atm	10 atm
Gross power output		
SOFC electrical power	247.8 MW	247.8 MW
Cathode exhaust expander	63.4 MW	72.1 MW ↑
Steam turbine	2.6 MW	2.7 MW
Syngas reactor/expander topping cycle	9.3 MW	7.6 MW
Total gross power generated	323.3 MW	330.4 MW ↑
Auxiliary power consumption (incomplete list)		
ASU	2,186 kW	2,186 kW
SOFC air compressor/blower	66,906 kW	84,748 kW ↑
Recycled H_2 compressor	8,235 kW	9,792 kW ↑
Total internal power consumption and losses	84.7 MW	104.3 MW ↑
Net electric power	238.6 MW	226.1 MW ↓
Overall thermal efficiency	61.5% (HHV)	58.2% (HHV) ↓

Li, M., Rao, A.D., Brouwer, J., and Samuelsen, Journal of Power Sources, Vol.195, Iss. 17, pp. 5707-5718, 2010.

Dynamics to Complement Loads/Renewables

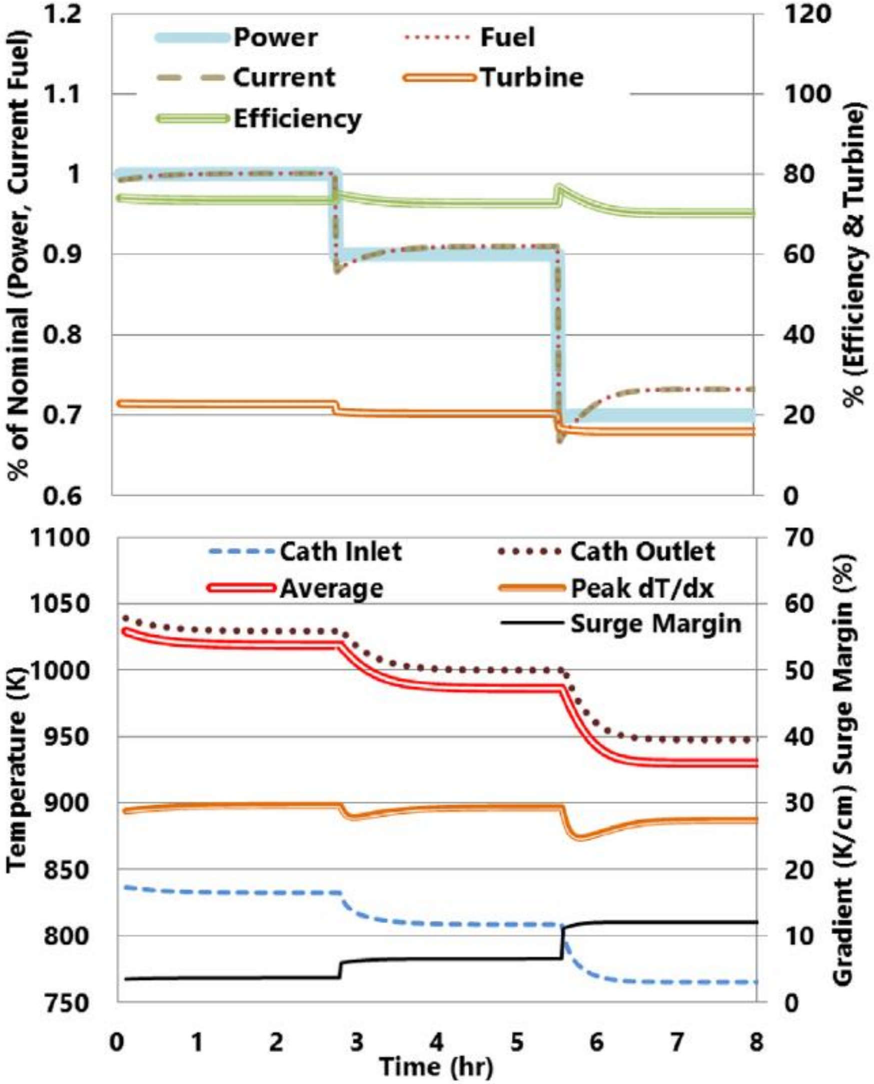


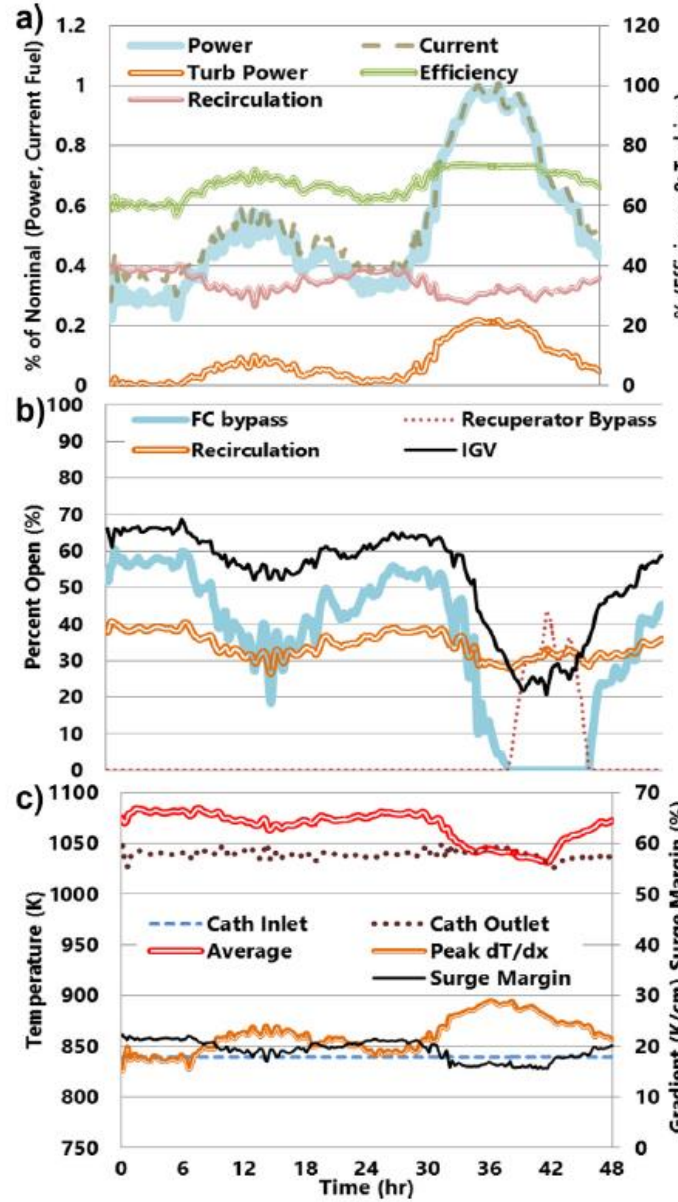


McLarty, D. and Brouwer, J., Journal of Power Sources, Vol. 254, pp. 126-136, 2014.

Dynamics to Complement Loads/Renewables

- **10% & 20% load-shed** **30-100% diurnal load-following**





McLarty, D. and Brouwer, J., Journal of Power Sources, Vol. 254, pp. 126-136, 2014.

Backup Slides

Sample Dynamic Conservation Equations

Species Conservation

$$V\frac{dC_i}{dt} = N_{i_{inlet}} - N_{i_{outlet}} + R_i$$

Momentum Conservation

$$V\frac{d(\rho\bar{v})}{dt} = P_{inlet}A_{inlet} - P_{outlet}A_{outlet} - F_s$$

Nernst Equation

$$E = E^{o} + \frac{R_u T}{nF}\ln\left[\frac{[y_{H2}][y_{O2}]^{1/2}[y_{CO2,c}]P^{1/2}}{[y_{H2O}][y_{CO2,a}]}\right] \quad , P_c = P_a = P$$

Electrochemical Losses

$$L_R = R_{cell} i$$

$$L_A = \frac{R_u T}{n\alpha F}\ln(i/i_o)$$

$$L_C = -\frac{R_u T}{nF}\ln(1 - i/i_L)$$

Cell Voltage

$$Vcell = E - L_R - L_C - L_A$$

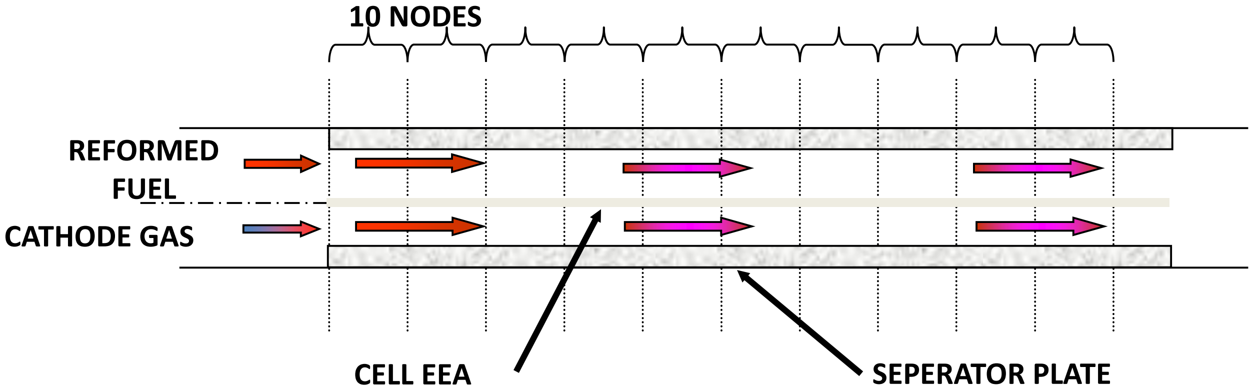
Sample Mass Conservation Equations

$$\begin{cases} C_{out} = \dfrac{P_{out}}{RT_{out}} \\ N_{out} = N_{in} + N_R - \dfrac{d(C_{out}V)}{dt} \\ (X_{H2})_{out} = \dfrac{N_{in}(X_{H2})_{in} + R_{H2} - \dfrac{d(C_{H2}V)}{dt}}{N_{out}} \\ (X_{CO2})_{out} = \dfrac{N_{in}(X_{CO2})_{in} + R_{CO2} - \dfrac{d(C_{CO2}V)}{dt}}{N_{out}} \\ (X_{H2O})_{out} = \dfrac{N_{in}(X_{H2O})_{in} + R_{H2O} - \dfrac{d(C_{H2O}V)}{dt}}{N_{out}} \\ (X_{N2})_{out} = \dfrac{N_{in}(X_{N2})_{in} - \dfrac{d(C_{N2}V)}{dt}}{N_{out}} \end{cases}$$

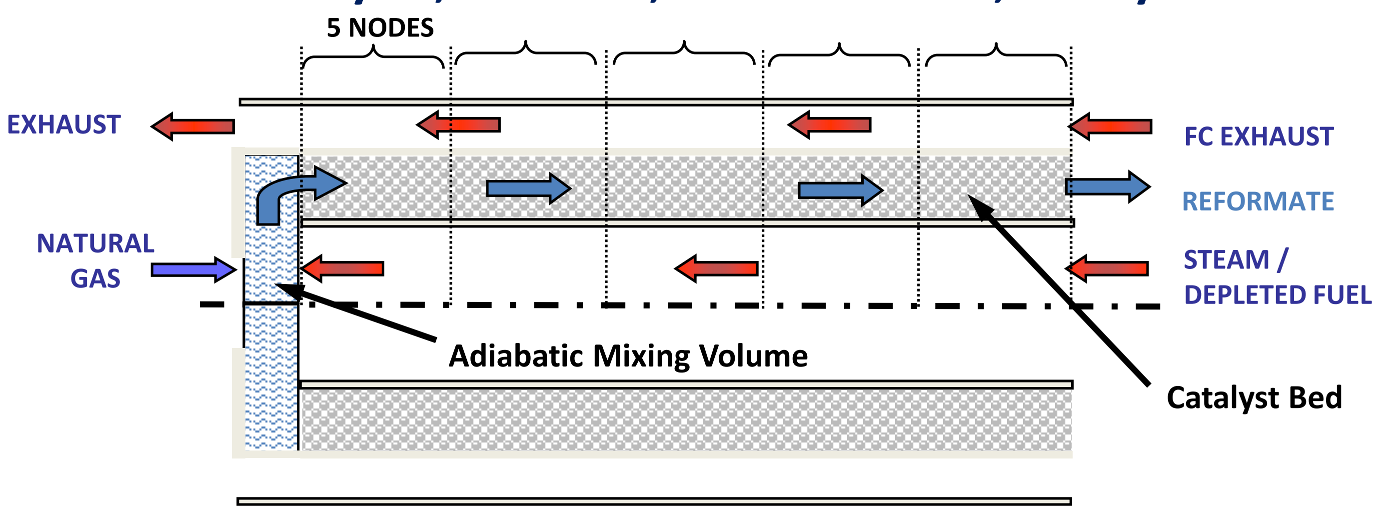
Roberts, R., Mason, J., Jabbari, F., Brouwer, J., Samuelsen, S., Liese, E. and Gemmen, R., ASME Paper Number 2003-GT-38774, 2003.

Sample Dynamic Simulation Module Geometries

- **Planar SOFC with 10 Discrete Computational Nodes**
  - **Anode Gas, Cathode Gas, Cell EEA, Separator Plates**



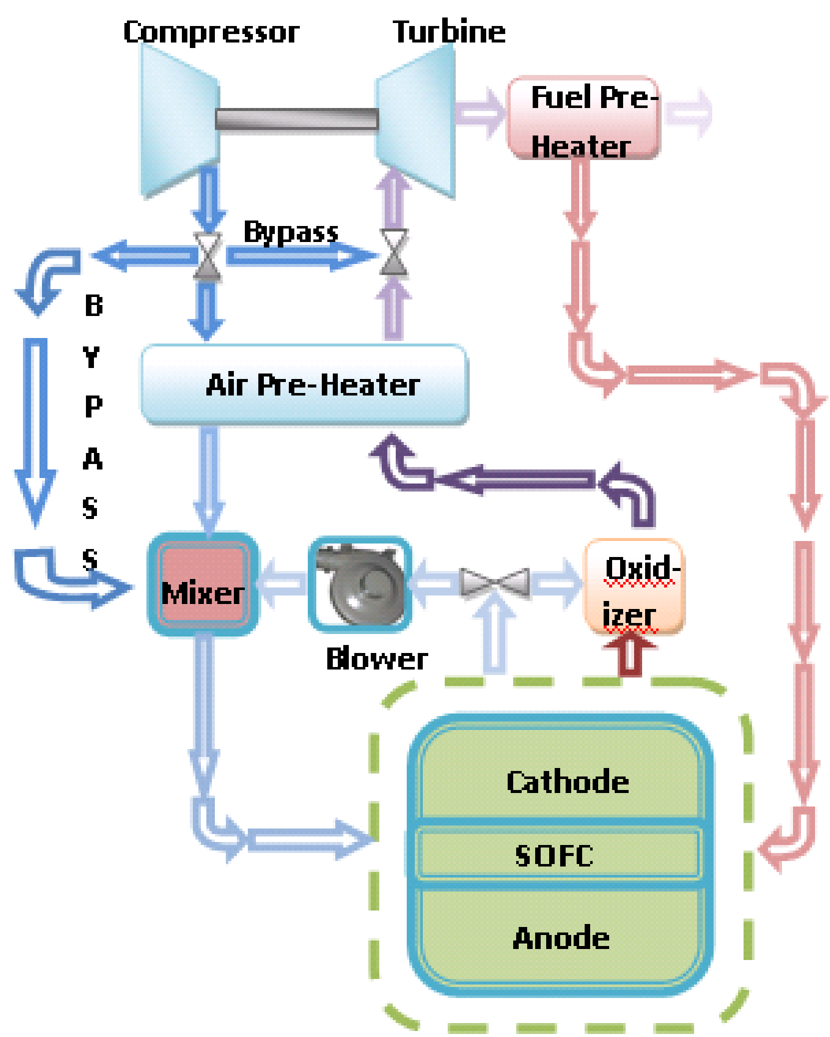
- **Reformer Module with 5 Discrete Computational Nodes**
  - **Anode Off-Gas Recycle, Fuel Mix, Combustor HX, Catalyst Bed**



How Can We Do It?

Hybrid SOFC/GT System

- **Manipulate:**
  - Recirc. blower power
  - Fuel flow
  - Air preheat bypass valve
  - SOFC air bypass valve
- **Control:**
  - System power
  - Peak SOFC temperature
  - SOFC temperature gradient
  - Oxidizer temperature
- **Perturbation:**
  - Sudden decrease from 100% to 50% full power

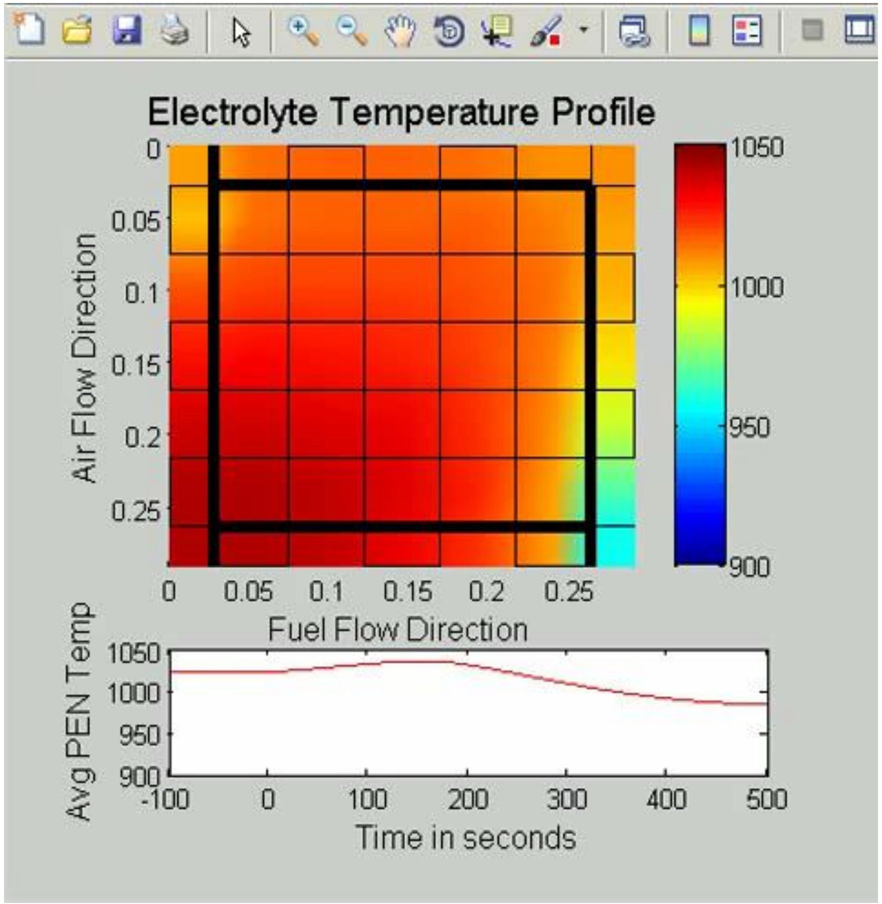


McLarty, D.F., Samuelsen, S., and Brouwer, J.
ASME Paper FC2010-33328, June, 2010

How Can We Do It?

Hybrid SOFC/GT System

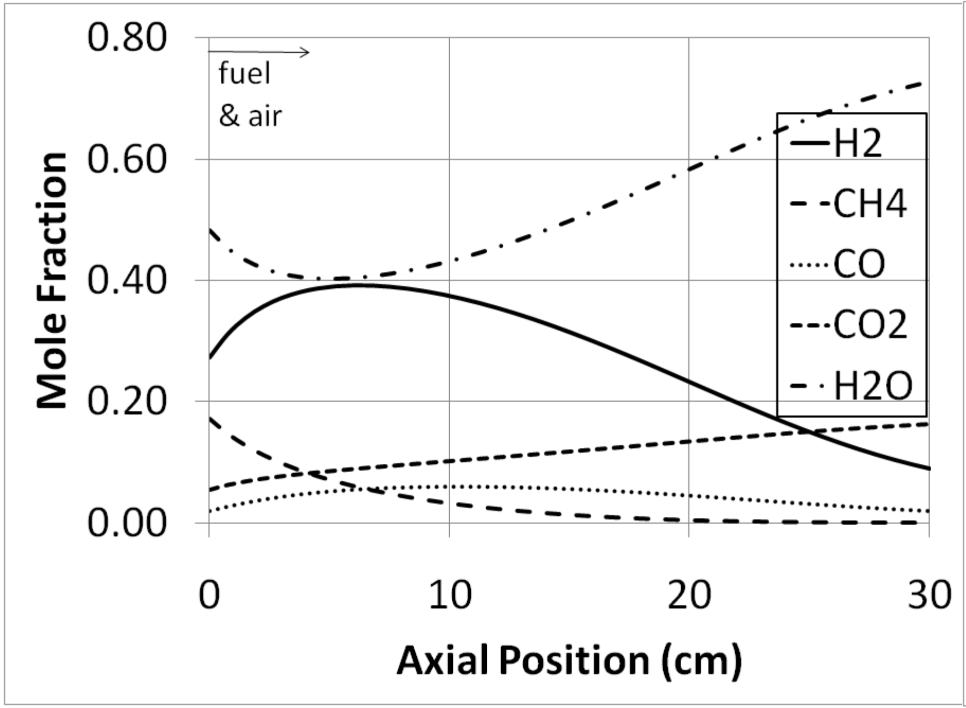
- Met sudden decrease in power demand
- Kept SOFC peak temperature < 1073 K during transient
- Kept SOFC temperature gradient < 150 K during transient



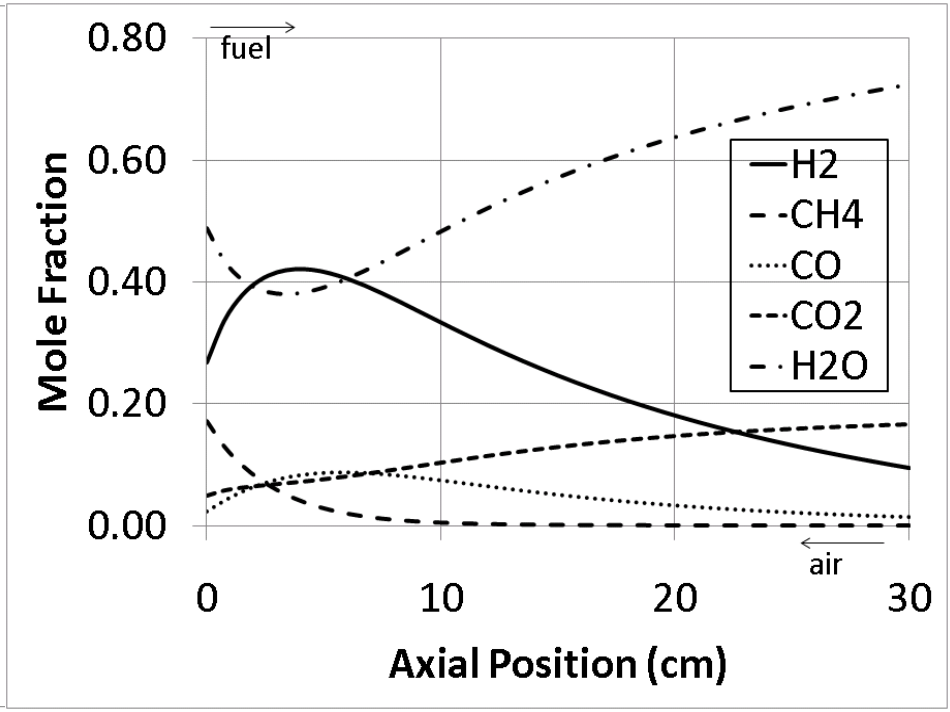
McLarty, D.F., Samuelsen, S., and Brouwer, J.
ASME Paper FC2010-33328, June, 2010

Sample Model Results: Syngas (1/3)

co-flow
species distribution



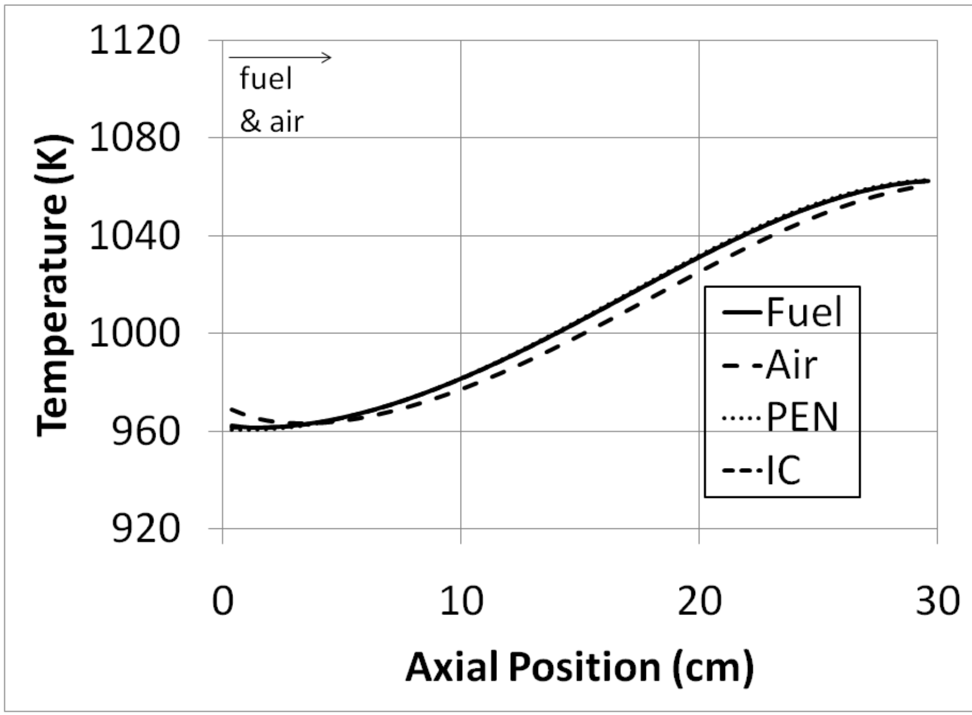
counter-flow
species distribution



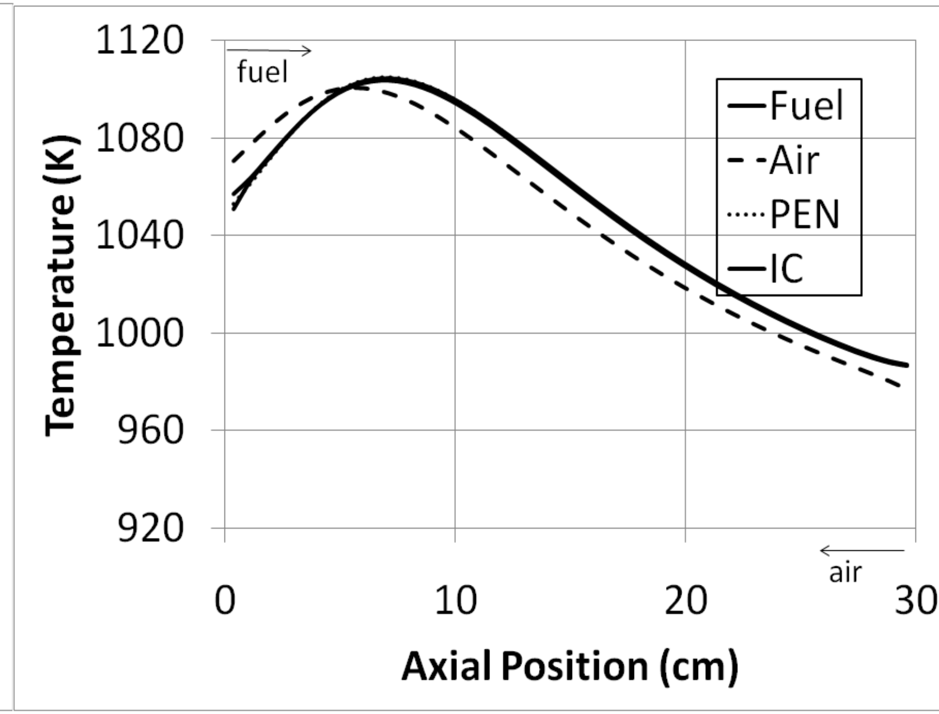
- fuel molar composition:
  26.26% H_2, 17.1% CH_4, 2.94% CO, 4.36% CO_2, 49.34% H_2O
- adiabatic, atmospheric operation
- 85% fuel utilization, 14.3% air utilization

Sample Model Results: Syngas (2/3)

co-flow temperature



counter-flow temperature



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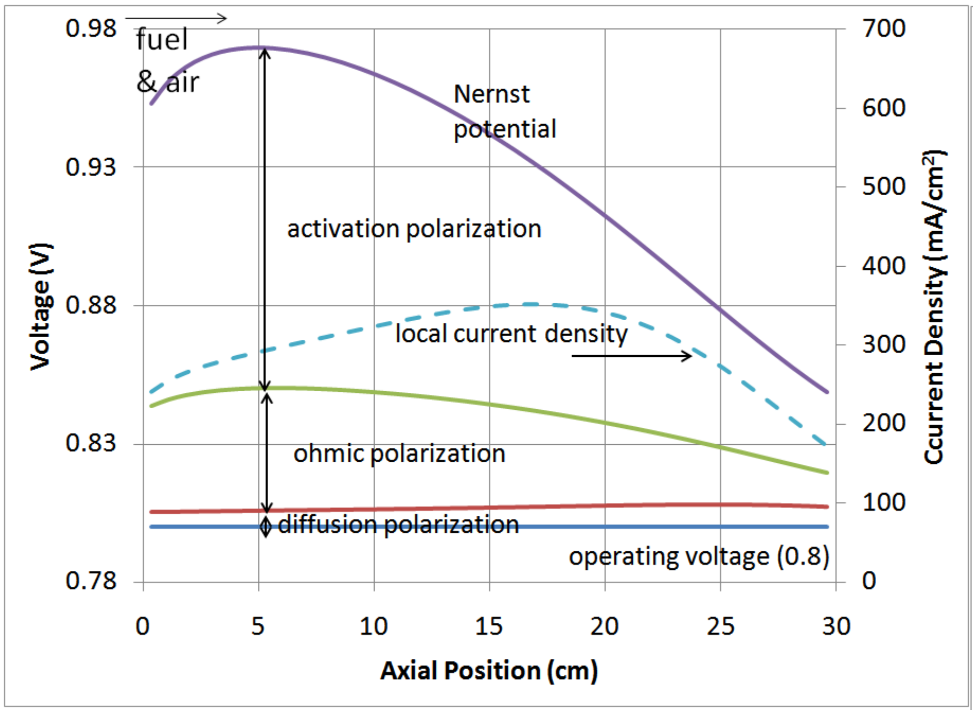
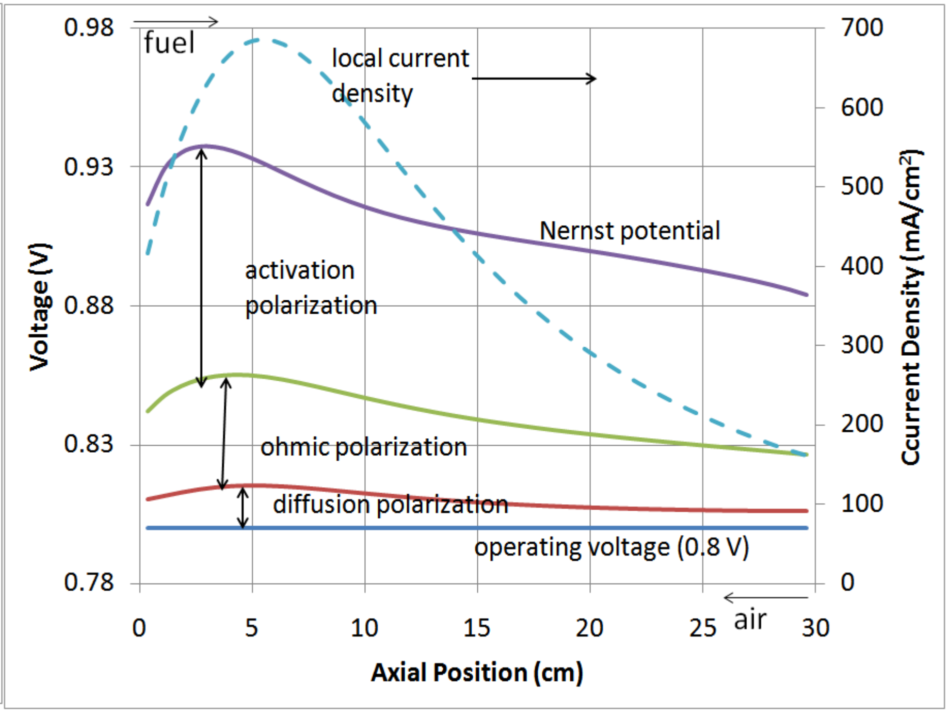
- 85% fuel utilization, 14.3% air utilization

Sample Model Results (3/3)

co-flow
electrochemical performance



counter-flow
electrochemical performance



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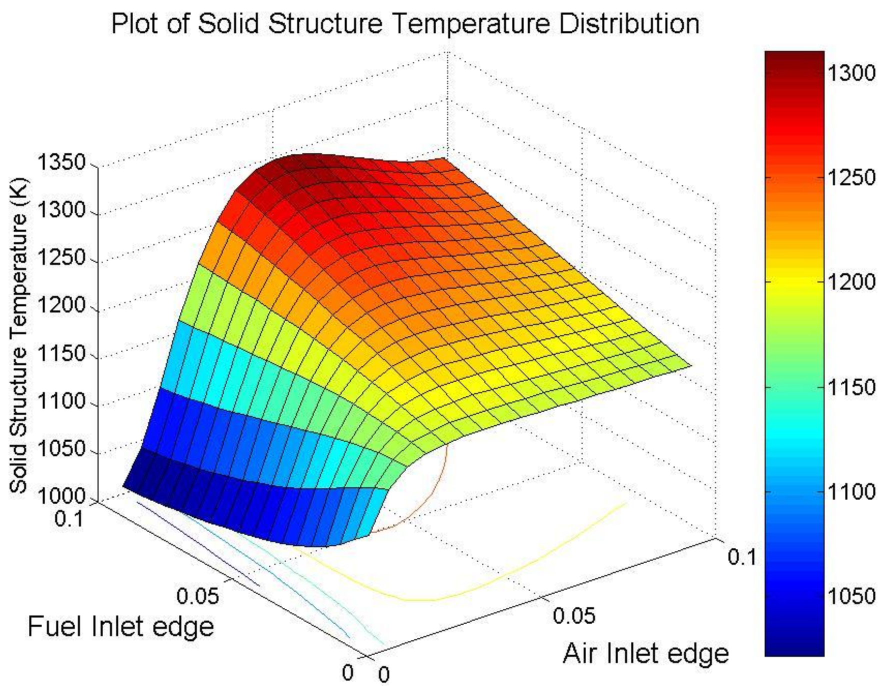
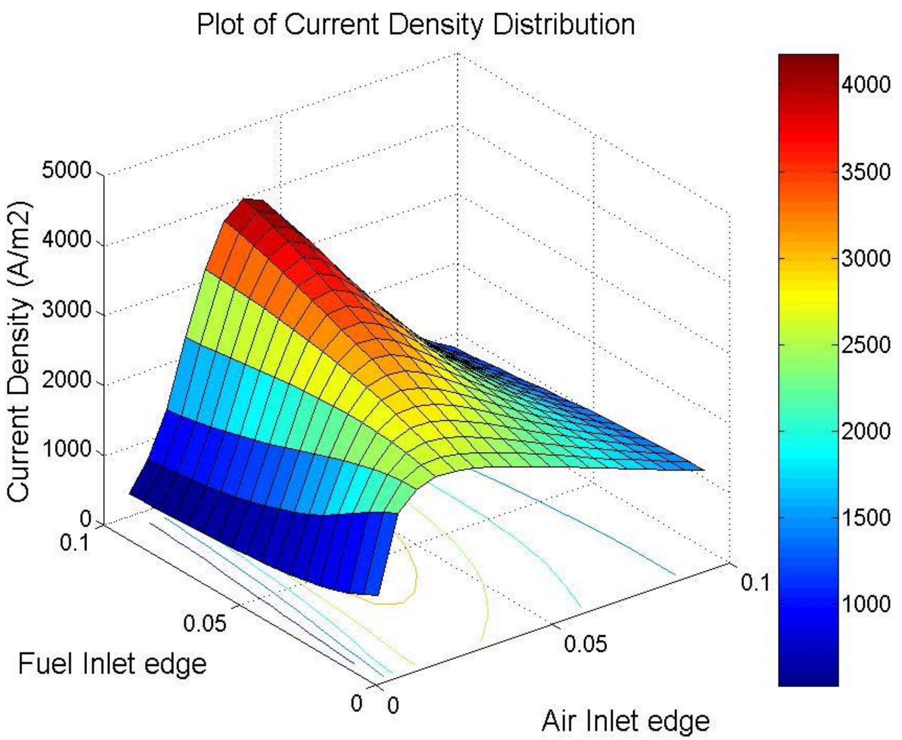
- adiabatic, atmospheric operation
- 85% fuel utilization, 14.3% air utilization

Extend to Quasi-3D Cross-flow Planar SOFC

Quasi-3D cross-flow planar SOFC model – sample results

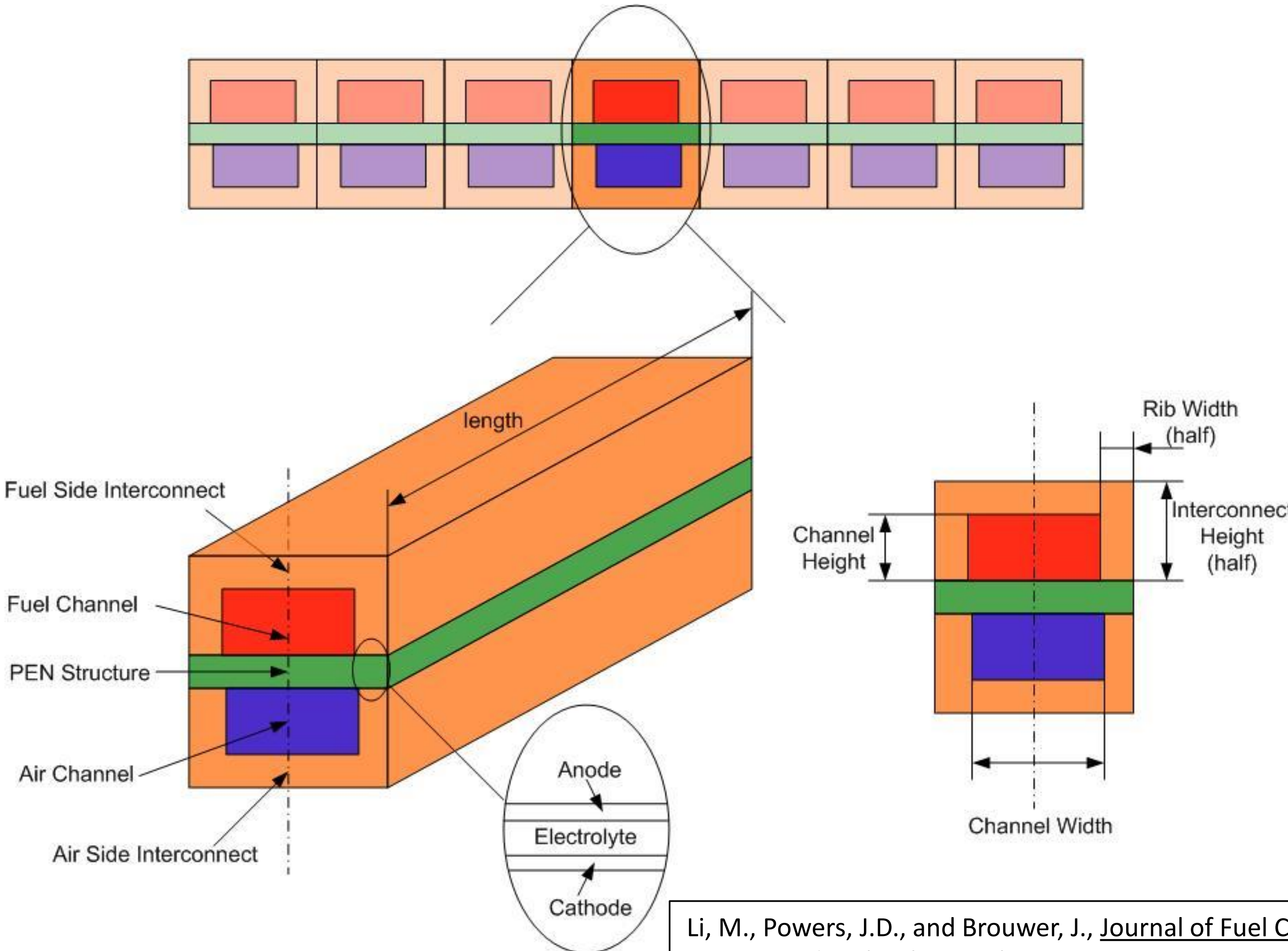




plots of cross flow planar SOFC PEN temperature and current density distributions operated on syngas containing ~17 vol.% CH_4 U_f = 85%, U_a = 14.7%

Planar SOFC Model Geometry

Quasi-2D co/counter flow planar SOFC model



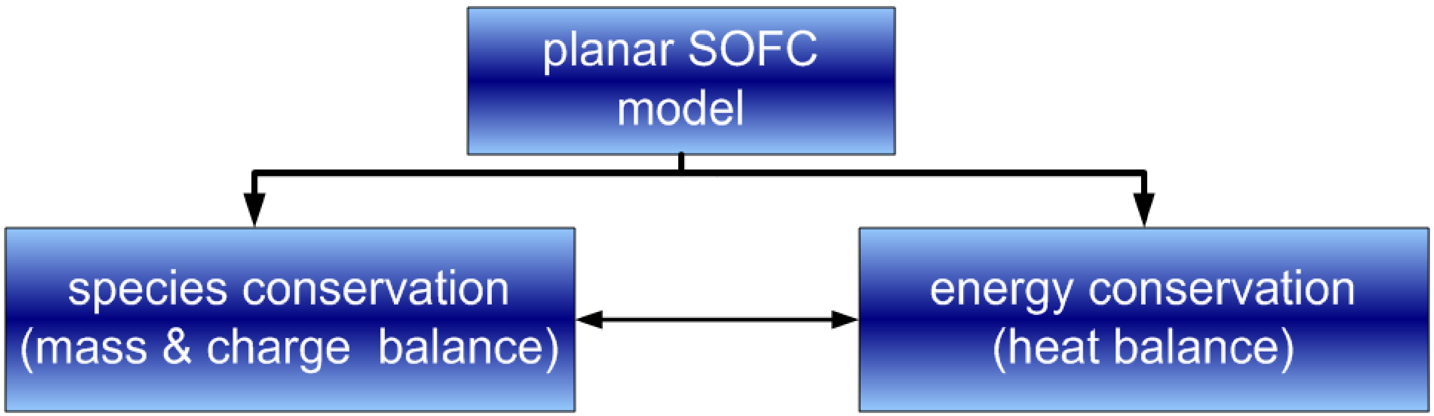
Li, M., Powers, J.D., and Brouwer, J., Journal of Fuel Cell Science and Technology, Vol. 7, pp. 041017-1-12, 2010

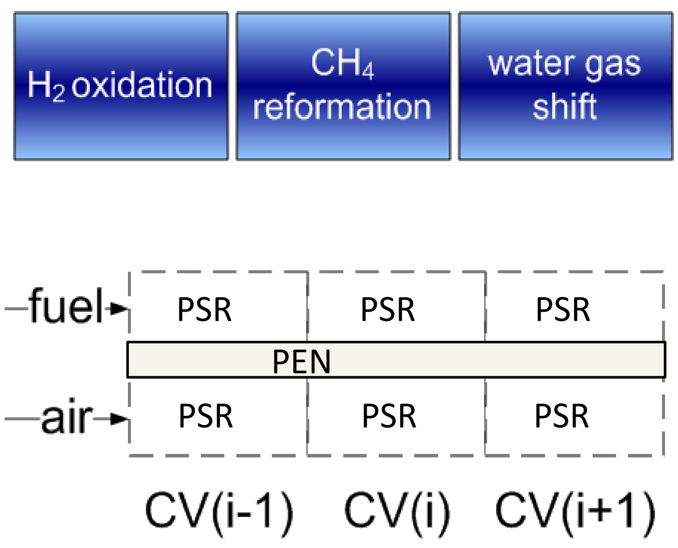
Key Simplifications & Assumptions

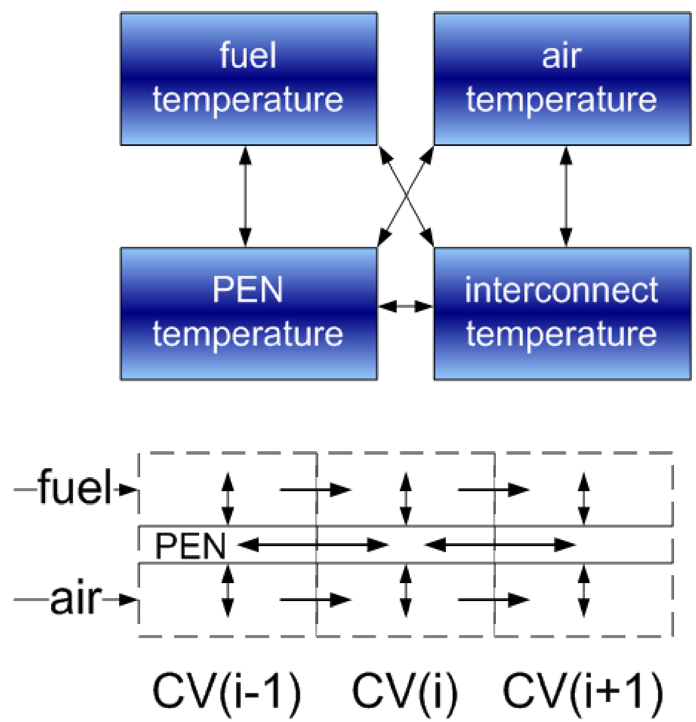
- Steady state model
- Resolve gradients in primary flow direction
- 4 separate temperatures resolved in each node
  - Positive electrode-electrolyte-negative electrode (PEN) structure
  - interconnect
  - fuel flow
  - air flow
- H_2 electrochemical oxidation only (CO oxidized through water-gas shift reaction)
- Water-gas shift reaction is always in equilibrium
- Methane reformation is controlled by local chemical kinetics
- External heat loss is by radiation heat transfer to vessel only
- Large Peclet number, thus the effect of axial heat conduction in gas phases is negligible

Li, M., Powers, J.D., and Brouwer, J., Journal of Fuel Cell Science and Technology, Vol. 7, pp. 041017-1-12, 2010

Numerical Scheme





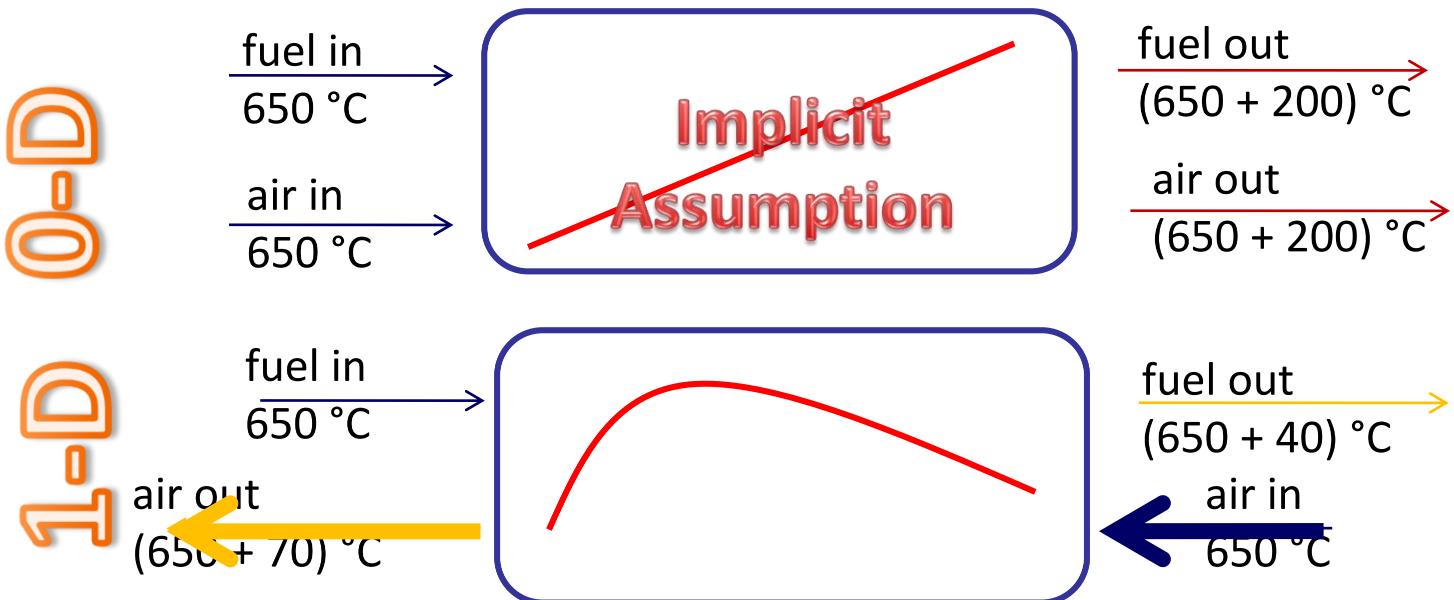


Li, M., Powers, J.D., and Brouwer, J., Journal of Fuel Cell Science and Technology, Vol. 7, pp. 041017-1-12, 2010

Challenges Identified: 0-D vs. 1-D

1-D counter-flow SOFC model in integrated IGFC analysis

- Peak temperatures move to SOFC interior
- Inlet & outlet temperatures no longer represent peak ΔT
- Outlet fuel/air temperatures are decreased – disabling downstream heat use
- Air flow required for ΔT_{max}=200°C is 4X that of 0-D model



FuelCell Energy

Ultra-Clean, Efficient, Reliable Power

Hybrid System Experience at FCE

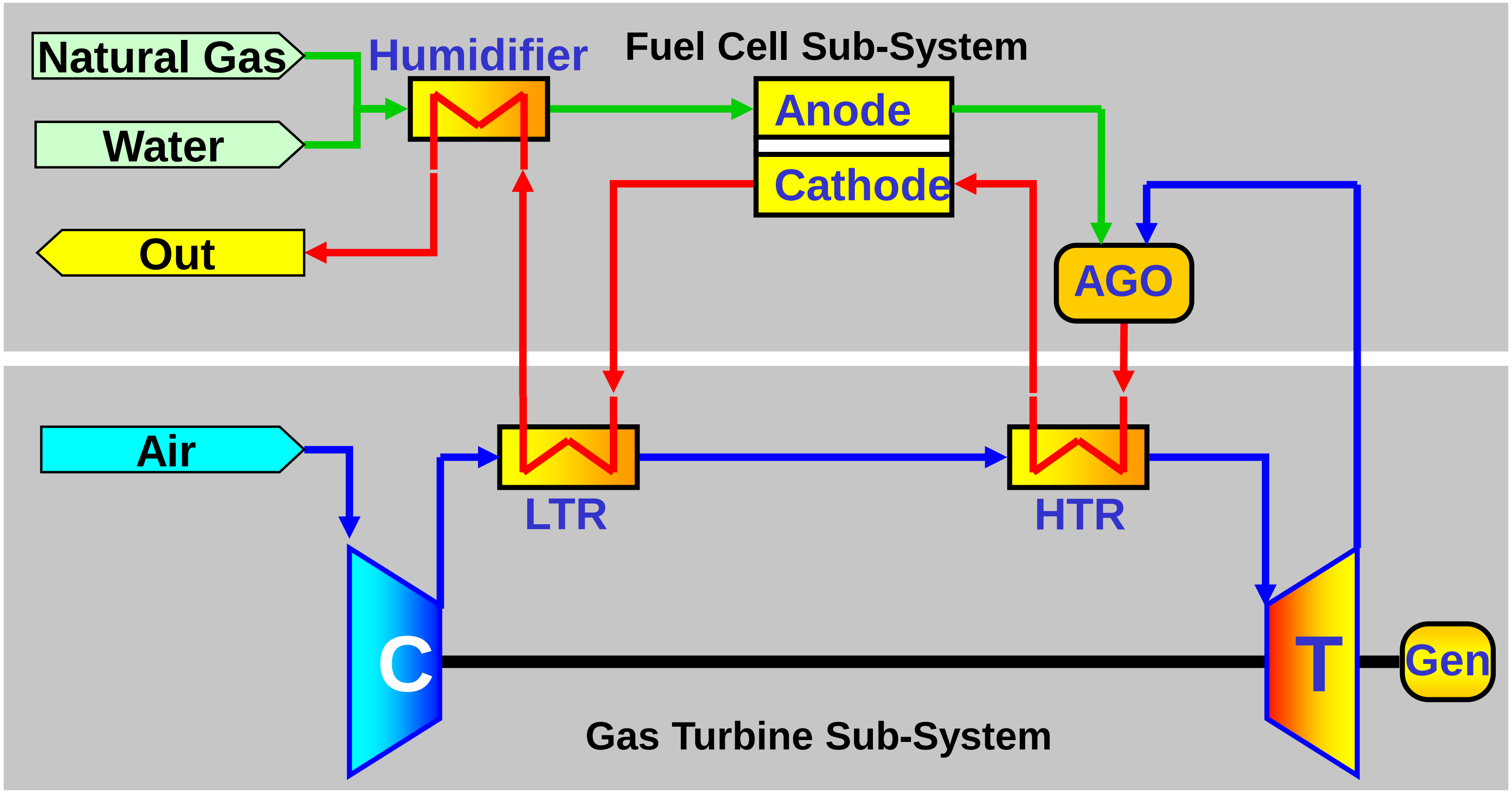
Hossein Ghezel-Ayagh

ARPA-E Workshop

January 27, 2017

Ultra-Clean | Efficient | Reliable Power

Process Flow Diagram of DFC/T Power Plant



- Operating pressures of fuel cell and turbine are **independent**
- Turbine integration increases overall efficiency by 20-30%

FuelCell Energy

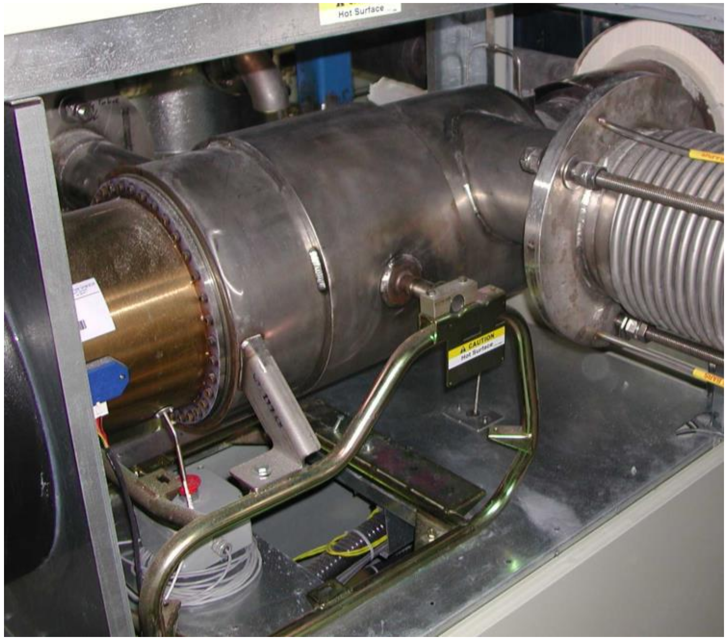
Direct FuelCell® Stack Module

- A 250 kW DFC® stack module was utilized in the subMW DFC/T Power Plant

Capstone Microturbine Features

FuelCell Energy

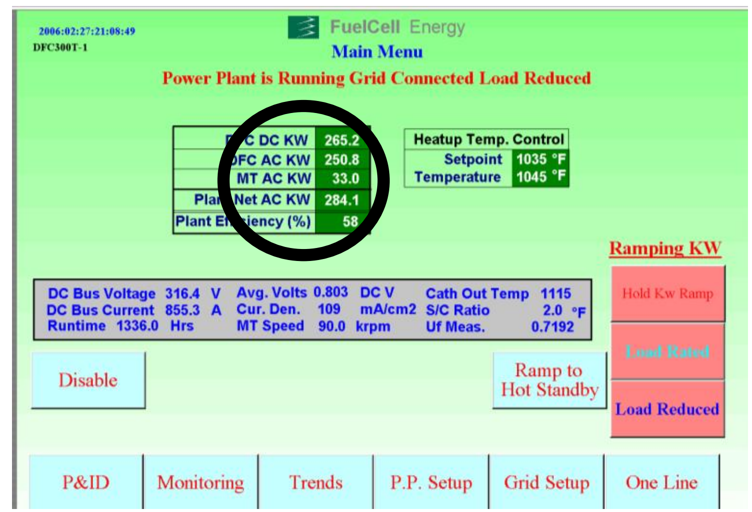
- Compression ratio of ~ 3 - 4
- Mechanical Connections:
  - > Compressor exit port and turbine inlet port for integration with fuel cell system
- Range of air flows suitable for fuel cell stack operation (0.8-1.0 lbs/sec)
- Capability to control air flows with load (Speed Control)
- Microturbine's controller modifiable for integration with fuel cell control system
- Single Shaft Design



Integrated Capstone C60 Microturbine

Alpha Unit Factory Test

FuelCell Energy



DFC®/T achieved a net efficiency of 58% during the factory tests

- **Tests by an independent firm indicated California Air Resources Board's (CARB) 2007 emissions standards for NOx and VOC were met.**

FuelCell Energy

Alpha Unit at Montana Test Site

- **Completed operation at host site >8000**
- **Achieved availability of >87% in producing power**

Billings Clinic, Billings, MT