Technical Development Issues and Dynamic Modeling of Gas Turbine and Fuel Cell Hybrid Systems

Eric Liese & Randall Gemmen (FETC)
Faryar Jabbari & Jacob Brouwer (NFCRC)

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Outline

- Introduction
- Hybrid Technology, Plant Description
- Modeling Needs
- Dynamic Modeling Tools Applied to Fuel Cells
- Reformer Model
- Solid Oxide Fuel Cell Model
- Model Results
- A Look Ahead
- Summary & Conclusion

Hybrid Technology

- SYNERGY
  - Efficiency higher than combination of components
  - Costs for a given efficiency are lower
- ENVIRONMENT
  - Extremely low criteria pollutant (NOx, SOx, CO, HC)
  - Lower global climate change gas emission (e.g., CO_2)
- TIMING
  - High temperature fuel cell performance (power, scale, longevity)
  - Fuel cell pilot production, prototype plants
  - Micro-turbine generator emergence

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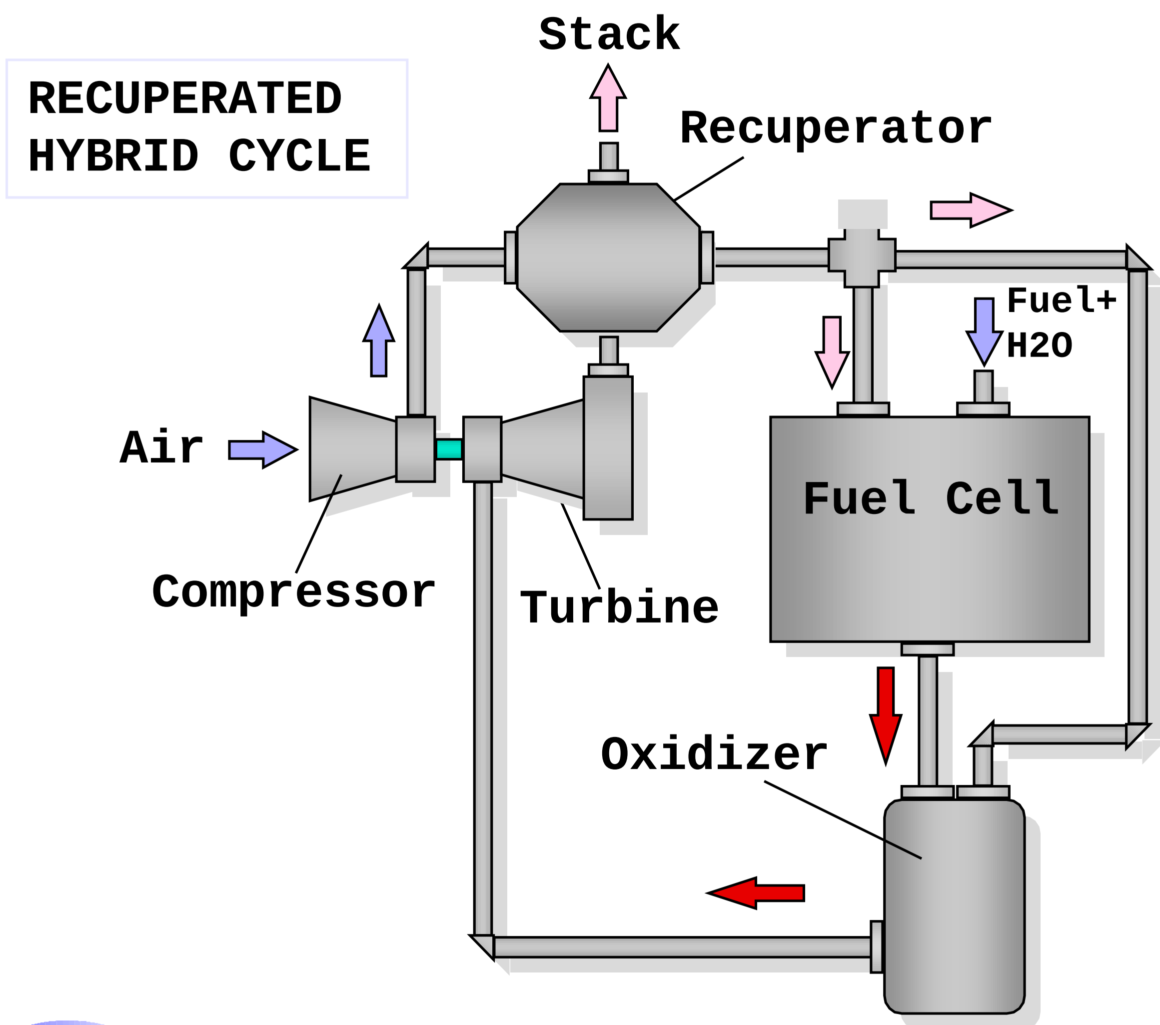
Hybrid Technology

- Myriad Cycles
  - Topping Mode
    - Fuel Cell replaces combustor and generator of Gas Turbine
    - Gas Turbine is balance of plant - with some generation
  - Bottoming Mode
    - Fuel Cell uses Gas Turbine exhaust as air supply
    - Gas Turbine is balance of plant
  - Indirect Systems
    - Use high temperature heat exchangers

Hybrid Technology



Benefits:
- Very High Efficiency
- Very Low Emissions

Issues:
- Controls
- Start Up
- Load Upset
- Combustion
- Thermal Management
- ...

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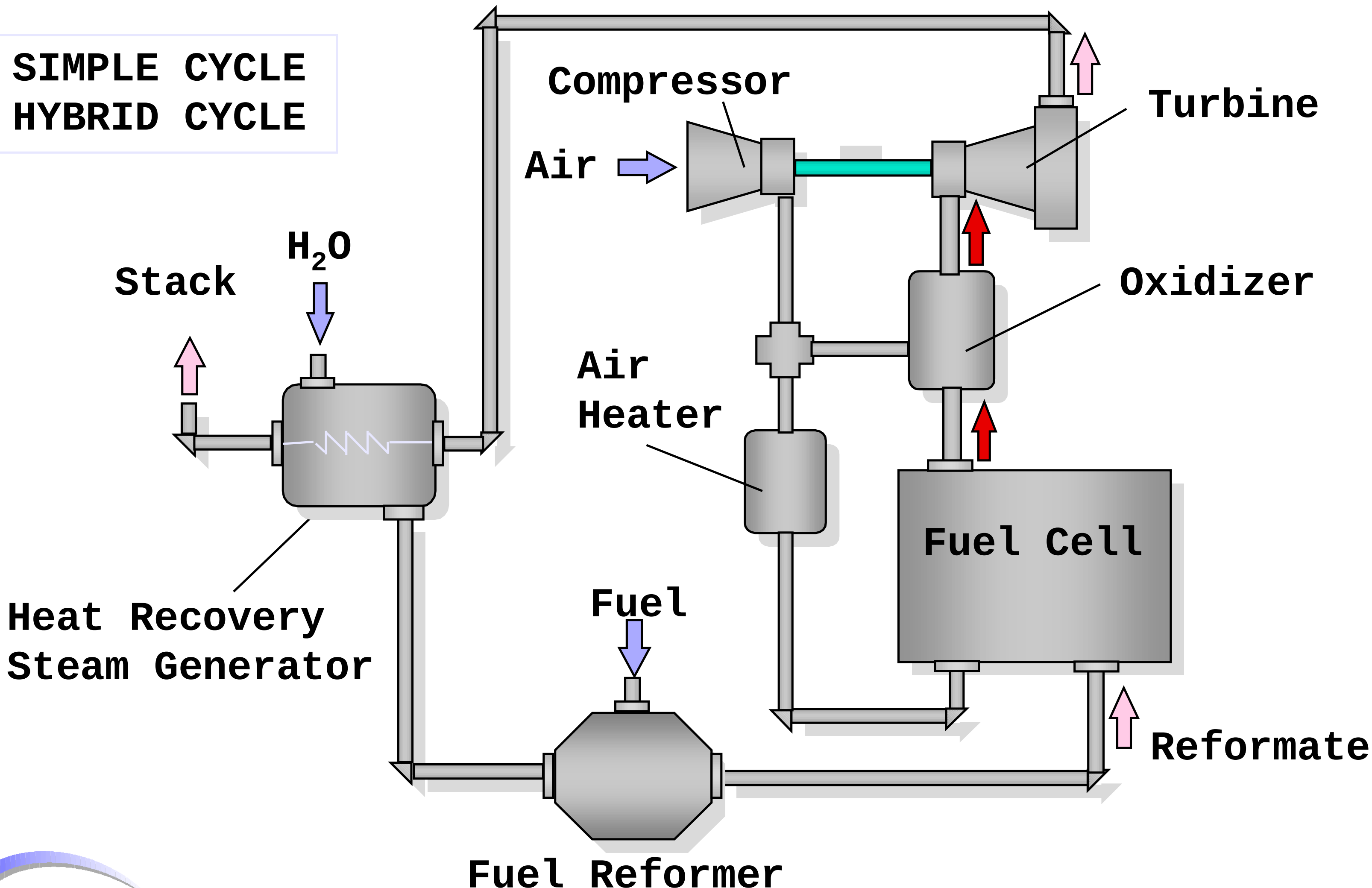
Hybrid Technology

SIMPLE CYCLE
HYBRID CYCLE



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Hybrid Modeling Needs

- System Transient Performance
- System Dynamic Control Requirements
- Electrical outputs (FC and GT), power inversion, and control
- Flow requirements (fuel, air, water, diluents) and control
- Heat exchanger/ancillary component transient response
- Varying Time Scales
  - Fuel Cell thermal mass
  - Turbine response times

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Model Developments

- Technical Status
- Current Approach:
  - Simplified treatment of system components:
    - 1-D reformer and combustor ("state-of-the-art")
    - simplified gas turbine model (Morre-Grietzer?)
    - 1-D fuel cell mass and energy transport--non cross-flow
    - etc.
  - Model-constants specified with available data
  - Generic results published
  - Establish partnerships for proprietary models and other technical assessments

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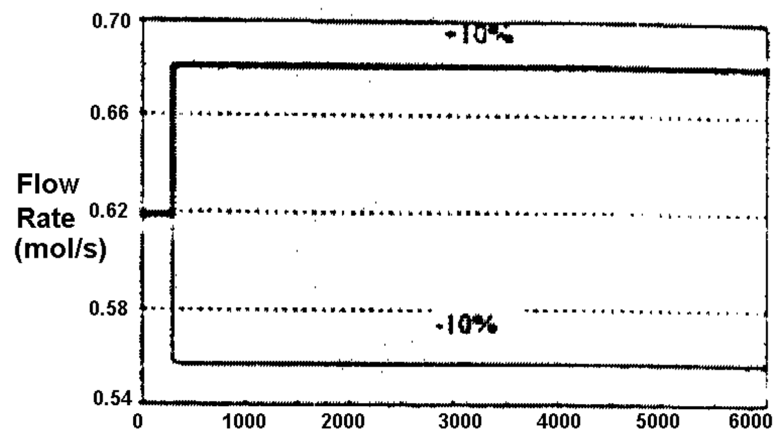
Dynamic Analysis Software

- **ProTRAX**
  - Reasonable cost/licensing
  - Previously employed for fuel cells--Kortbeek, et al. (1998)
  - Models most standard power plant equipment
    - heat exchangers
    - control valves and controller characteristics
    - gas compressors and turbines
  - No Fuel Cell or Reformer modules
  - Build FORTRAN code for integration w/ ProTRAX

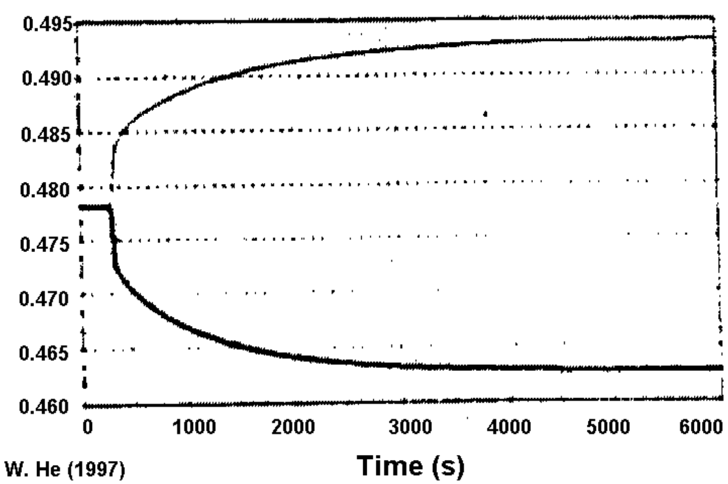
Dynamic Models in Power Generation Applications--Reformer Transients

- Reformer transients cause fuel & temperature variations downstream and influences fuel cell performance...
- FETC combustion work shows flame-out or poor combustor performance possible.

Natural Gas 10% Step Change



Hydrogen Concentration at Outlet vs. Time



Ref. W. He (1997)

Reformer Model

- **External Steam-Methane Catalytic Reformer**
  - Literature:
    - Alatiqi & Mezion (1-D, transient)
    - Xu & Froment (1-D, steady state)
    - Murray & Snyder (1-D, steady state)
    - Ohl, Smith & Stein (0-D, transient)
    - He (0-D, transient)
  - Current Development:
    - Counter-flow packed bed reformer.
    - 1-D, transient model following Alatiqi.
    - Nickel based catalysts with dedicated model equations available through literature.

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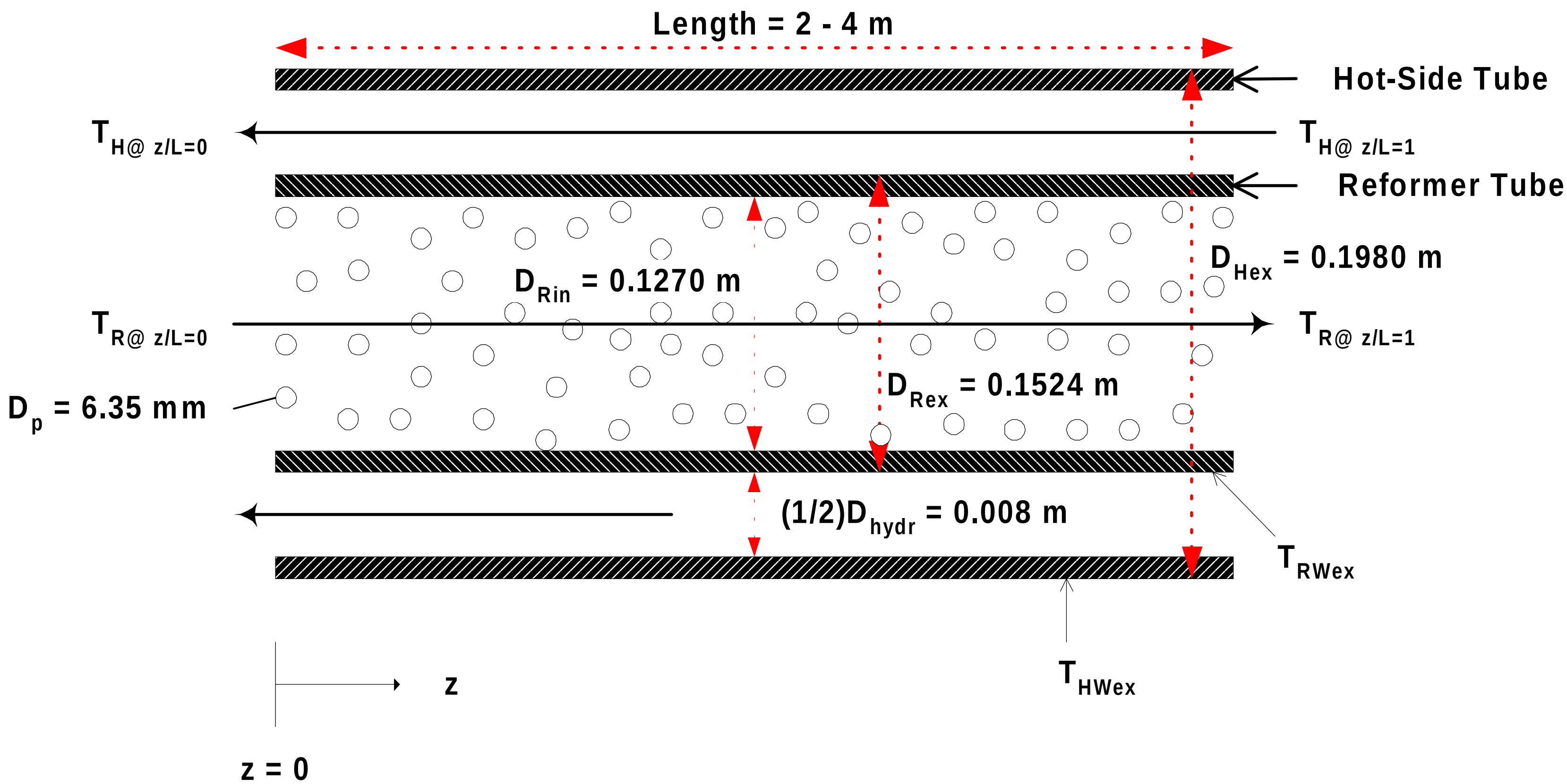
Reformer Geometry



Reformer Model

- Stoichiometry
  - Reforming: $CH_4 + H_2O = CO + 3H_2$
  - Watershift: $CO + H_2O = CO_2 + H_2$
  - Overall: $CH_4 + 2H_2O = CO_2 + 4H_2$
- Assumptions
  - A standard porous media heat transfer coefficient is used for the reformer-side heat transfer (Xu & Froment).
  - Heat transfer from hot side path is by convection and wall-to-wall radiation.
  - There is no carbon deposition.
  - Methane conversion is given by (Hyman):

$$r_{CH_4} = k_2 (K_2 P_{CH_4} P_{H_2O}^2 - P_{H_2}^4 P_{CO_2})$$

  - The CO_2 concentration is proportional to the methane conversion:

$$\frac{d(CO_2)}{dz} = \left(0.666 - 0.10\frac{z}{L}\right)\left(\frac{dx}{dz}\right) - \left(\frac{0.10}{L}\right)x$$

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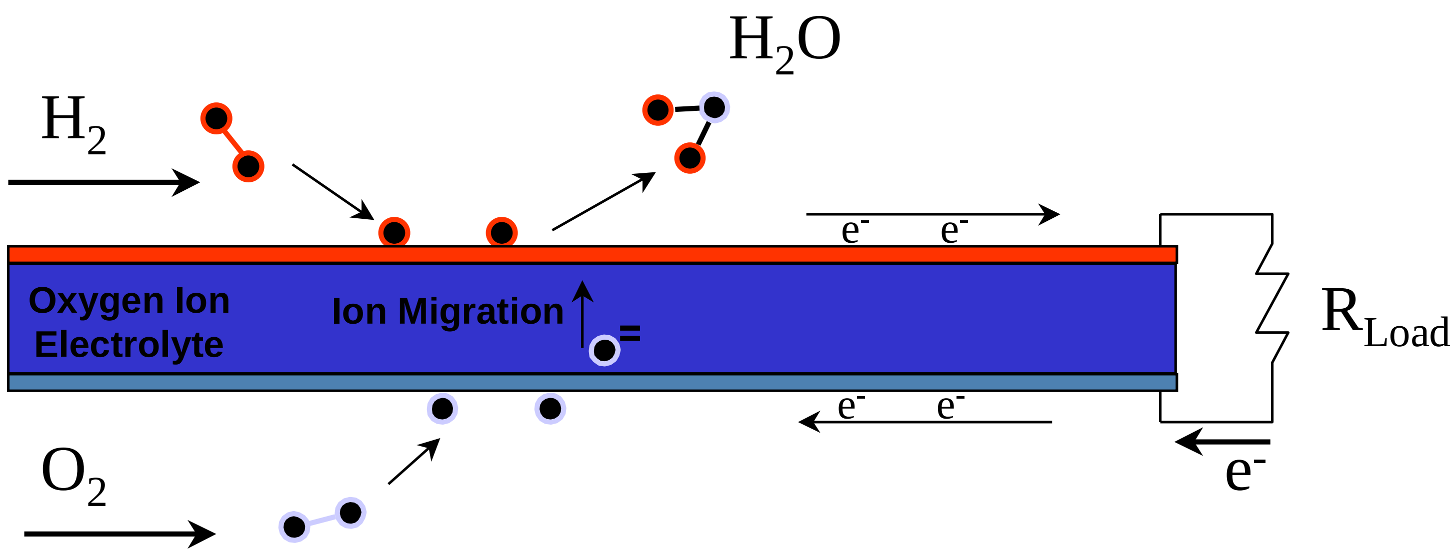
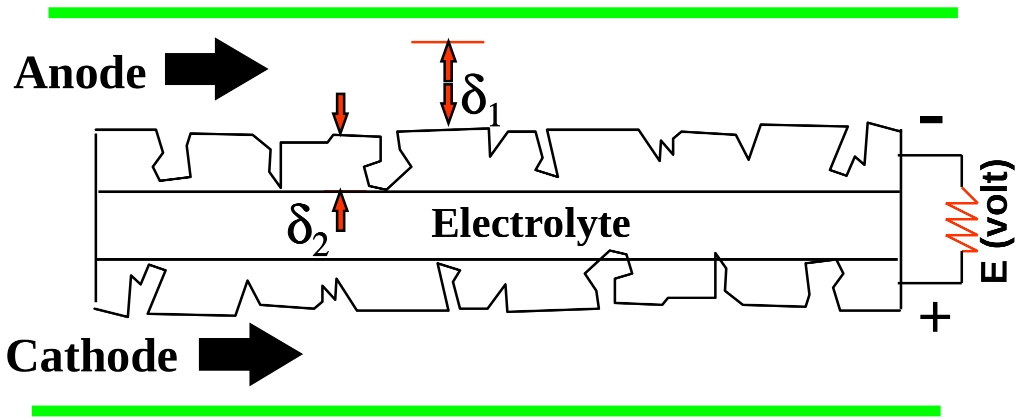
Basic Fuel Cell Electrochemistry



(Solid Oxide)

Fuel Cell Model



$$E = E_{Nernst} - \Sigma\, \eta_j$$

$$\eta_j = \text{Overpotential} = f(i, T, P)$$

Electrode/Electrolyte Dynamics:

•Complex, but main features understood.

•Assume:

QS electrode-electrolyte chemistry.

Thermally massive electrode-electrolyte and gases.

•Employ overpotential models as appropriate; e.g. Butler-Volmer.

•Neglect carbon deposition.

•Specify unknown parameters with available data.

Model Equations:

$E_{Nernst} = -\Delta G^o / nF$

Ohmic Loss:

$i\, R$

Concentration Loss:

$-R_u T \ln(1 - i/i_L) / nF$

Activation Loss:

$R_u T \ln(i/i_o) / \alpha nF$

Fundamental Heat Loss:

$-4.18\, \Delta S\, i / nF$

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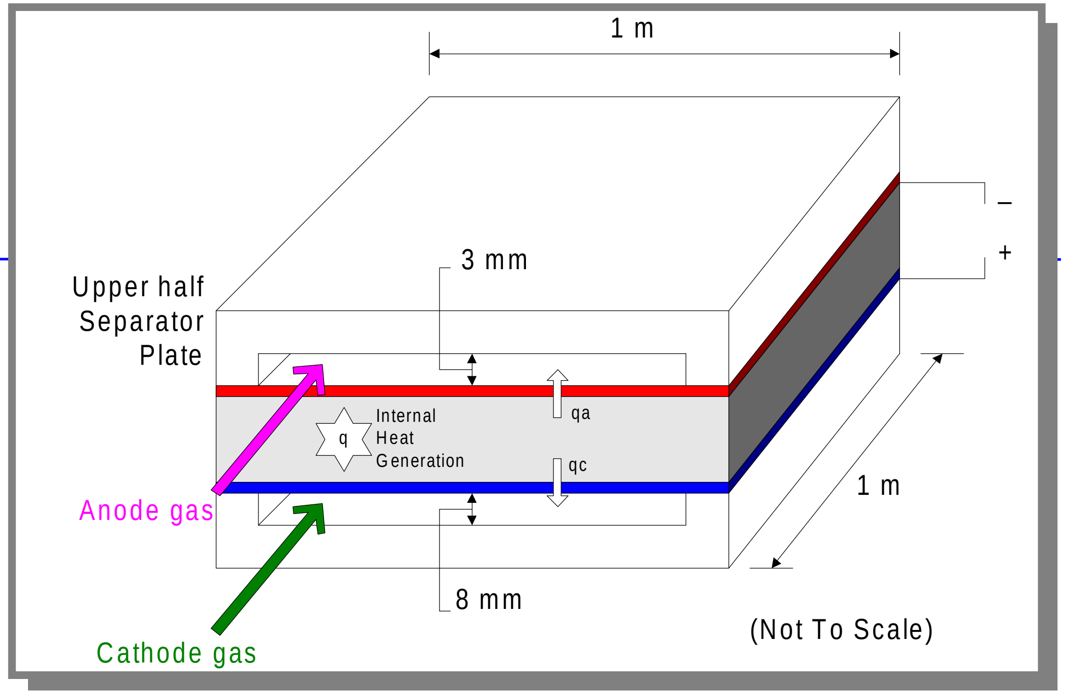
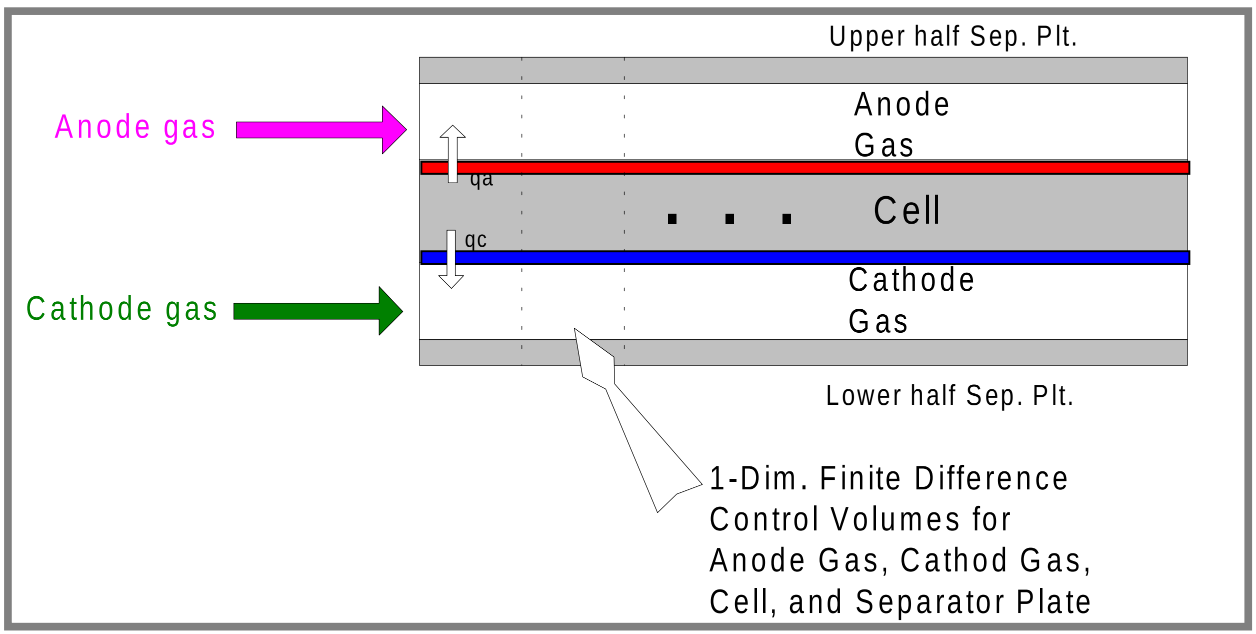
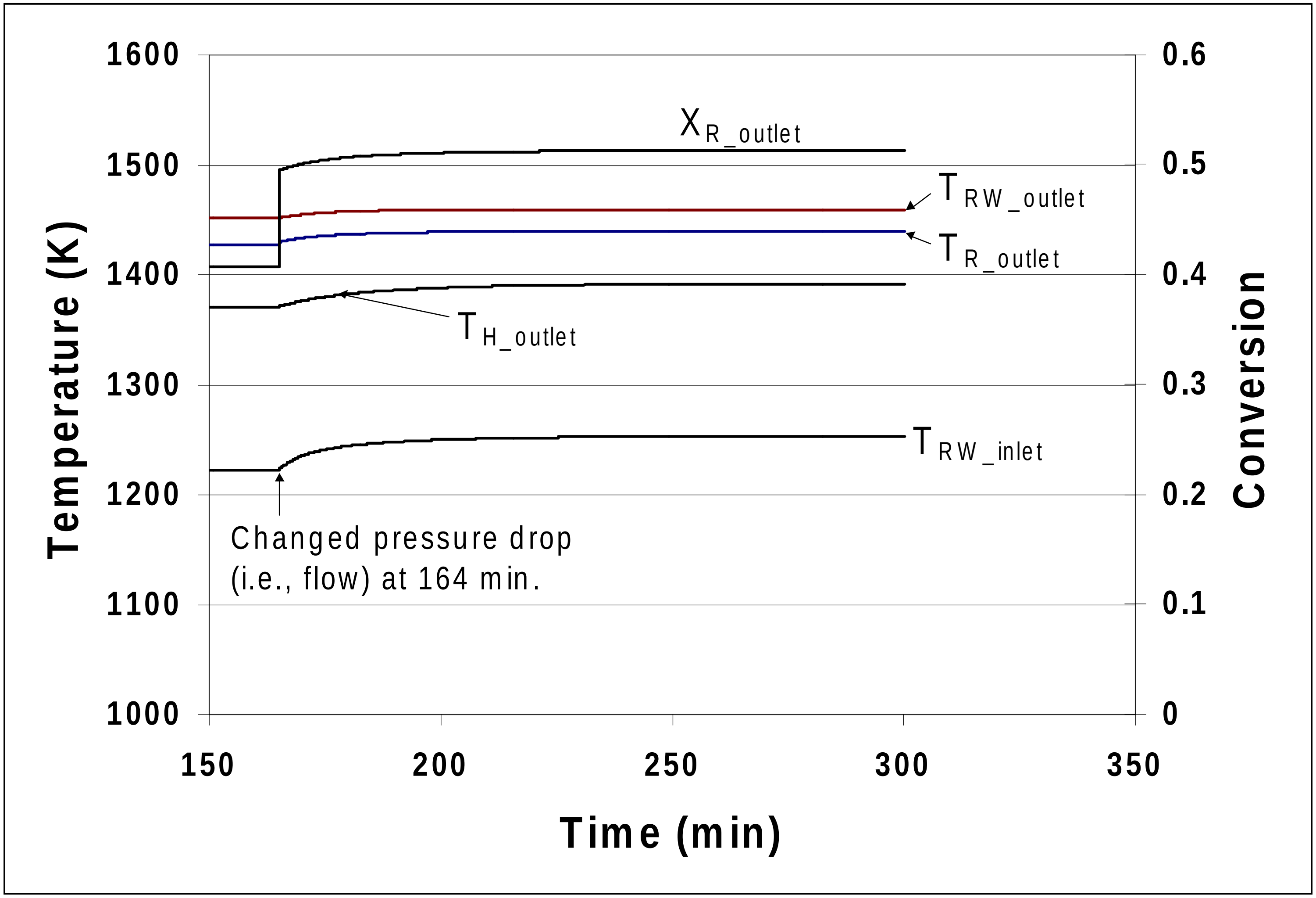
Fuel Cell Geometry

- Bipolar Planar FC
- Co-Flow
- One-Dim. Analysis





Decrease Reformer Gas Flow (30% by vol.)



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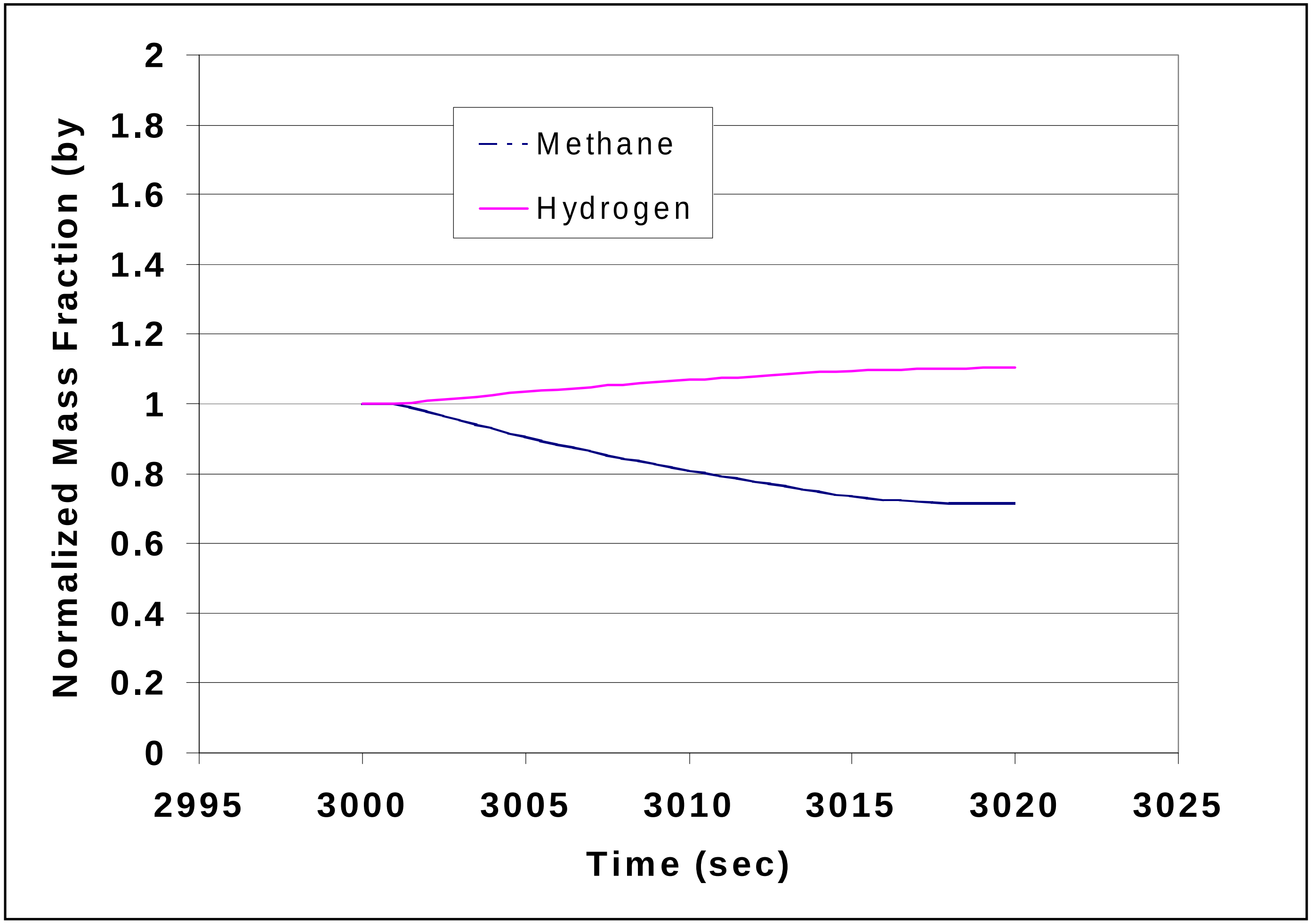
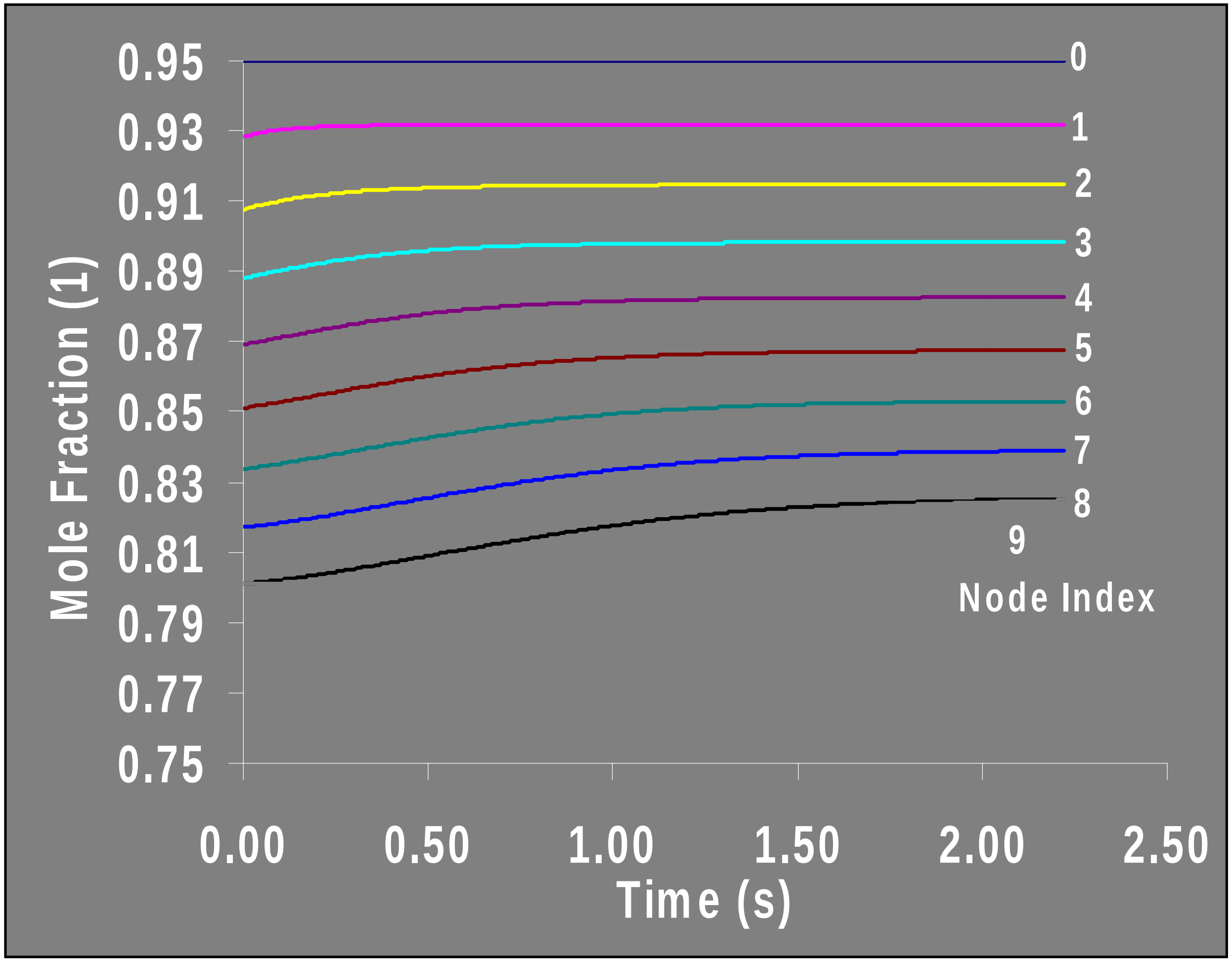


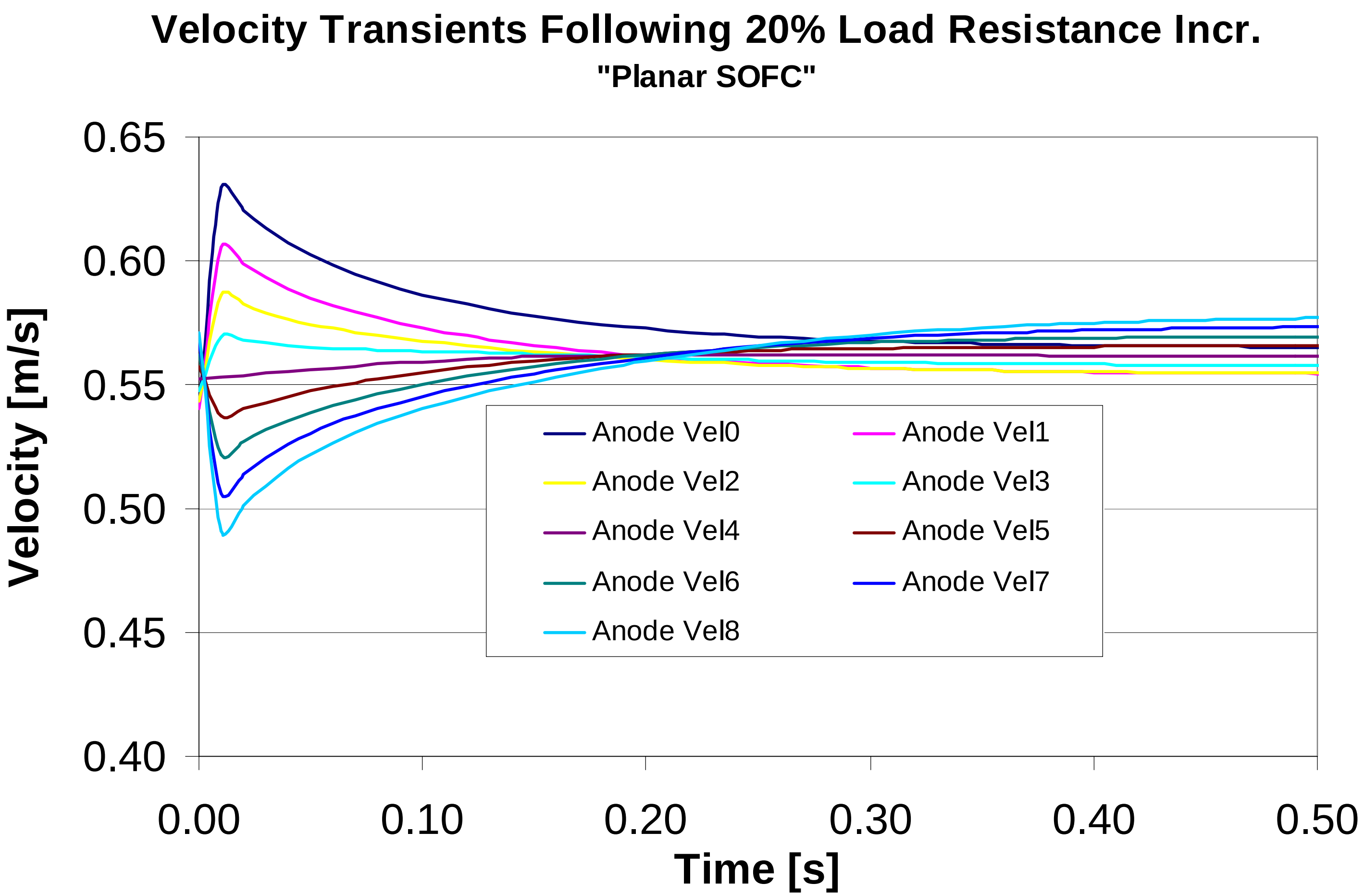
Fuel Cell Model Results



•Bipolar Planar (SOFC) Fuel Cell
•Hydrogen Fuel
•Time Scales:
-Thermal ~ 10^1 sec.
-Transport ~ 10^0 sec.

•20% Load (R) Increase Gives 20% Decrease in Fuel Utilization

Fuel Cell Results (cont.)



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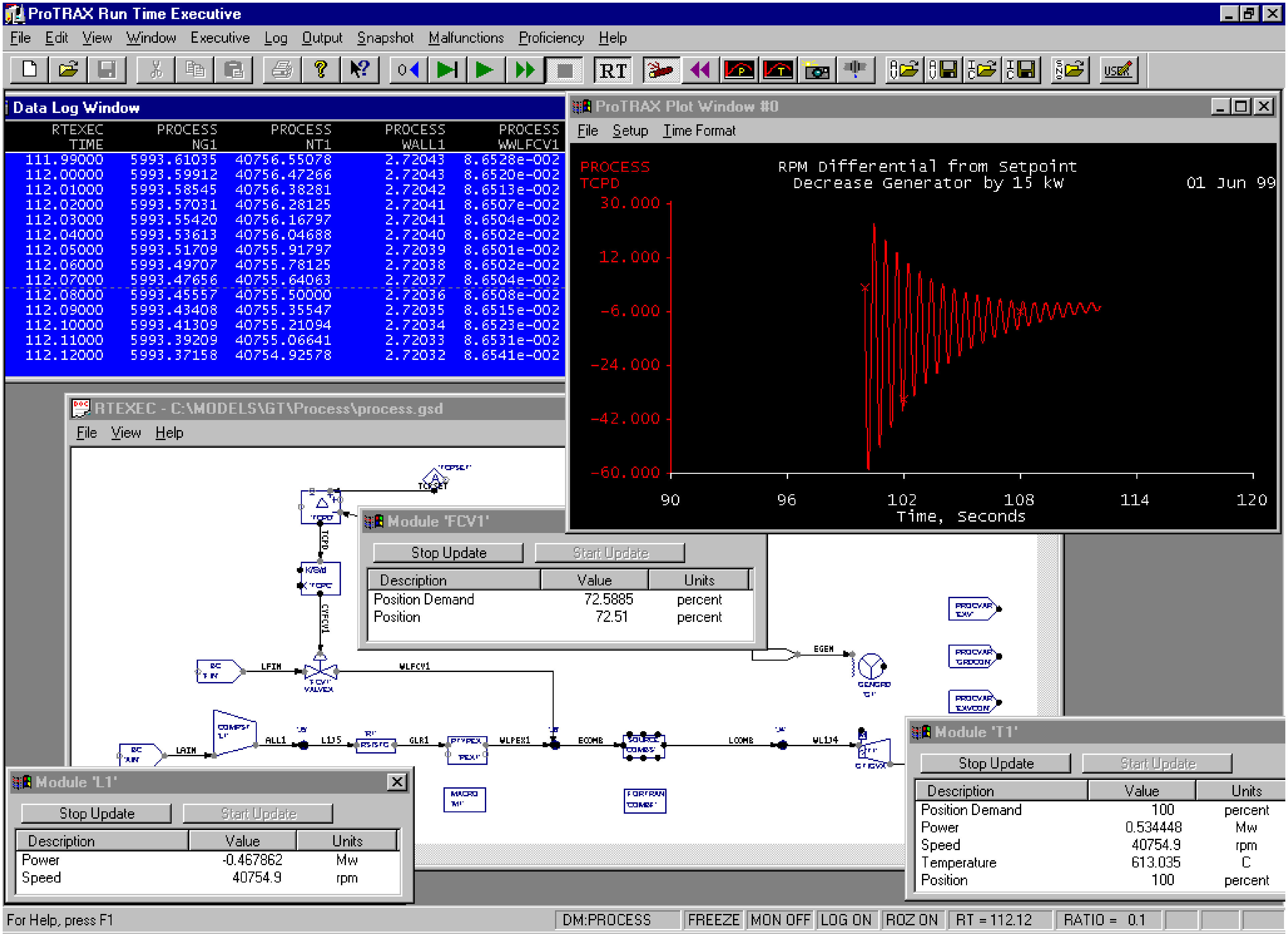
ProTRAX Run Time Executive
File Edit View Window Executive Log Output Snapshot Malfunctions Proficiency Help
RT
Data Log Window
RTEXEC TIME | PROCESS NG1 | PROCESS NT1 | PROCESS WALL1 | PROCESS WWLFCV1
111.99000 5993.61035 40756.55078 2.72043 8.6528e-002
112.00000 5993.59912 40756.47266 2.72043 8.6520e-002
112.01000 5993.58545 40756.38281 2.72042 8.6513e-002
112.02000 5993.57031 40756.28125 2.72041 8.6507e-002
112.03000 5993.55420 40756.16797 2.72041 8.6504e-002
112.04000 5993.53613 40756.04688 2.72040 8.6502e-002
112.05000 5993.51709 40755.91797 2.72039 8.6501e-002
112.06000 5993.49707 40755.78125 2.72038 8.6502e-002
112.07000 5993.47656 40755.64063 2.72037 8.6504e-002
112.08000 5993.45557 40755.50000 2.72036 8.6508e-002
112.09000 5993.43408 40755.35547 2.72035 8.6515e-002
112.10000 5993.41309 40755.21094 2.72034 8.6523e-002
112.11000 5993.39209 40755.06641 2.72033 8.6531e-002
112.12000 5993.37158 40754.92578 2.72032 8.6541e-002
ProTRAX Plot Window #0
File Setup Time Format
PROCESS TCPD
RPM Differential from Setpoint
Decrease Generator by 15 kW
01 Jun 99
30.000
12.000
-6.000
-24.000
-42.000
-60.000
90 96 102 108 114 120
Time, Seconds
RTEXEC - C:\MODELS\GT\Process\process.gsd
File View Help
Module 'FCV1'
Stop Update
Start Update
Description | Value | Units
Position Demand 72.5885 percent
Position 72.51 percent
LFIN
WLFCV1
EGEN
LAIN
ALL1
L1J5
GLR1
WLPEX1
ECOMB
LCOMB
WL1J4
Module 'L1'
Stop Update
Start Update
Description | Value | Units
Power -0.467862 Mw
Speed 40754.9 rpm
Module 'T1'
Stop Update
Start Update
Description | Value | Units
Position Demand 100 percent
Power 0.534448 Mw
Speed 40754.9 rpm
Temperature 613.035 C
Position 100 percent
For Help, press F1
DM:PROCESS FREEZE MON OFF LOG ON ROZ ON RT = 112.12 RATIO = 0.1

Summary

- Past steady state model results provide motivation for *Hybrid Technology*.
- Need dynamic analysis/prediction capability.
- NFCRC/FETC modeling activity achieves:
  - predictive tools for hybrid systems.
  - technology development & transfer through future partnerships.
  - provide direction to future DOE programs.
- Present results begin to show *generic* behavior for reformers and fuel cells, with future applications showing implications for hybrid systems.

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