“Dynamic Modeling and Control of Fuel Cell Hybrid Systems”

3rd Annual DOE / U.N. Hybrid Conference and Workshop

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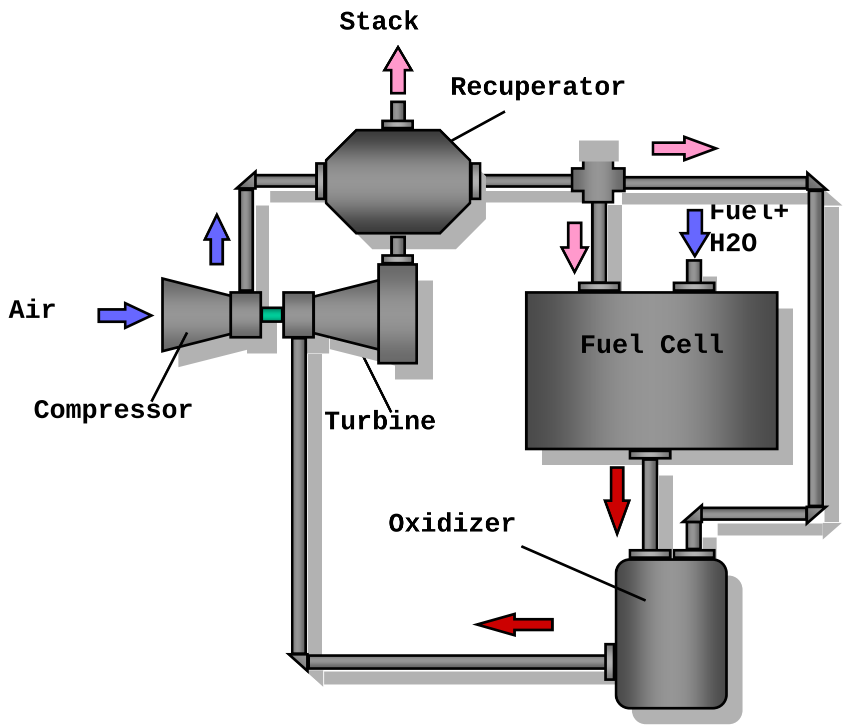
Challenge

DYNAMIC MODELING OVERVIEW : Fuel cell and fuel cell hybrid systems

- Various time scales
- BOP transients
- Turbine response times
- Start-Up
- Load Upset/Load following
- Thermal Management
- Etc

Fuel Cell Simulation Tools Needed



Dynamic Modeling

Main Benefit:

- Better understanding of FC behavior
- Faster design and evaluation of new hybrid concepts
- Evaluation of stress points, limits, etc.
- Control design and evaluation

Main Challenges:

- Identification of key features
- Scales of dynamic behavior
- Balance between details and speed
- Integration of FC with BOP

Options

Things to measure:

- Temperatures
- Concentrations (real time?)
- Electrical output, pressures, etc

Things to manipulate:

- Power electronics
- Fuel, Oxidizer, vapor etc flows
- Cooling air
- Flow tripping, etc

For control: actuators, sensors, objectives, MODELS (Dynamic)

Benefits of Control

More or less analytical aspects:

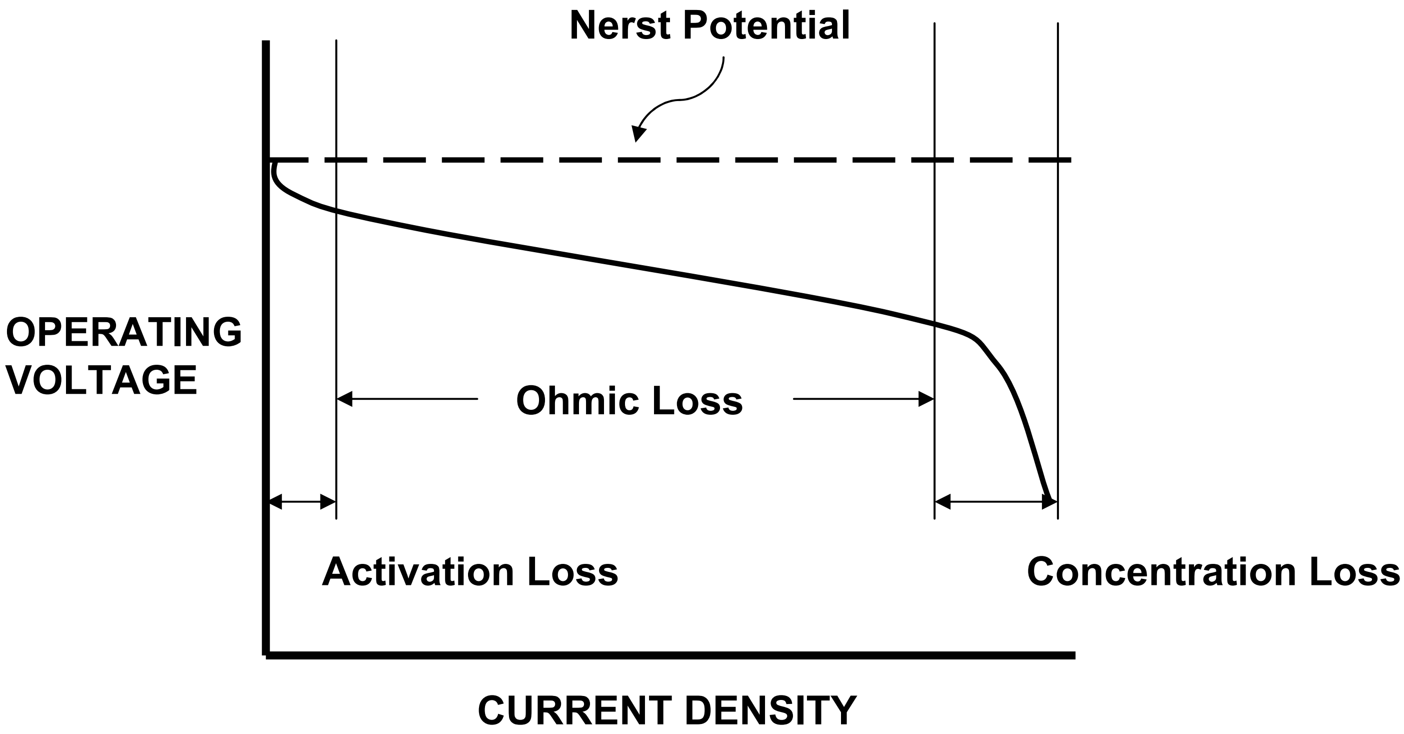
- Study of performance limits
- Sensitivity and sensitivity reduction
- Identifications of actuator and sensor needs
- Control `architecture' and design (non-minimum phase, hierarchical)

Practical Aspects:

- Subsystem level control
- Interactions among subsystems
- System level control

FUEL CELL MODEL(S)

FUEL CELL OPERATION



Actual operating voltage characteristic: Bulk Model

MODEL EQUATIONS

Species Conservation

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

Momentum Conservation

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

Electrochemical Losses

$$L_R = R_u i$$

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

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

Cell Voltage

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

Nernst Equation

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

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

BASIC APPROACH

Common platform (SIMULINK)

- Fuel Cell
- Power electronics
- Reformers, heat exchanges, etc

Spatial Resolution:

- 1-D model
- discretized into several nodes

Thermal Conditions:

- Reliability
- Model fidelity (temp dependence of electro-chemistry)

HYBRID SYSTEMS COMPONENT MODELS

DYNAMIC MODELS FOR A REFORMER, SOFC, AND GAS TURBINE

SIMPLIFYING MODEL ASSUMPTIONS

- 1D process flow
- Well-stirred at nodal level
- Slow pressure transients

FUEL CELL ASSUMPTIONS

- H_2 electrochemically oxidized only
- CO consumed via water-gas shift
- Shift always at equilibrium (constraint)
- Equipotential: $V_{cell} = V_{node\ 1} = V_{node\ n}$

Controls Research Challenges

Thermal Profile:

- Thermal loads, durability and reliability
- Temperature control

Interaction between spatial and thermal variations

- Temperature dependence of electrochemistry (Ohmic resistance, activation energy constants, etc)

Non-Minimum Phase response

- System level: accumulators
- System level: power management
- Cell Level: electro-chemistry `constants'

Dynamic Model Status: FC

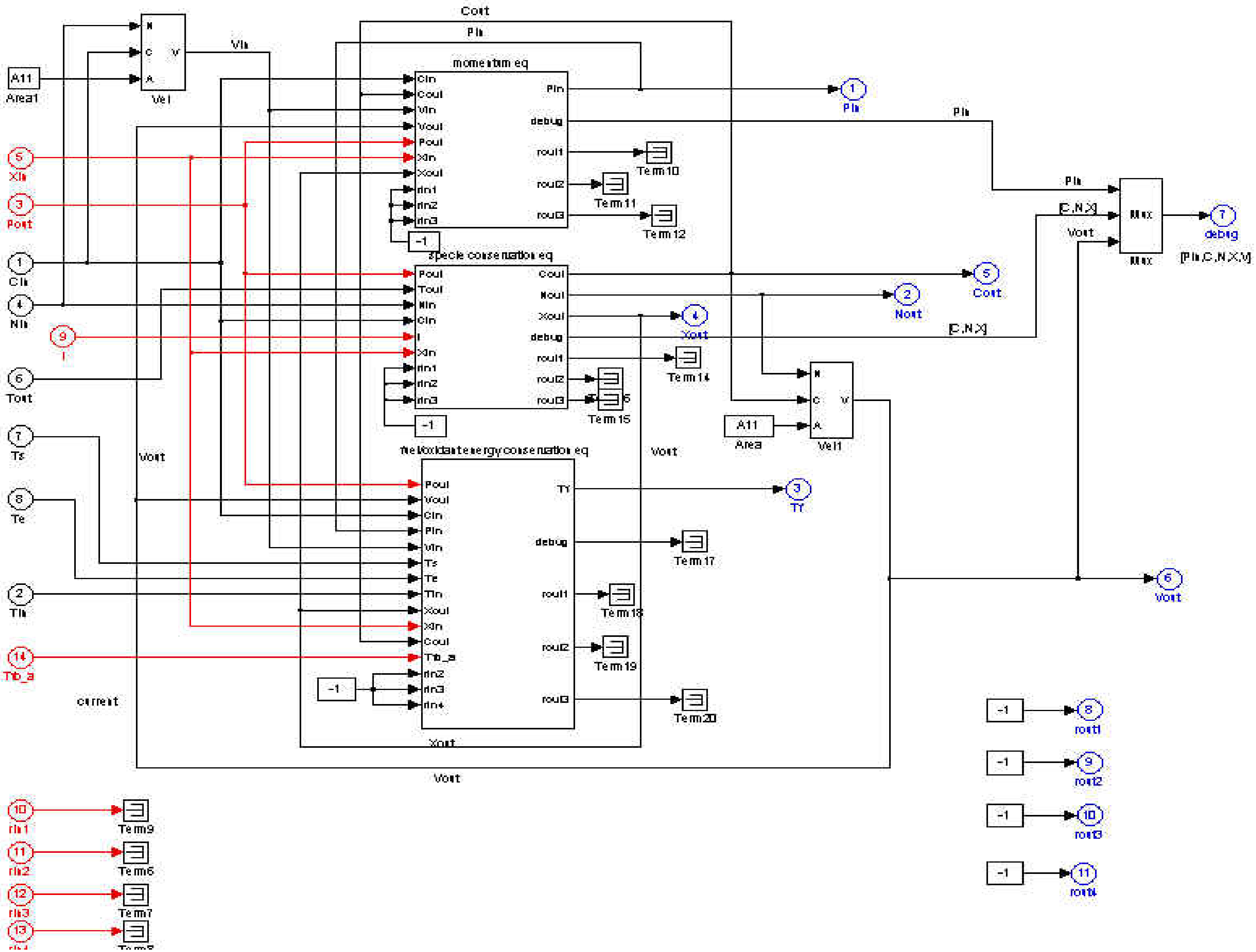
Main assumptions:

- quasi-steady state electro-chemical (e.g., no intermediate species, etc.)
- No turbulence!

Focus on the the essential FC features

- Nernst potential
- Voltage losses
- Species concentrations and Mass conservation
- Energy conservation
- Momentum conservation

Anode Equations Simulink® Example



Challenges

What constants are really constants (dynamically speaking)

Heat transfer (energy) terms –

- relatively slow time scales
- Computationally intensive and problematic
- Do we really need it?

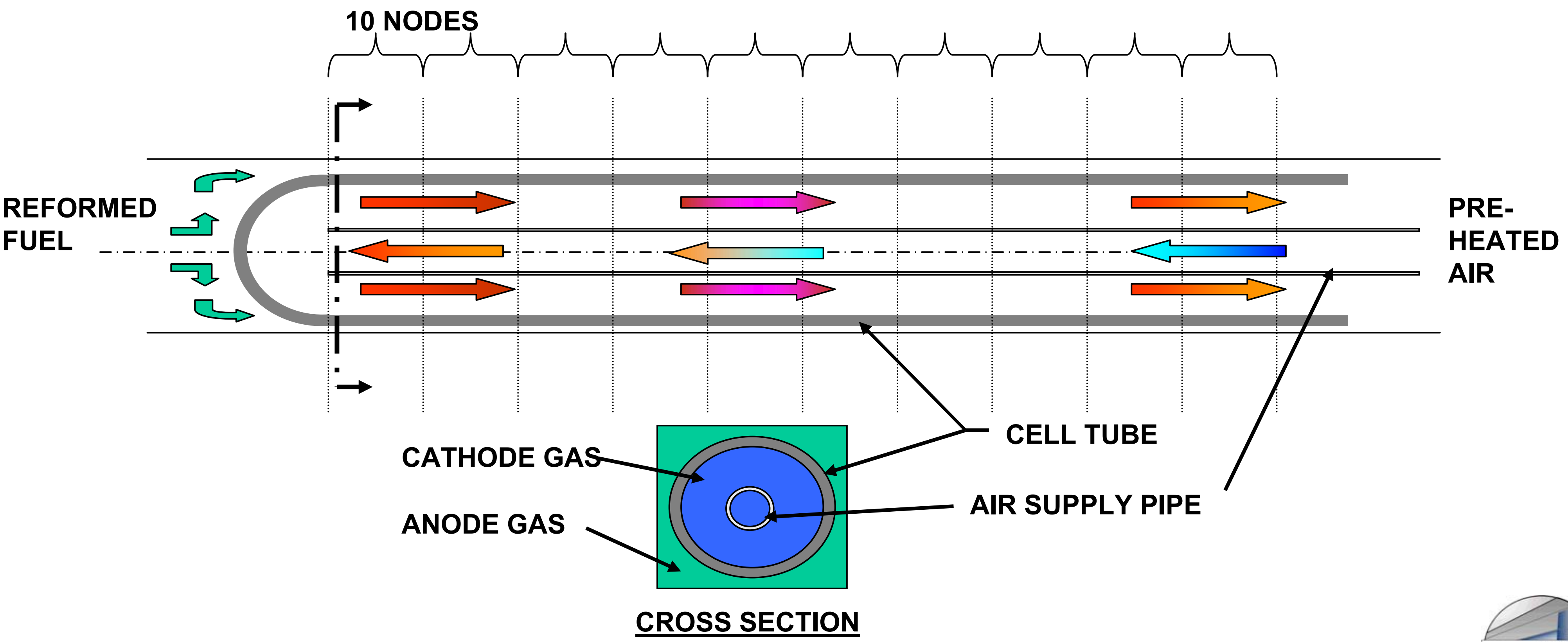
Experimental verification

FUEL CELL MODEL(S)

TUBULAR (TSOFC) FUEL CELL DISCRETIZATION

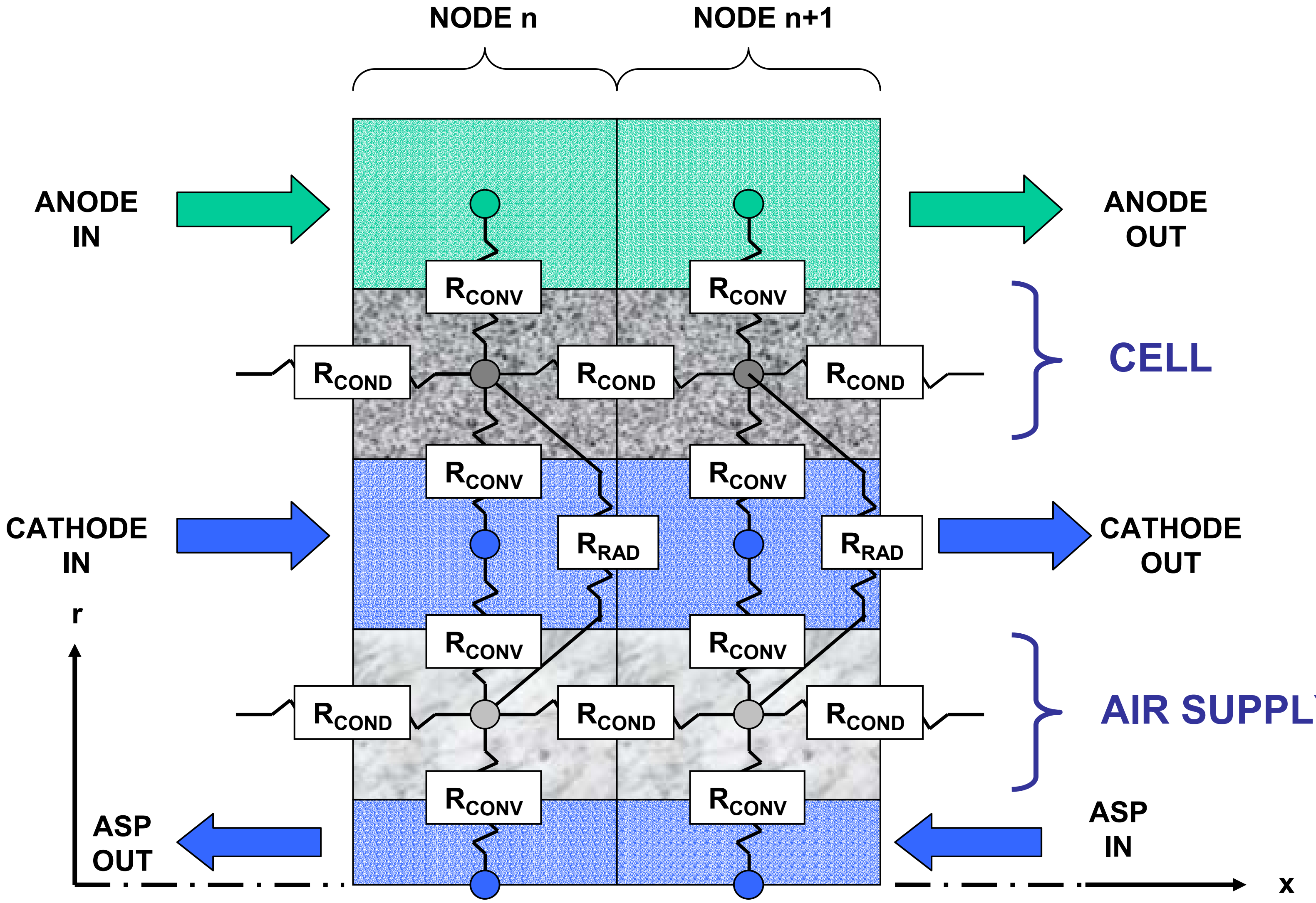
10 Discrete Computational Nodes

- Anode Gas
- Cathode Gas
- Cell Solid
- Air Supply Pipe Solid
- Air Supply Gas



FUEL CELL MODEL(S)

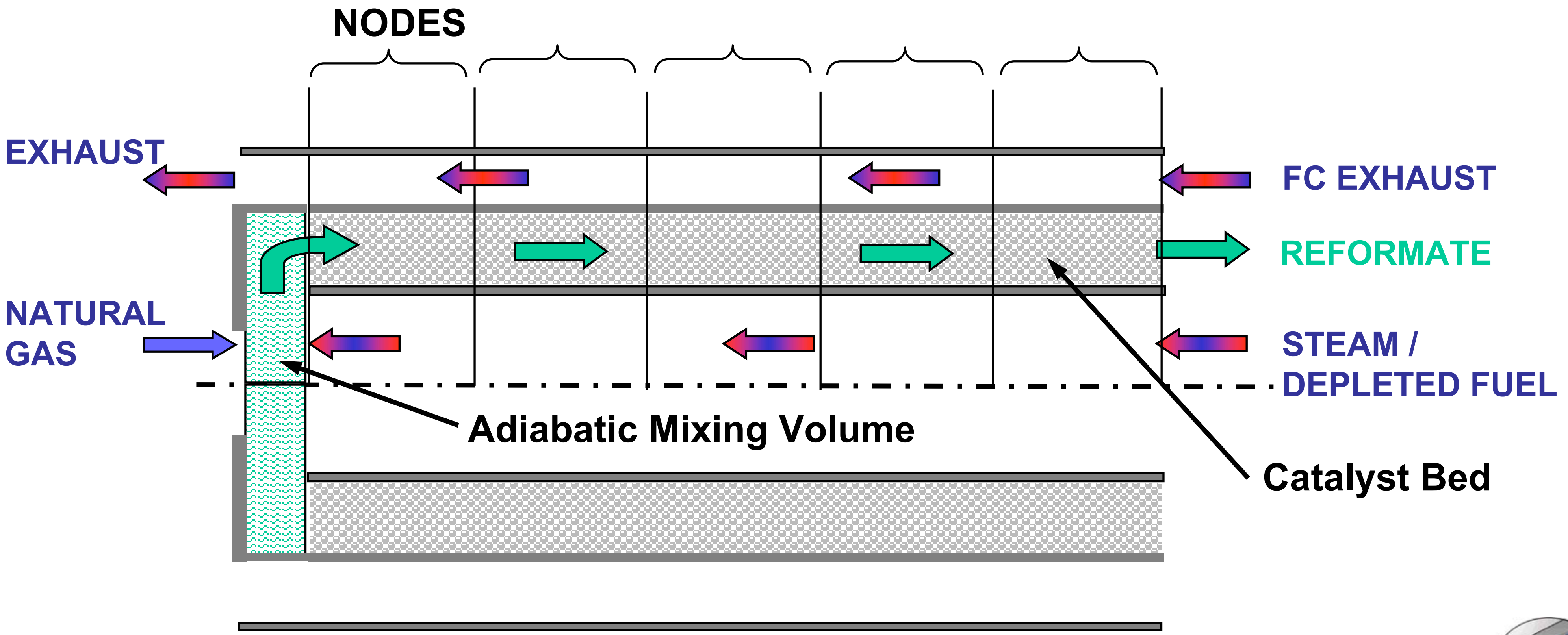
TSOFC NODAL FUEL CELL HEAT TRANSFER RESISTANCES



REFORMER MODEL

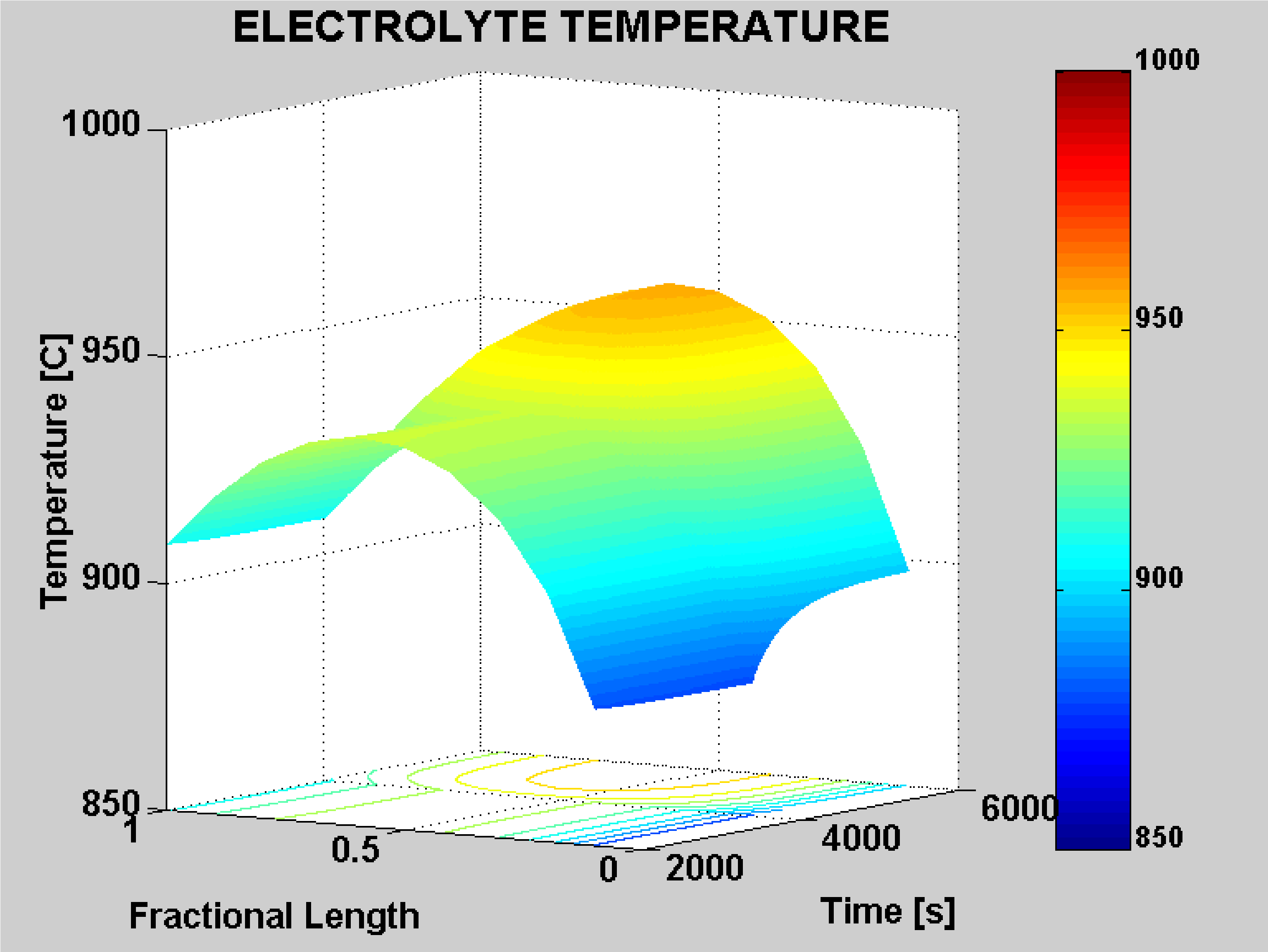
REFORMER

- 5 node model
- Concentric cans
- Heat from exhaust gas heat exchange



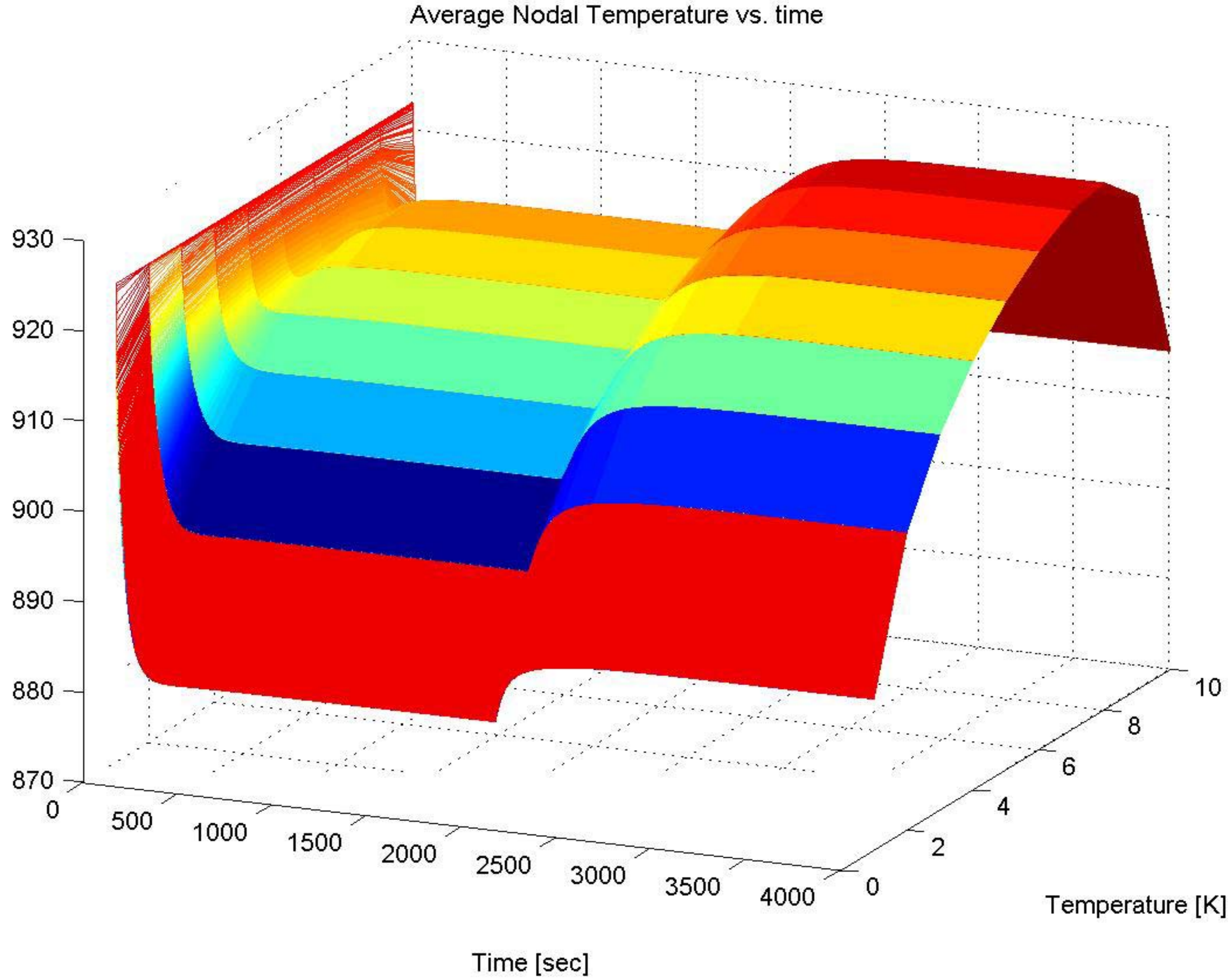
FUEL CELL MODEL(S)

SAMPLE TSOFC OUTPUTS: 10% LOAD INCREASE



Dynamic Temperature Profile

Response to Load Demand Increase at t=2000 seconds



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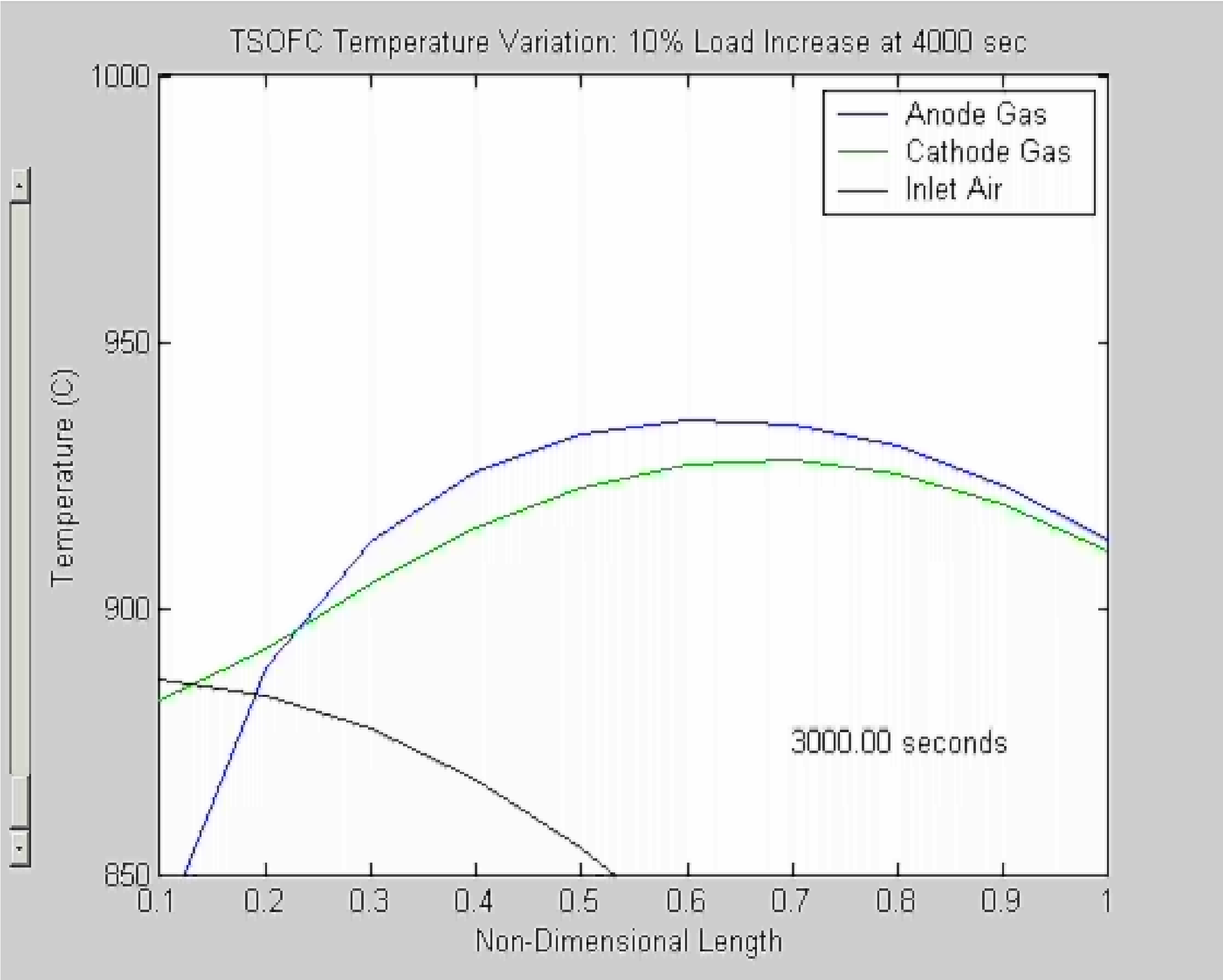
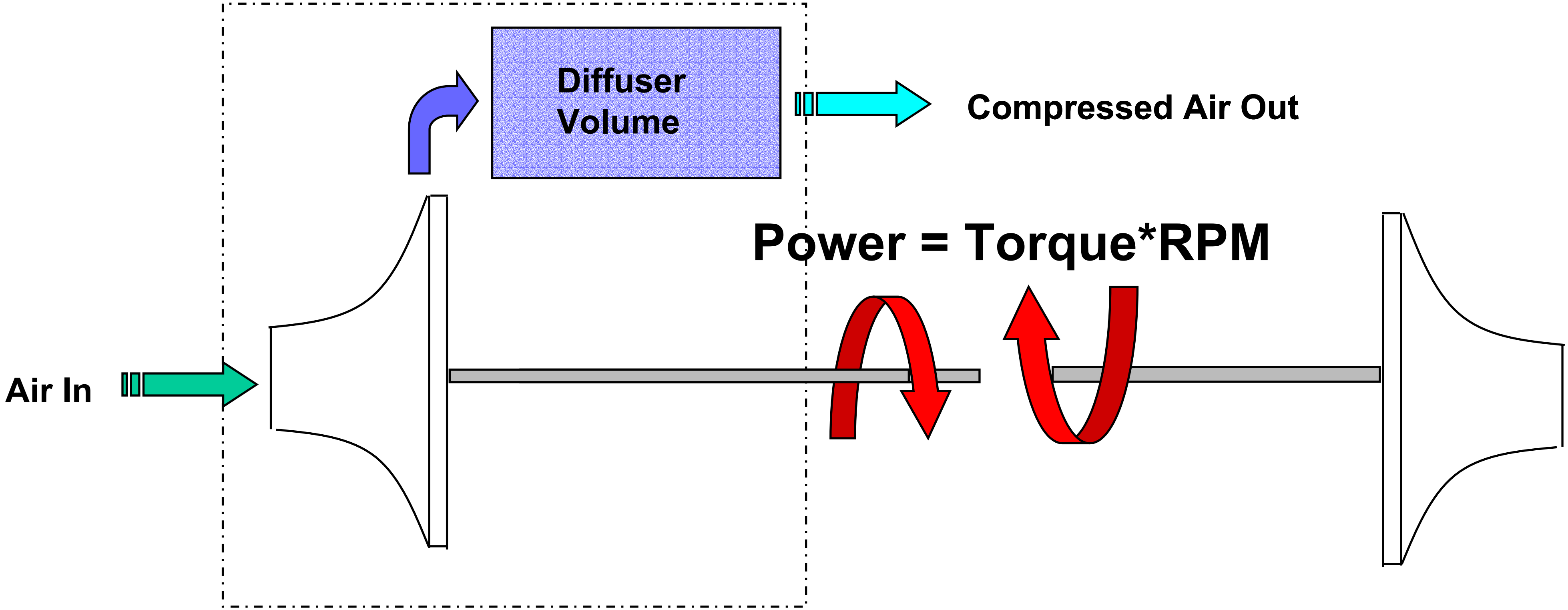


GAS TURBINE MODEL

COMPRESSOR

- **Lumped Parameter**
  - Incompressible Compressor
  - Compressible representative diffuser volume

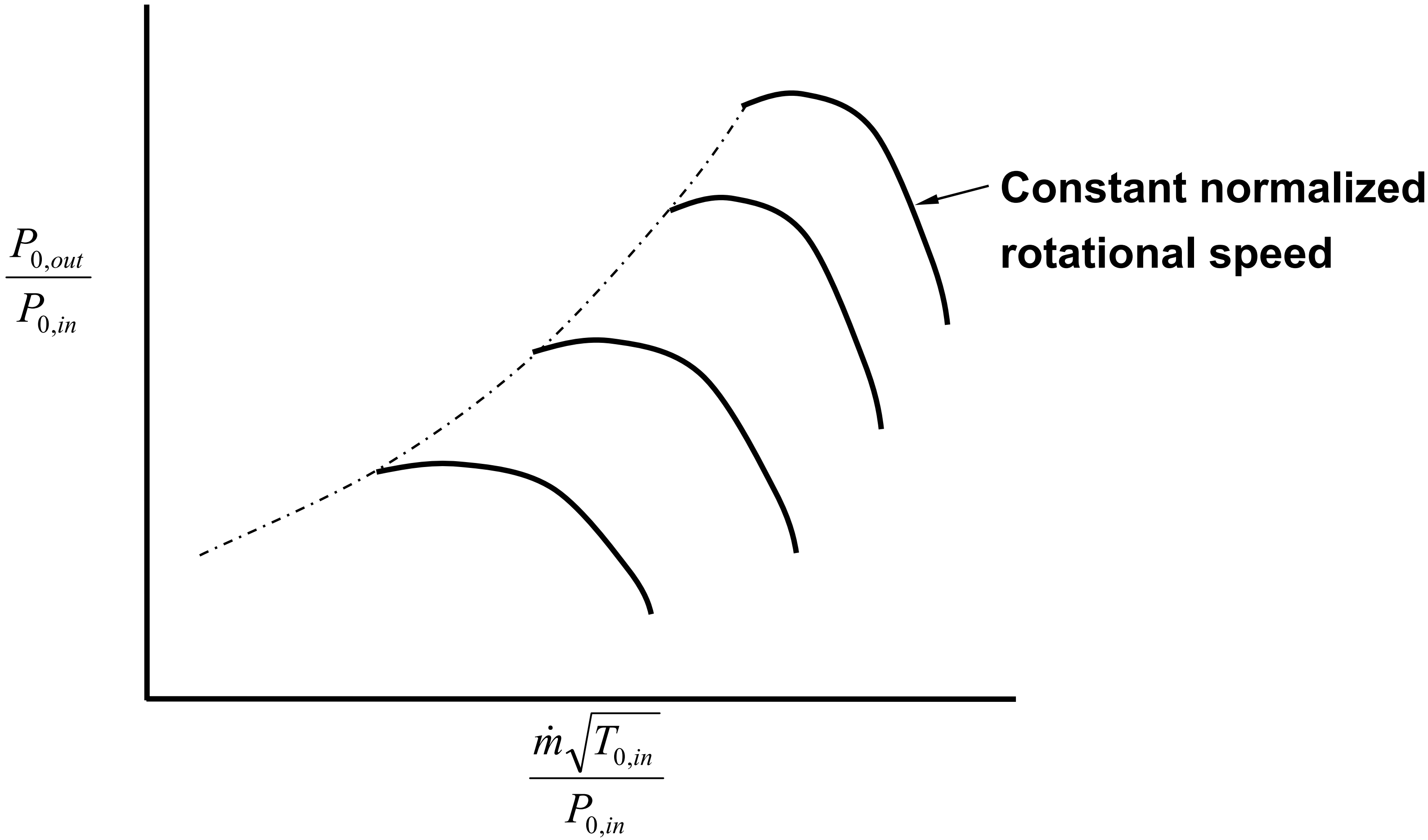


Compressor Control Volume

GAS TURBINE MODEL

COMPRESSOR MAPS

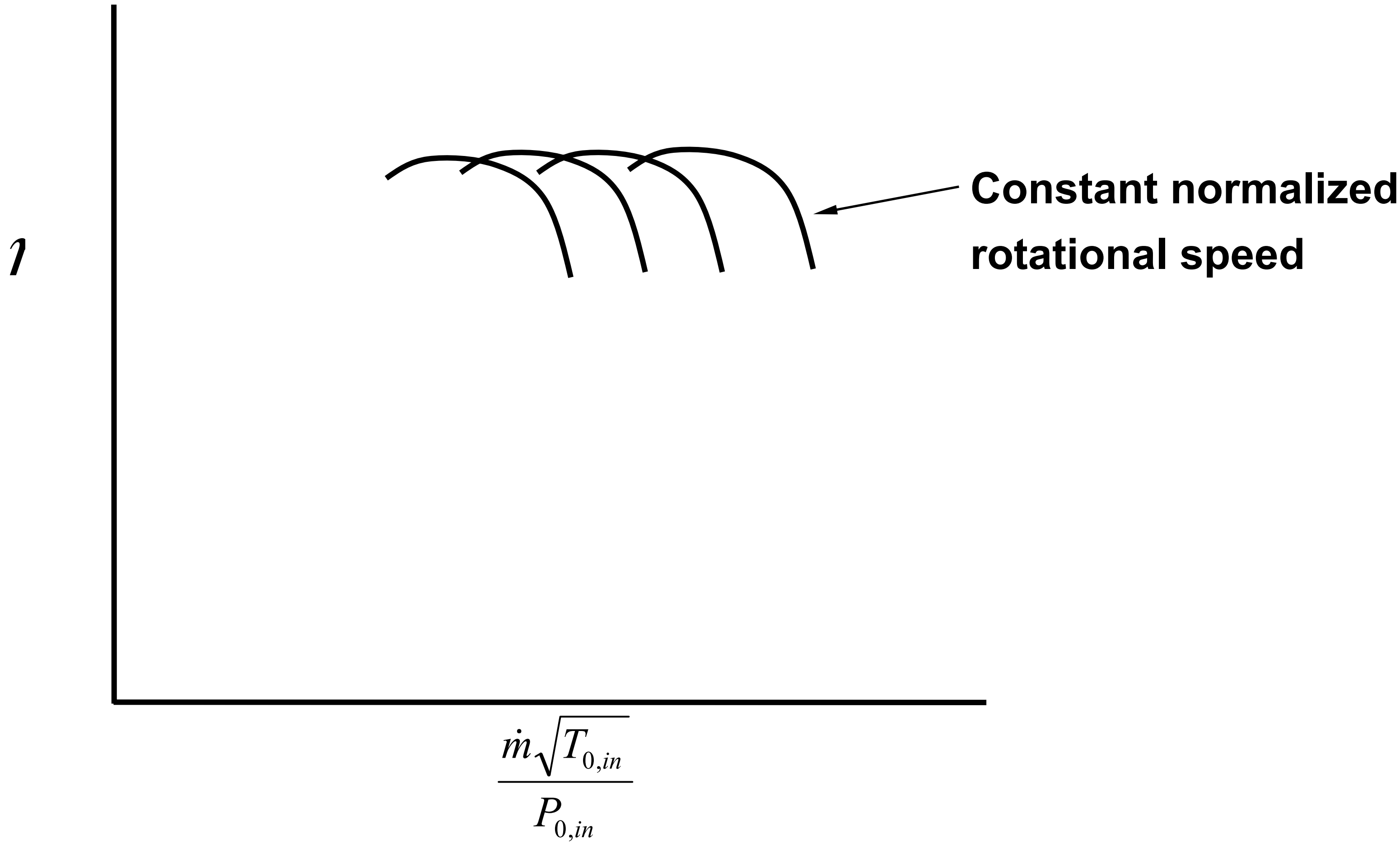
- Total pressure ratio vs. normalized mass flow



GAS TURBINE MODEL

COMPRESSOR MAPS

- Isentropic efficiency vs. normalized mass flow

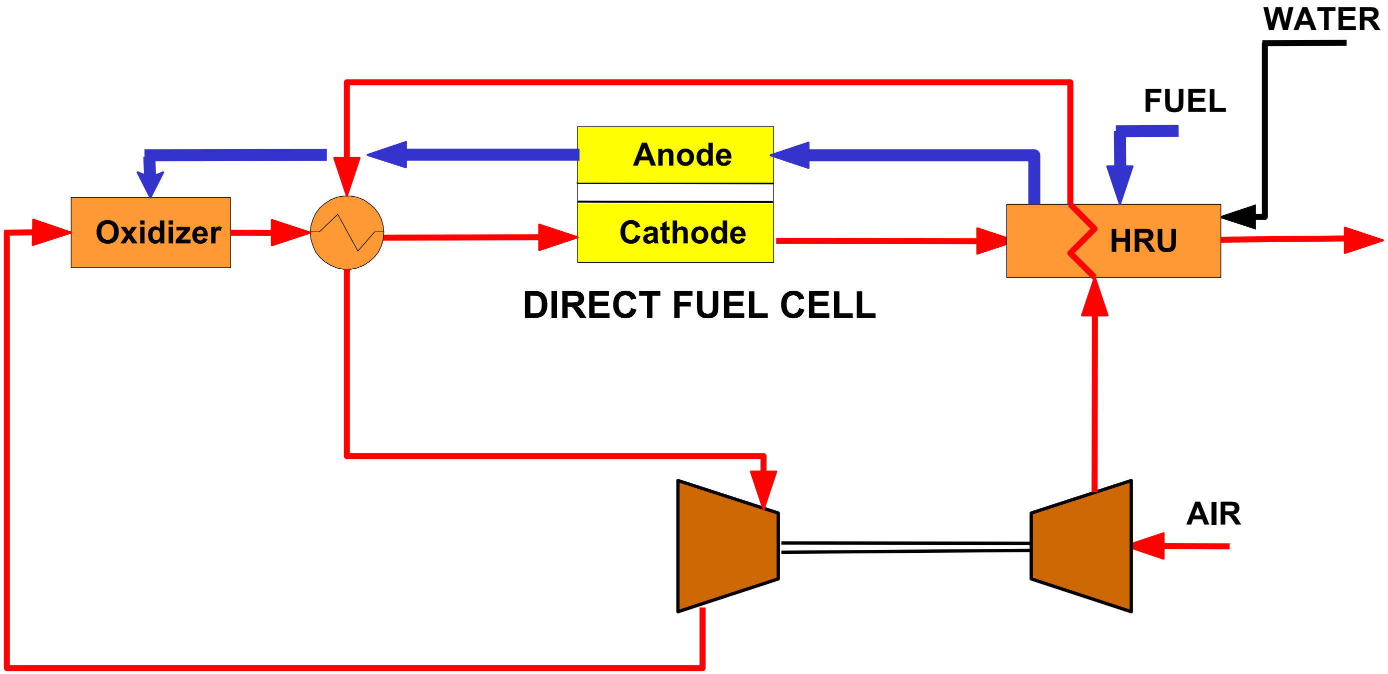


HYBRID SIMULATION

Dynamic Modeling Tools – Example Results - MCFC

FCE Direct FuelCell™ / Gas Turbine Hybrid System

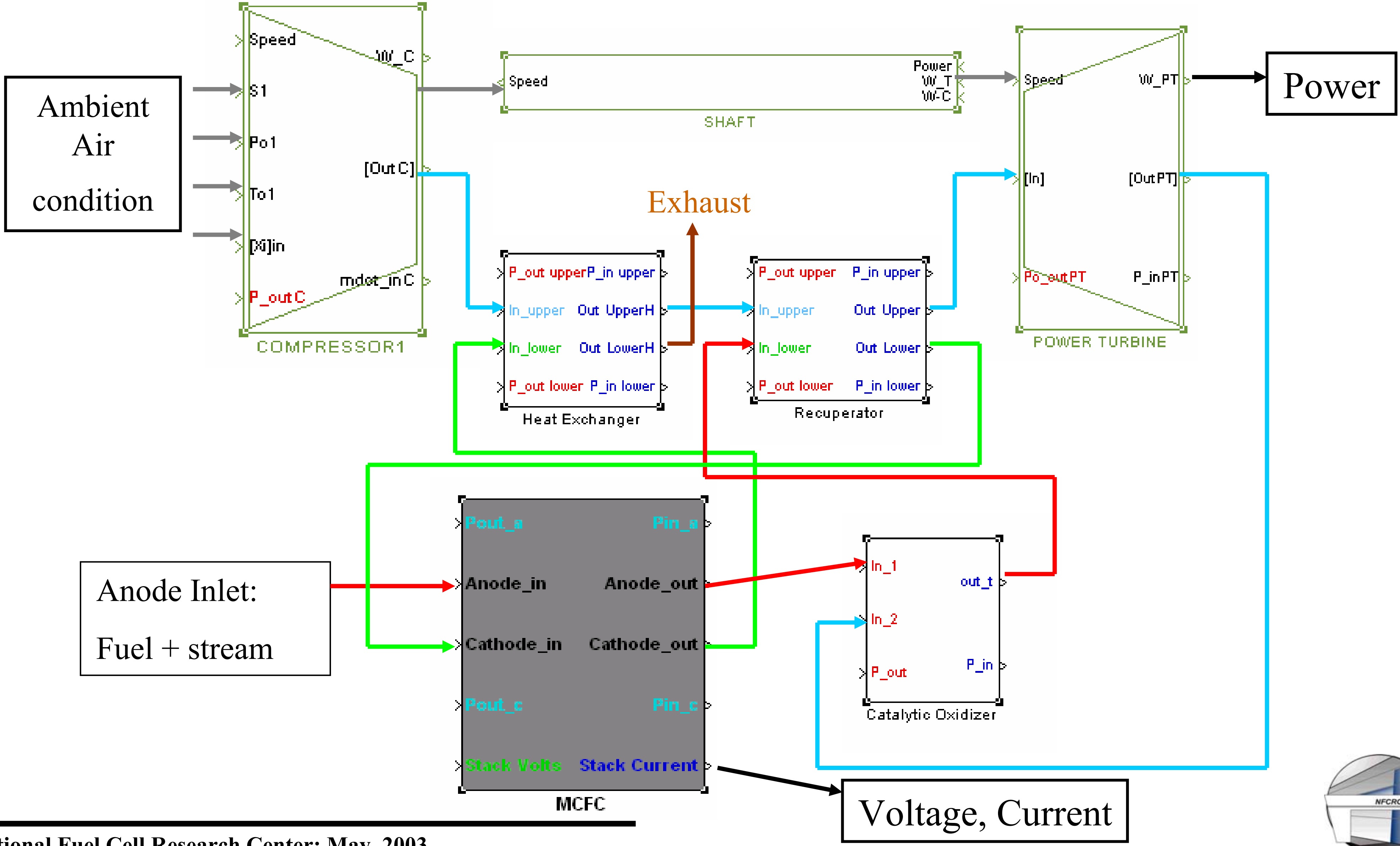
Compressed Air is Heated with Fuel Cell Waste Heat, Expanded, and then Used as the Fuel Cell Oxidant



- ***Efficiencies of ~ 75% are possible***
- ***Potential to Significantly Lower $/kW Cost***

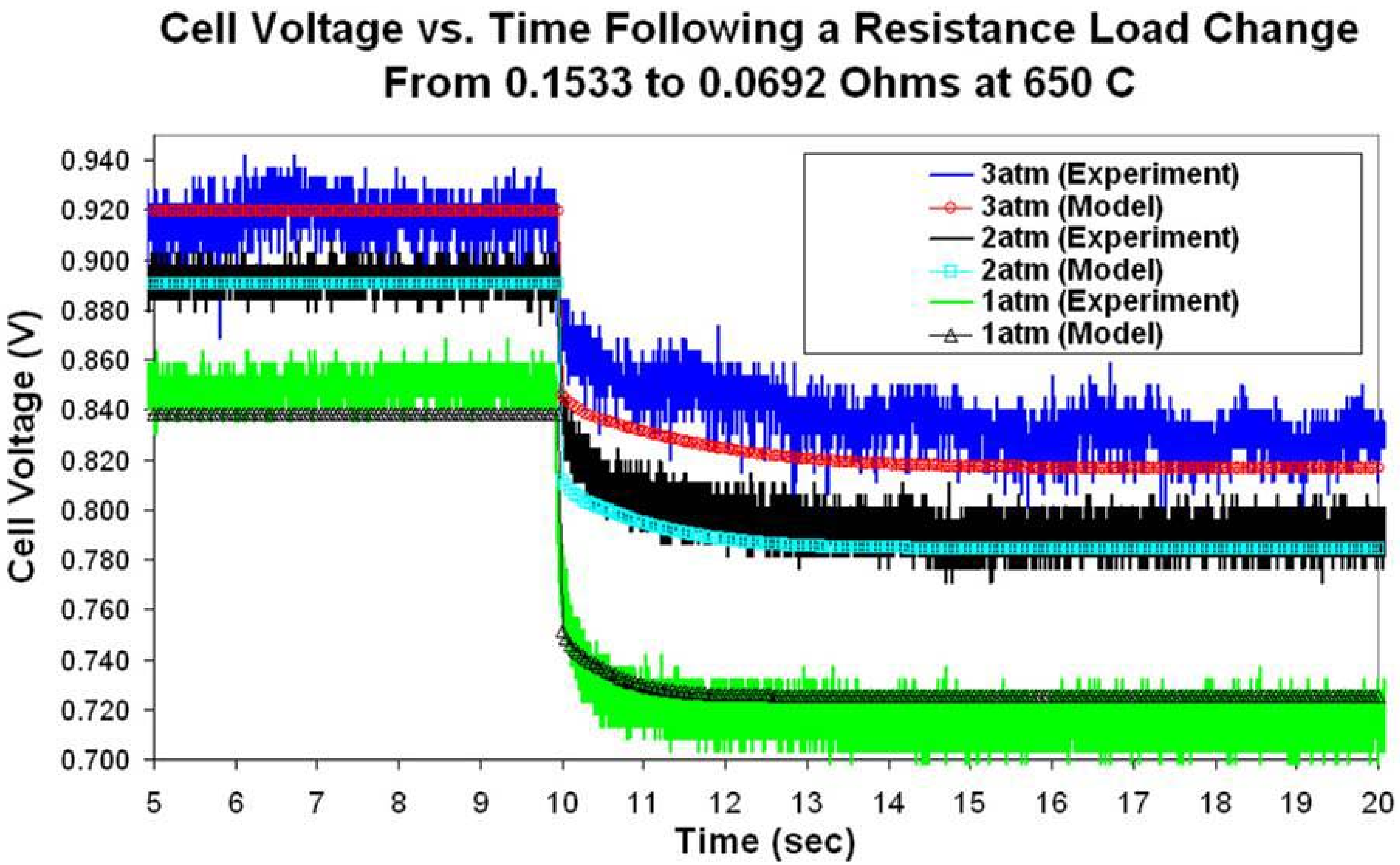
HYBRID SIMULATION

MCFC Hybrid Implementation



DATA AND VALIDATION

SINGLE CELL MCFC MODULE



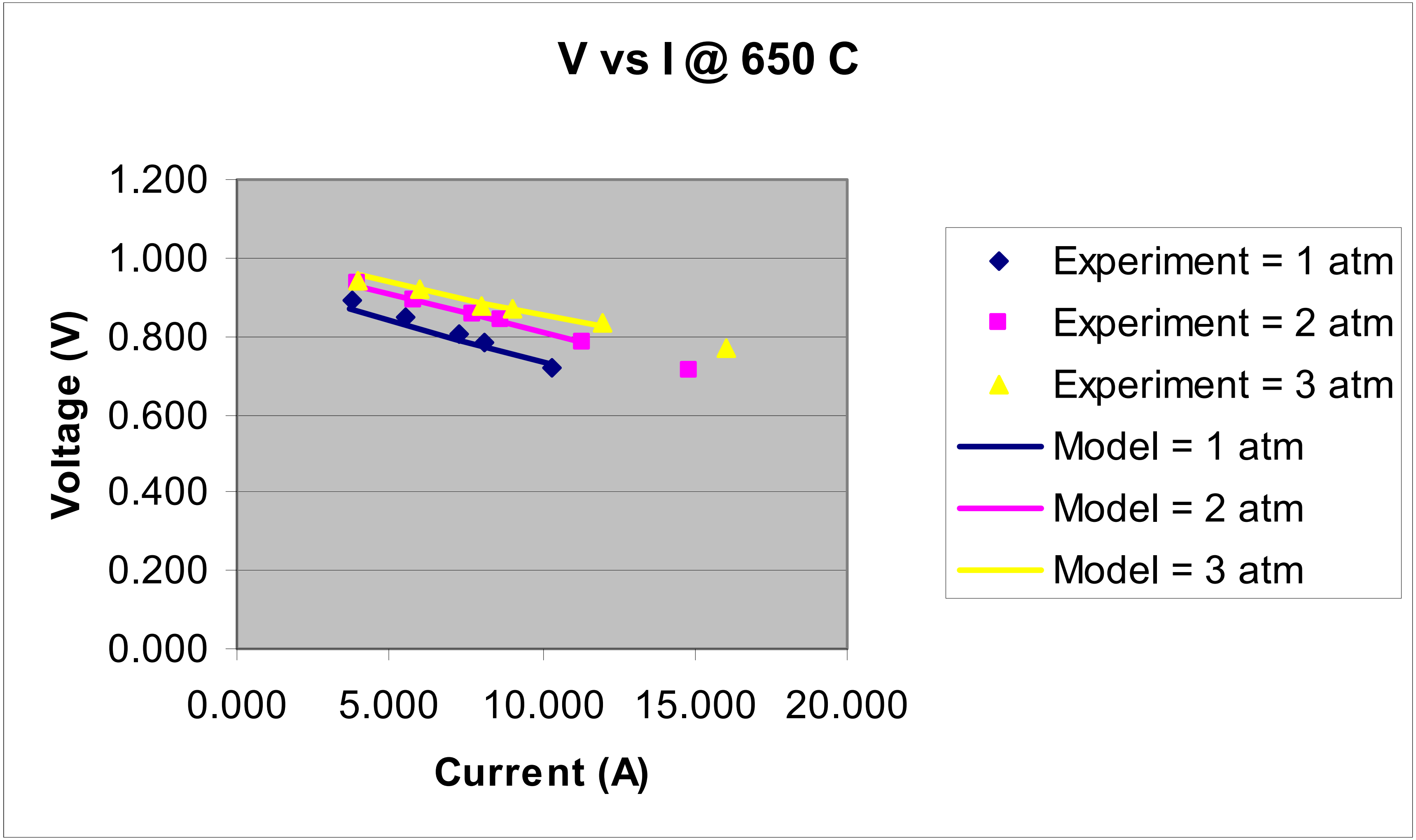
Model Exchange Current Density

Based on experimental fits:

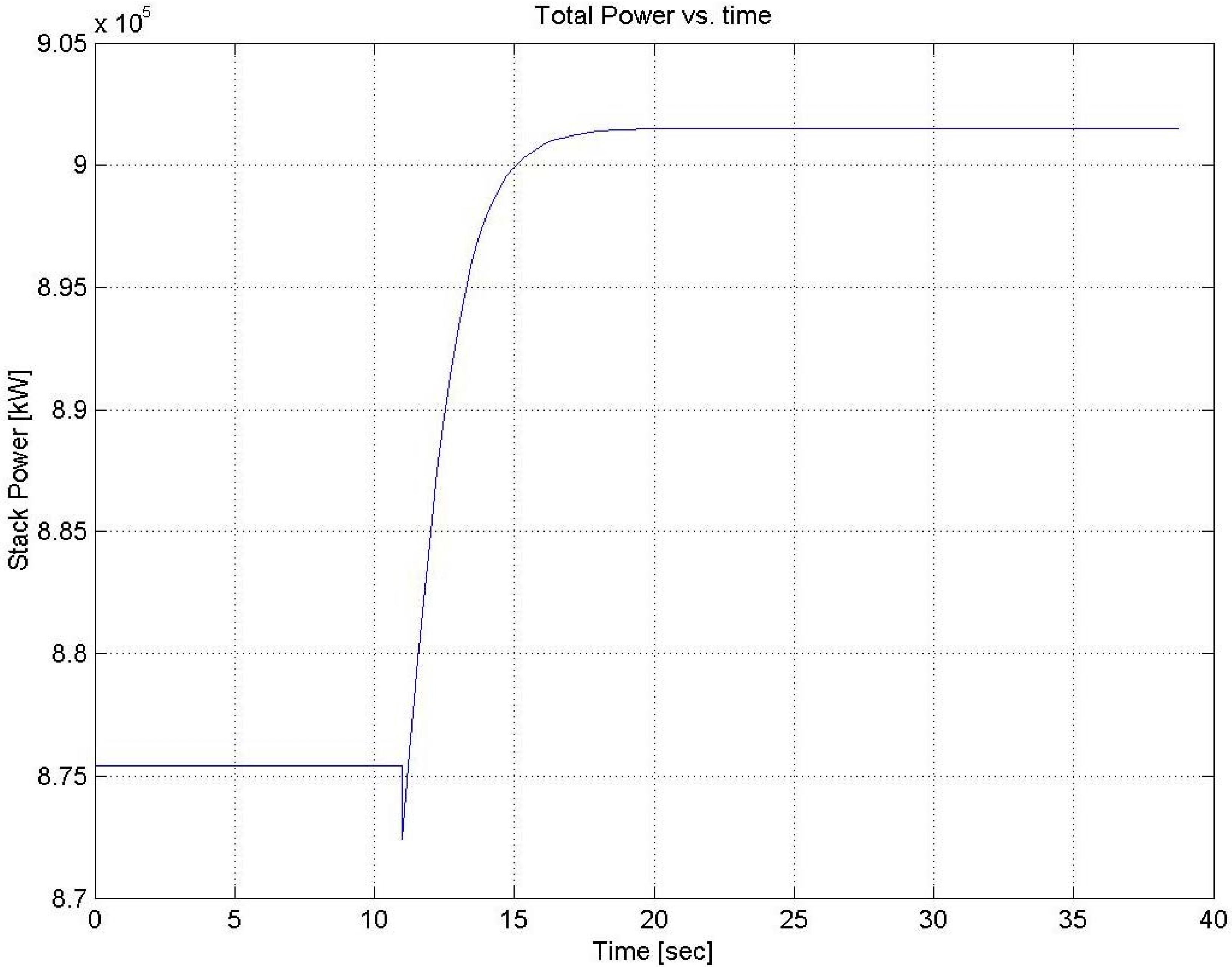
$$L_A = \frac{R_u T}{n \alpha F} \ln(i/\ i_o)$$

$$i_o = \mathrm{a}\, P + \mathrm{b}\, T + \mathrm{c}\, PT + \mathrm{d}$$

Model Validation



Control Challenge – Non-Minimum Phase



UNIVERSITIES FOR FUEL CELLS

PRINCIPLE: It takes village!

NFCRC OUTREACH INITIATIVE

- DEPARTMENT OF ENERGY
- DEPARTMENT OF DEFENSE

MISSION

- INITIATE UNIVERSITY AWARENESS AND PROGRAMS IN BOTH RESEARCH AND CURRICULA

- ADDRESS FUNDAMENTAL FUEL CELL ENGINEERING AND SCIENCE CHALLENGES

√
- DEVELOP WORK FORCE FOR NATION'S INDUSTRY

√
√

Results at: http://www.nfcrc.uci.edu/UfFC

RESEARCH CHALLENGES: CONTROLS

- DEVELOPING MODELS THAT AID IN CONTROL DESIGN AND ANALYSIS
- INTERFACES BETWEEN MODELS AT DIFFERENT SCALES / RESOLUTION
- CAPABILITIES FOR MODEL VALIDATION (EXPERIMENTS)
- SENSING AND ACTUATION TECHNOLOGIES
- UNDERSTANDING, INSIGHT, INTEROPERABILITY AND CONTROL OF THREE (3) MAIN PARTS OF A FUEL CELL POWER PLANT
- DIAGNOSTICS AND FAILURE PROGNOSIS
- COST (DESIGN FOR MANUFACTURING) AND COMPLEXITY (DESIGN FOR CONTROL) ISSUES
- IDENTIFICATION OF SYSTEM, HYBRID COMPONENTS OR ADDITIONAL CONTROLS REQUIRED TO APPLY FUEL CELLS TO ACTUAL DUTY CYCLES AND APPLICATIONS
- INTEGRATION ISSUES: NOT JUST THE COMPONENTS, BUT, INTEGRATION AND COMPOSITE PERFORMANCE

Control / Sensors / Actuators / Models

Model scale	Control	Control functions	Sensing and diagnostics needs	Actuation needs	Model type	Modeling tools
Vehicle	Active and passive	Driveability, performance, energy use	?	?	Quasi-static, Low-order lumped	Matlab Simulink
Power-plant	Active and passive	Meet demand, energy conversion efficiency,	Voltage, Power, Temperature, Humidity, flow, other	Valves, Regulators, temperature, voltage, power, motor controllers, etc.	Low-order lumped	Matlab Simulink
Fuel cell	Active and passive	Voltage and current (AC, DC), fuel supply	Gas composition Humidity	Valves, Regulators, Temp.	Low-order lumped	Matlab Simulink, nent
Stac						nt, al
Cell						nt,
Char	passive	mole fraction (bulk flow), pressure	Humidity Temperature Detailed diagnostics		3-D PDEs	Finite Element,
Micro	Passive	Thermal and molecular transport processes, gas diffusion layer, 2-phase flow resistance	Gas composition Humidity Temperature Detailed diagnostics	MEMS	3-D PDEs	?
Nano	Passive	Nanostructure and materials properties (e.g.: surface reactivity, catalysis, catalyst transport processes)	Gas composition Humidity Temperature Detailed diagnostics	?	?	?

- **Results at: http://www.nfcrc.uci.edu/UfFC**

SUMMARY

Control Research:

- Vital for operation AND design
- Lacks maturity (in modeling, control study, validations, etc)
- Needs further collaboration (especially with industry)
- It is hard!