CFC/BT/GTRI PERC/UIC EMI/VT

Modeling of Electrical Interactions with SOFCs

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SECA Modeling & Simulation Team – Integration Meeting

October 15, 2002

NETL, Pittsburgh

APU Overview

- Meet customer requirements, but also add new features
  - Pre-heat and Pre-cool
  - Engine-off electrical accessories
  - Remote and emergency power
- Peak power of 4-5 kWe for LDV
- Could reduce peripherals fuel consumption by 50 %
- Largest benefit for applications with high idle times

Key APU Requirements

- Common fuel, small, lightweight
- High system efficiency, low emissions
- Start-up in less than 3 minutes
- Maintenance, durability, cost consistent with application (commercial, RV, luxury, first applications?)
- Noise

SOFC APU Sizing

Typical vehicle APU application:

Maximum power = 5000 We (100 %)
Average power = 1500 We (30 %)
Minimum power = 500 We (10 %)

Transient Response

Different time constants - fast to slow:

- Electrochemistry – instantaneous (sufficiently fast to assume quasi-stationary behavior)
- Stack electrical response – fraction of a second
- Thermal-hydraulic response – seconds (e.g., POX) to minutes (e.g., SMR)
- PES electrical response - msec
- Load response with some energy storage - 1 sec
- Start up time - 10 sec to 3 min

OBJECTIVES (Phases I and II)

- Develop fully transient nonlinear, unified models for SOFC planar configurations, different PESs, and a variety of BOPS components

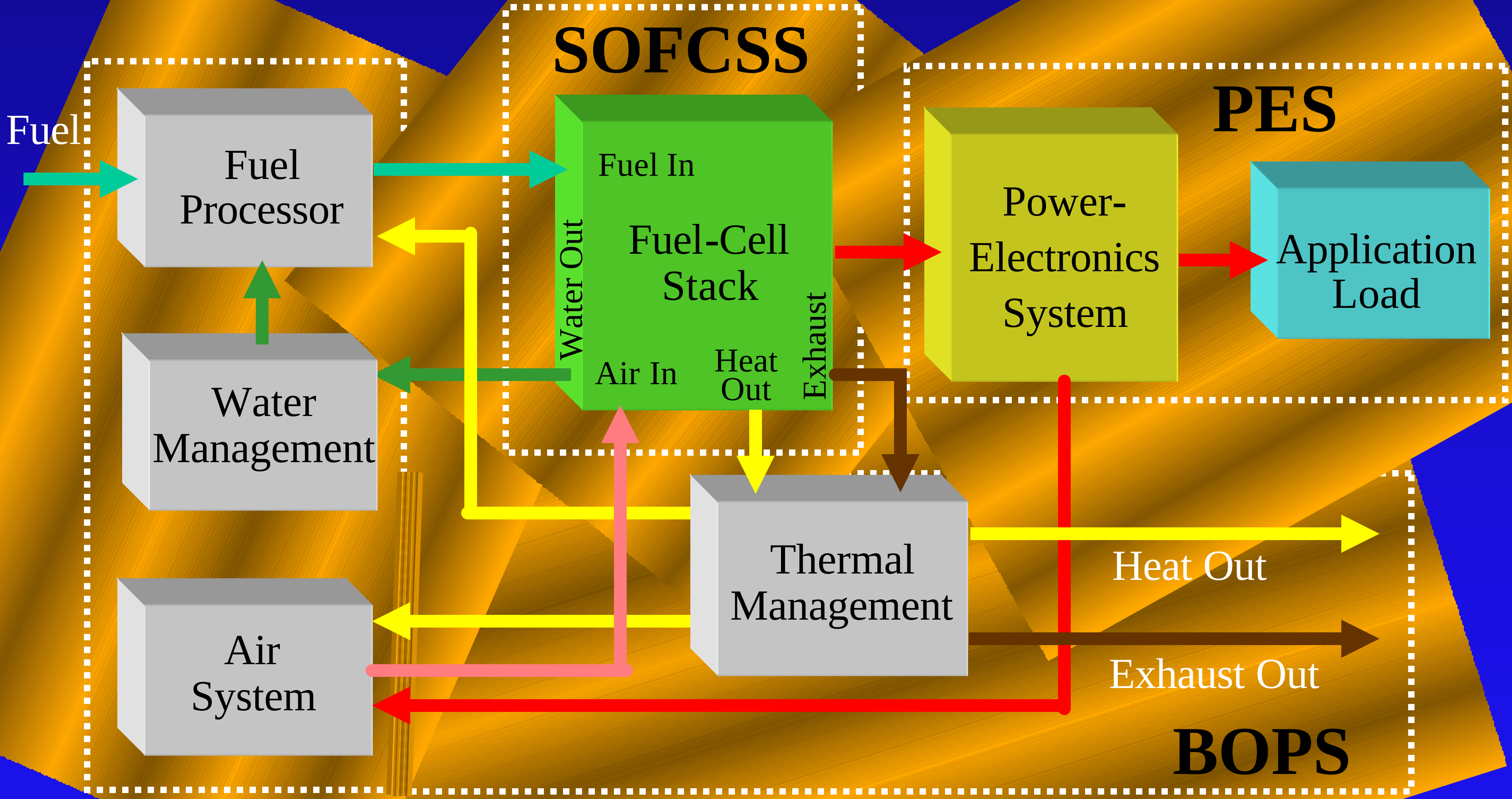
- Implement models in the SaberDesigner and gProms dynamic simulation and optimization environments

- Demonstrate the feasibility of integrating these models into an overall systems-analysis and optimization tool (Phase I)

- Develop a prototypical software package (Phase II) for industry to understand the dynamics of SOFC stack, power electronics, and system interactions

- Conduct parametric studies (Phase I) and optimizations (Phase II) to determine control strategies and their effects on cell reliability, efficiency, and power density; as well as system response and configuration, and component designs.

SOFC Power-El nics Subsyste



SOFCSS

PES

BOPS

Fuel

Fuel Processor

Fuel In

Fuel-Cell Stack

Water Out

Air In

Heat Out

Exhaust

Power-Electronics System

Application Load

Water Management

Thermal Management

Air System

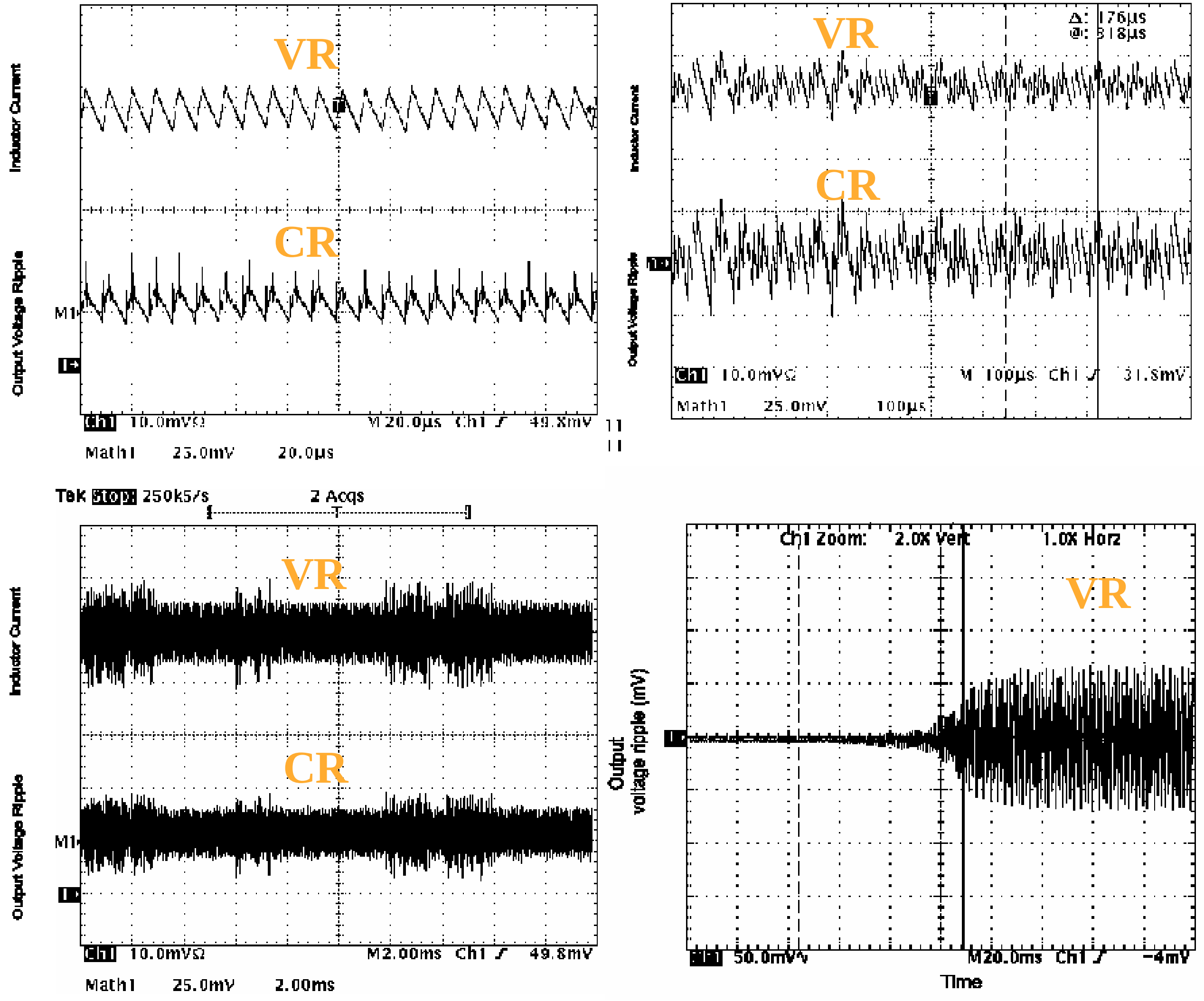
Heat Out

Exhaust Out

Technical Issues: PES

- To investigate the impact of critical parameters of a closed-loop PES, which can negatively affect the performance and integrity of a SOFC stack for a given application load *{Phase I (set cases); Phase II (experimental verifications of Phase-I results and extension to generalized analysis)}*
  - Circuit and control parameters of the power converters
  - Topological architectures (standalone, cascaded, or distributed).
  - Switching schemes (that is, whether the converters are operated with PWM, soft switching, interleaving etc.)
  - Application load (converter and stationary/non-stationary loads)

Impact of Parametric Variations on Ripple: An “Illustration” for a DC-DC Converter



By simply varying “only one” parameter (load in this case), the voltage and current ripples of the converter change drastically. In reality, more than one parameter can vary simultaneously.

VR: Voltage ripple

CR: Current ripple

Technical Issues: PES

- To investigate the steady-state and dynamic interaction problems due to the integration of the SOFCSS and PES for a given application load *{Phase I (set cases); Phase II (experimental verifications of Phase-I results and extension to generalized analysis)}*
  - Fast- and slow-scale scale instabilities in ripple dynamics
  - Impact of variations in SOFC output voltage on PES
  - Effect of time-varying perturbations of the stationary/non-stationary loads and PES on the SOFC

Technical Issues: PES

- To determine the criteria for the synthesis of an optimal power-electronic converter (for a given SOFC), which can increase the lifetime and efficiency of the fuel cell *{Phase II (robust)}*
  - What type of converter topology should one choose, for a given application load, so that the performance and efficiency of the SOFC can be maximized? (A SOFC can be interfaced to an application load using multiple converter topologies. The severity of the interactions among the subsystems is not the same for all the topologies.)
  - How should one optimize an existing power-electronics system so that it has minimal negative effect on the SOFC?

R&D Approach: PES

- Unified Model of PES
  - Power-electronic systems are “hybrid systems”; they comprise discontinuous differential equations, discrete differential equations, functional differential inclusions, digital automata, impulsive differential equations, non-smooth differential equations, ordinary and even partial differential equations
  - Unified framework is an indexed collection of dynamical systems along with a map for transitions among them that can account for “any” dynamical model of a PES and predict fast- and slow-scale ripple dynamics

Conventional Averaged Models of PES cannot account for all ripple dynamics and in many cases predict incorrect stability results.

R&D Approach: PES

System Interaction using “Bifurcation” Analyses

When does a nominal system loose stability?

For variations in one or more parameters, when can one expect the ripple magnitude and frequency of the PES to change?

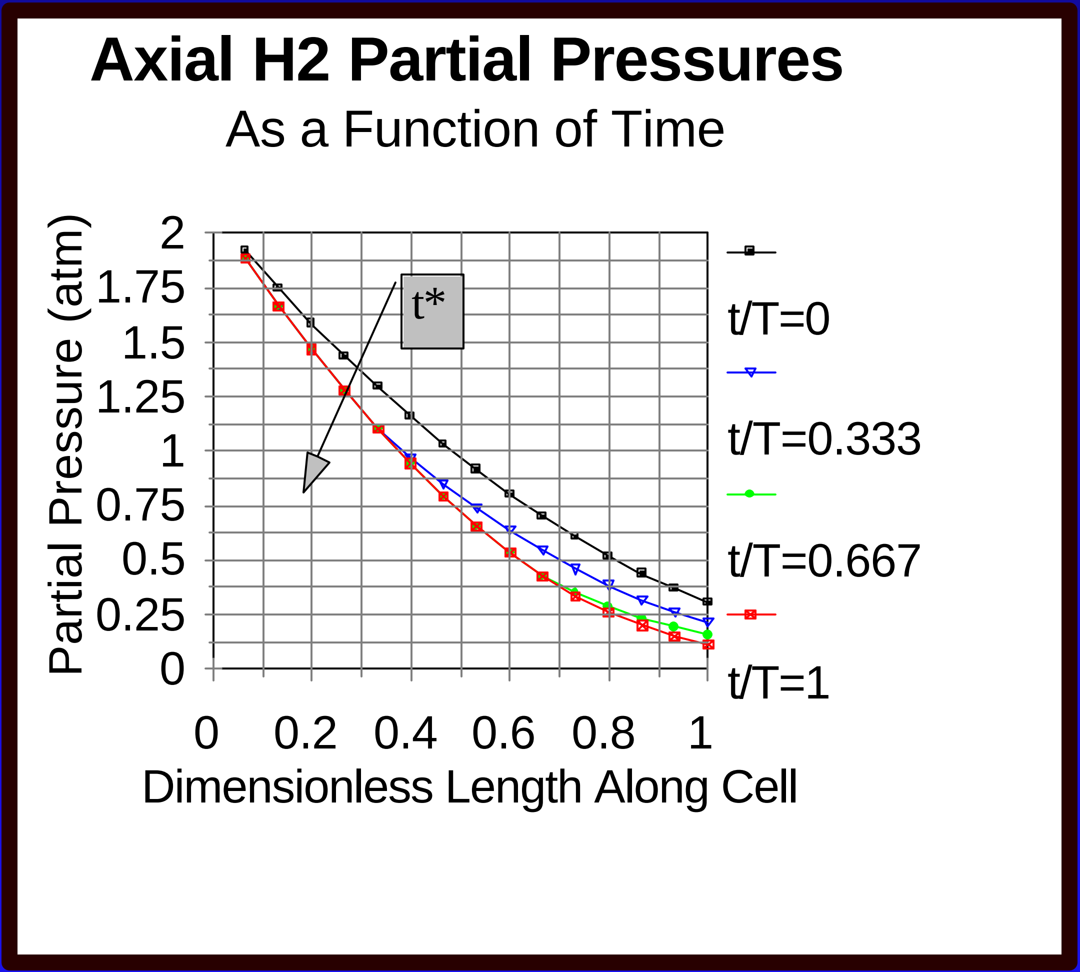
What is the mechanism of the instability?

How conservative should the PES design be?

What happens after the instability (post-instability dynamics)?

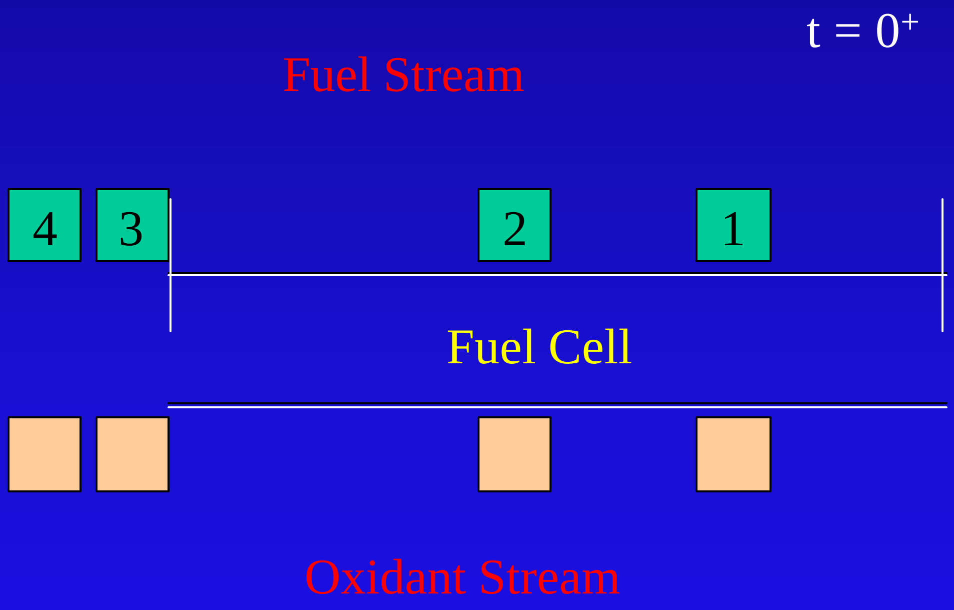
- Are the “new” voltage and current ripples dangerously high for the SOFC?

Previous Successes: SOFCSS - Modeling TSOFC Transients with Lagrangian Approach



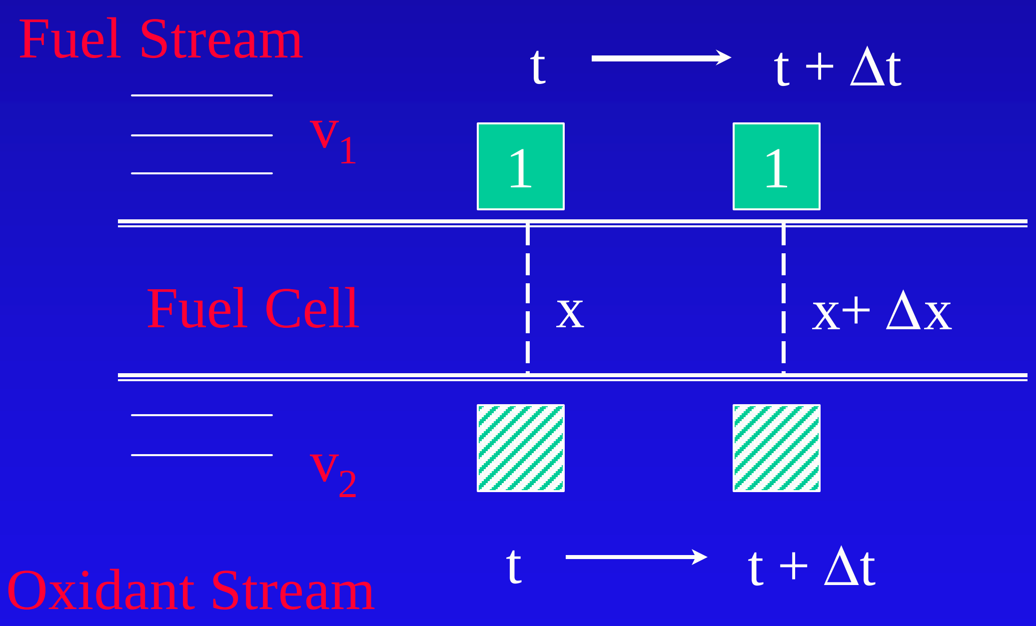
- At “$t^*=0^+$” the load increases and current initially “spikes” up
- The reactants supply, however, does not change
- A new steady state is reached wherein the hydrogen profile is decreased along the anode due to reactant depletion

Previous Successes: SOFCSS - Modeling TSOFC Transients with Lagrangian Approach



- Reactants’ inlet flow properties are the same
- The fuel elements’ exit properties depend upon their locations at $t^*=0^+$
- Steady state is regained when element 3 exits ($t^*=1$), because every successive element will then pass along the cell “seeing” only the new operating potential

Previous Successes: SOFCSS - Modeling TSOFC Transients with Lagrangian Approach



Fuel Stream

t → t + Δt

v_1

1

1

Fuel Cell

x

x+ Δx

v_2

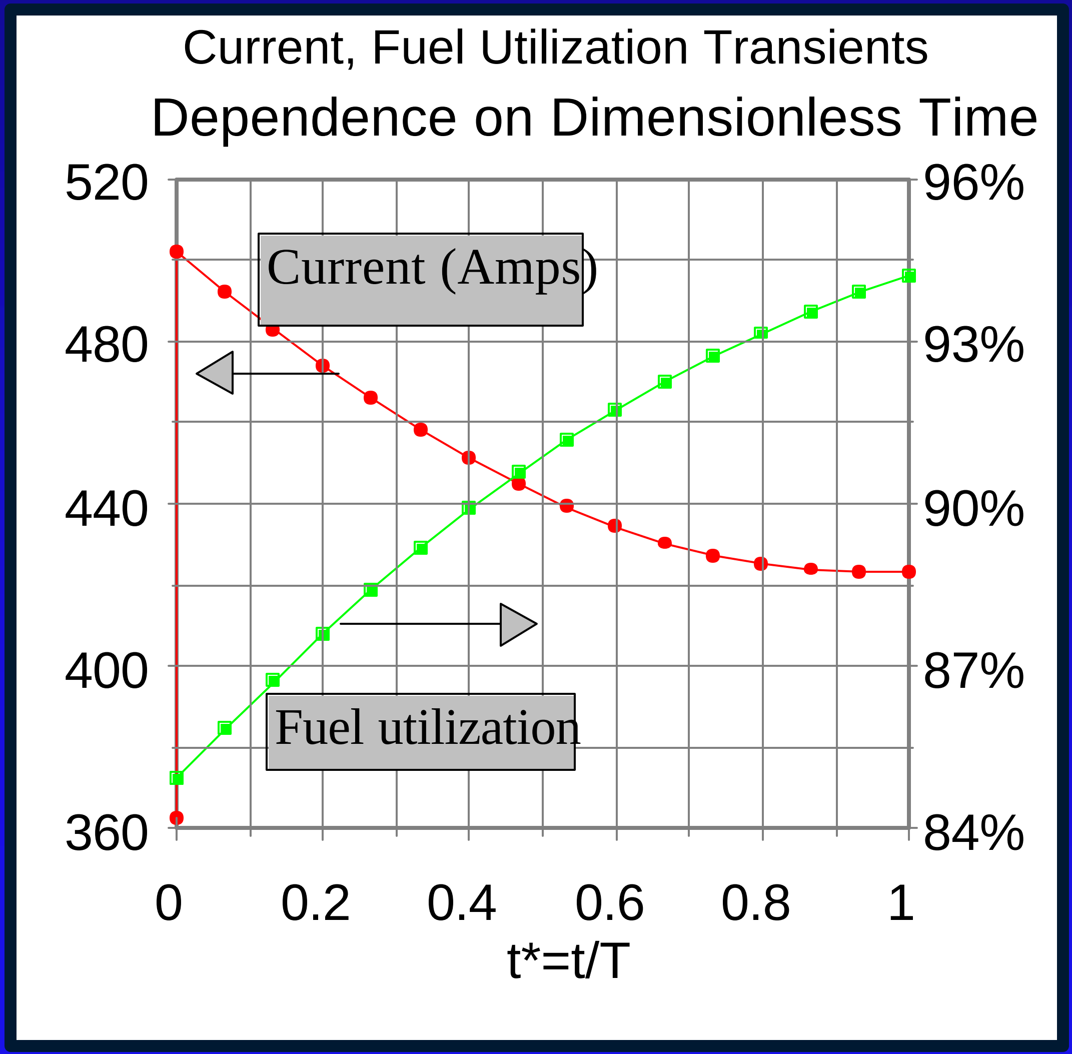
t → t + Δt

Oxidant Stream

$$\eta_{element}(t+\Delta t) = \eta_{field}(x+\Delta x, t+\Delta t)$$

Element properties were calculated by using the proven steady state model on an instant-by-instant basis until a new electrical steady state was reached

Previous Successes: SOFCSS - Modeling TSOFC Transients with Lagrangian Approach



- Current spikes up, yet the fuel supply remains invariant due to the *decoupling* of the cell

- Fuel utilization thus increases; this causes current (and power) to decrease from $t^*=0^+$ values, until a new steady state “match” occurs at the new voltage $(t^*=1)$

R&D Approach: SOFCSS
- Need Enhancements to Transient Model

- Dynamic response to current ripple

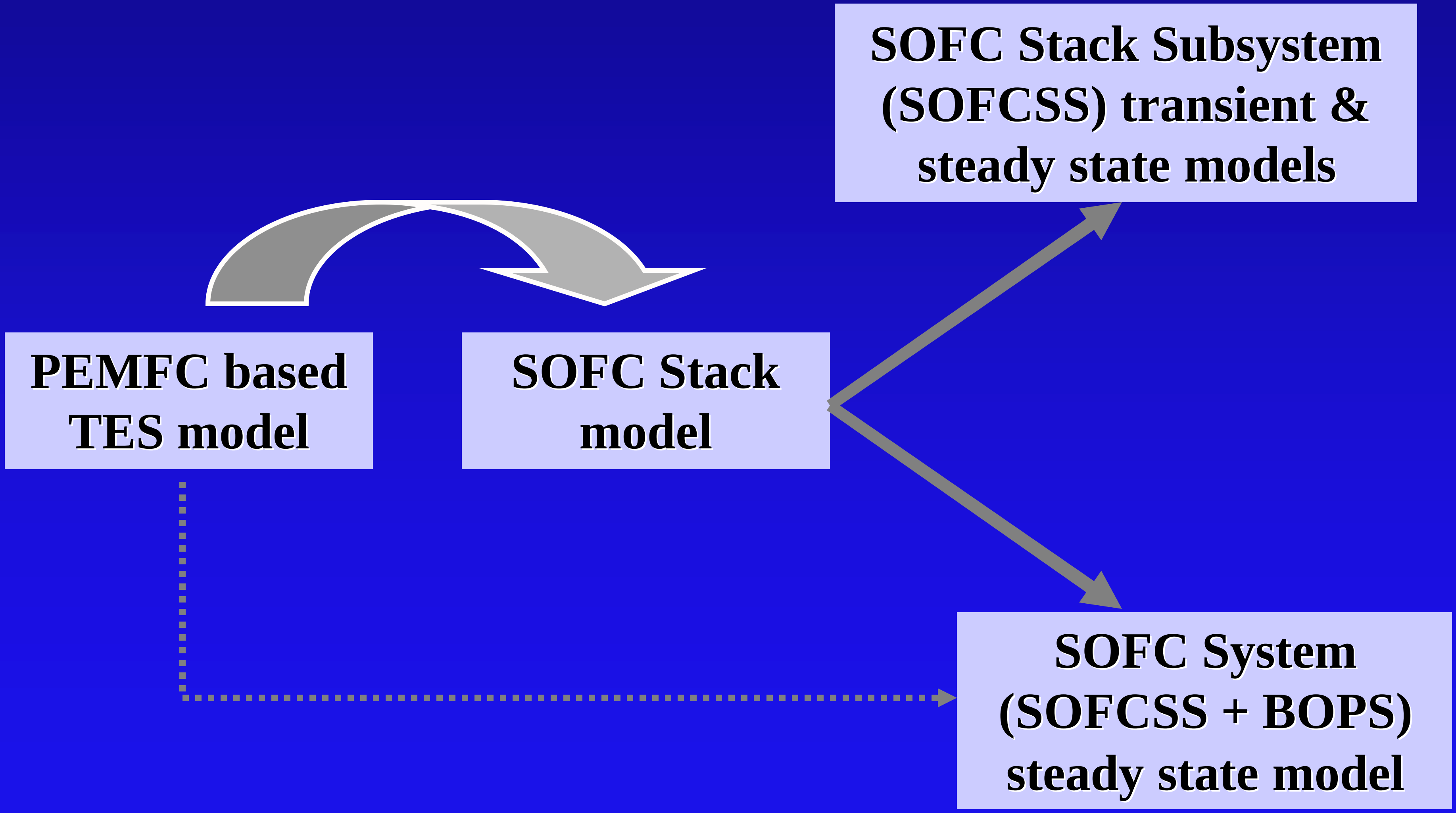
Superposition applied to original Lagrangian approach wherein multiple, periodic stimuli (as opposed to initial stimulus) serve as the "forcing function"

- Cell reliability under load variation

Resolution of operating environment via model(s)

Extensive communication with SECA teammates regarding cell sensitivity issues (*e.g.*, *"electrochemical fatigue" parameters??)*

Previous Work Modeling the SOFCSS/BOPS



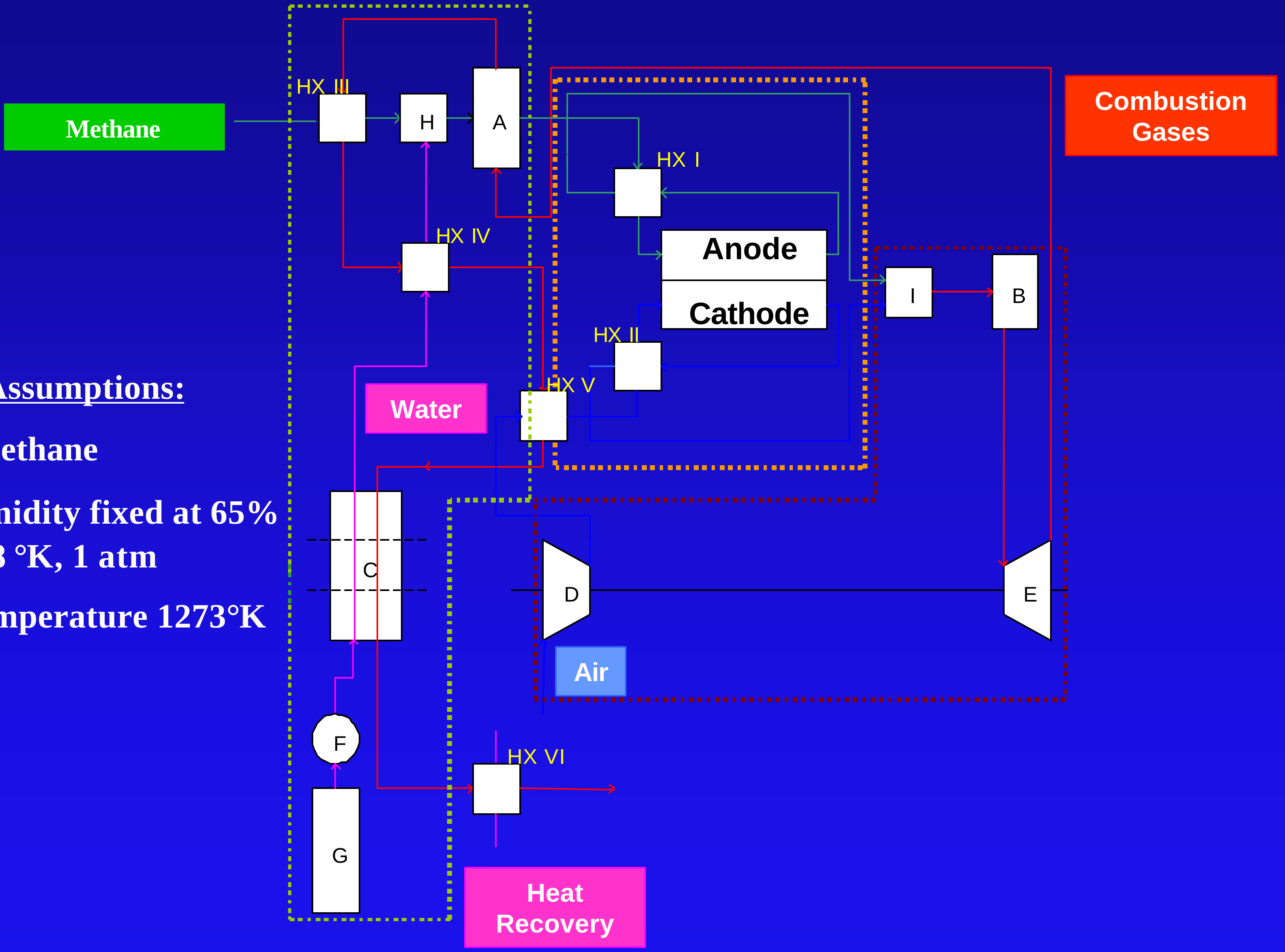
SOFC Stack Subsystem (SOFCSS) transient & steady state models

PEMFC based TES model

SOFC Stack model

SOFC System (SOFCSS + BOPS) steady state model

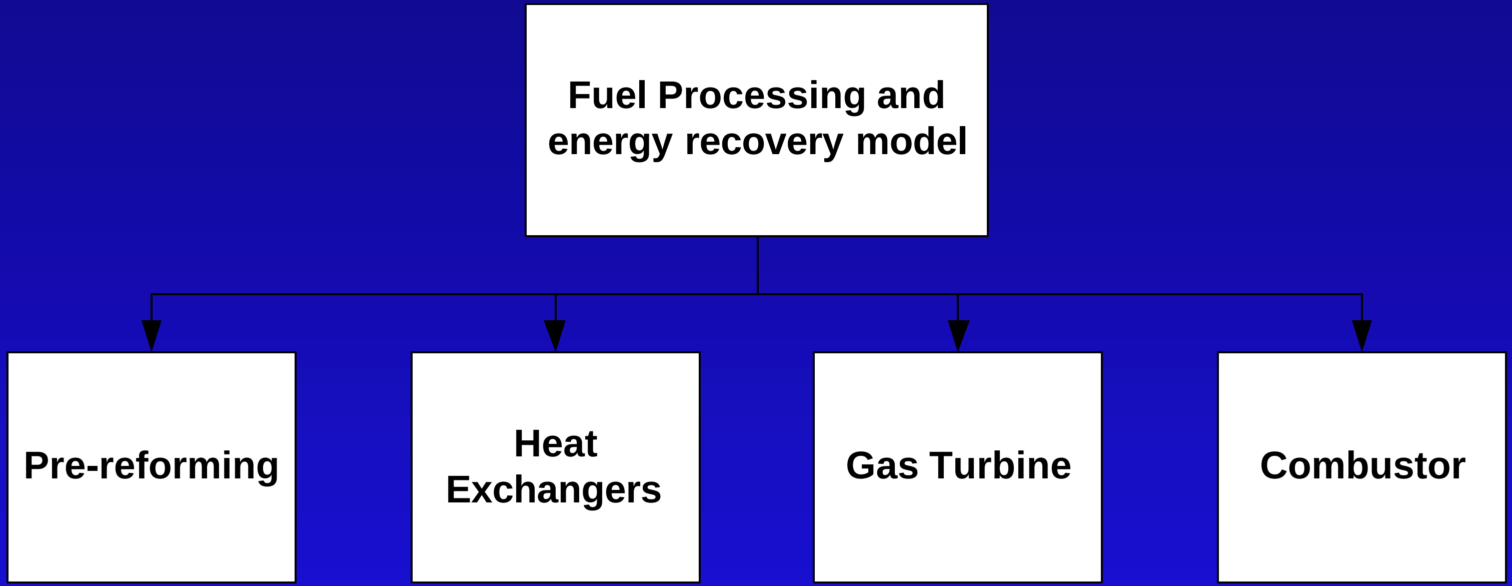
Previous Work: System (SOFCSS/BOPS) Modeled



Assumptions:

- Pure methane
- Air humidity fixed at 65% and 298 °K, 1 atm
- Cell temperature 1273°K

Previous Work: BOPS



Fuel Processing and energy recovery model

Pre-reforming

Heat Exchangers

Gas Turbine

Combustor

Pre-reforming model: *SMR* and *shift* reactions – kinetic / equilibrium / geometry based

$$L_{reactor} = \frac{n_{CH4,i}^{reactor}}{(n_{tubes} A_{cr} r_B)} \int_{X=0}^{X=X_{CH4}} \frac{dX}{-r_{CH4}}$$

Gas turbine, combustor, heat exchangers : thermodynamic / geometry based models

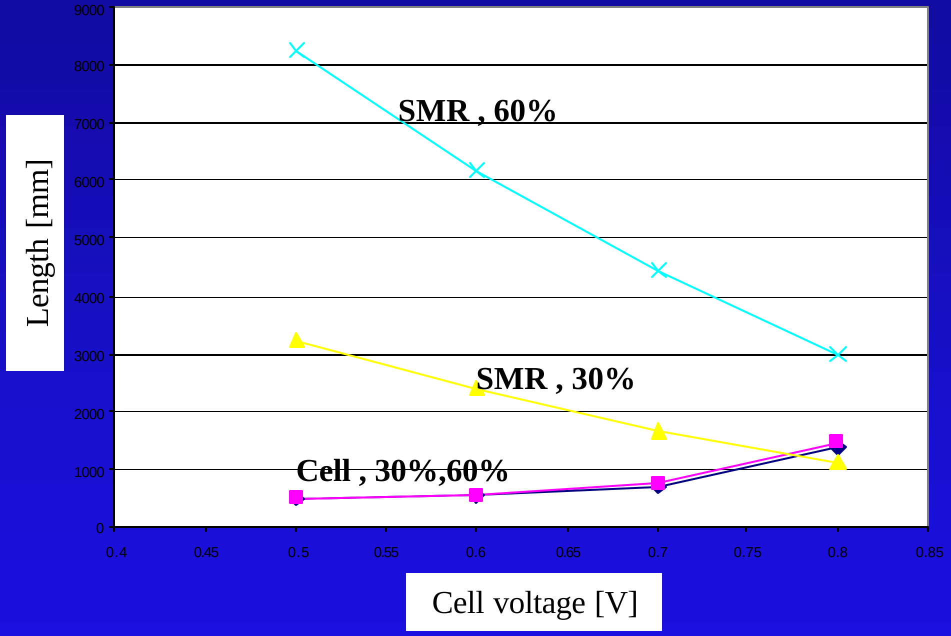
Previous Work: System (SOFCSS/BOPS) Results

Simulation in the Synthesis/Design mode

Fixed *cell power* at different *cell voltages*

- **The model works and can be used for trade-off analysis or large-scale optimization**
- **The model gives coherent and interesting results**

Influence of methane conversion



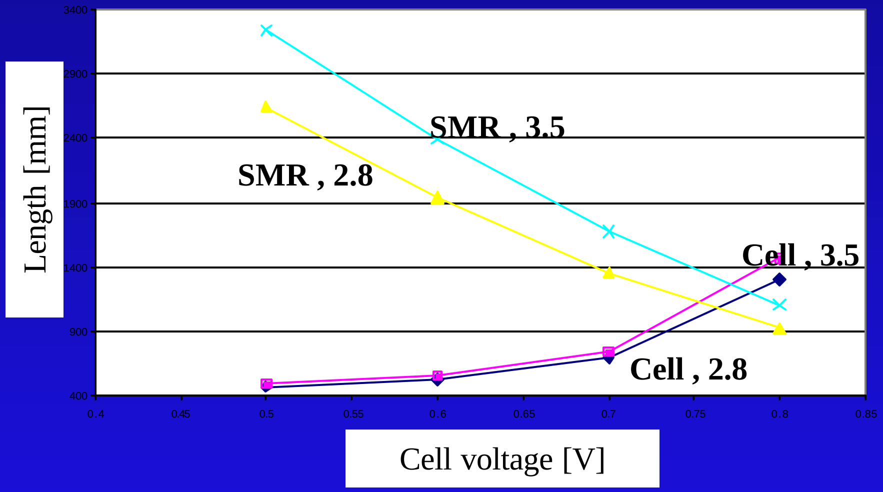
The parameters studied:

- **Methane conversion during pre-reforming**
- **Steam to carbon ratio**
- **Cell pressure**
- **Fuel utilization**

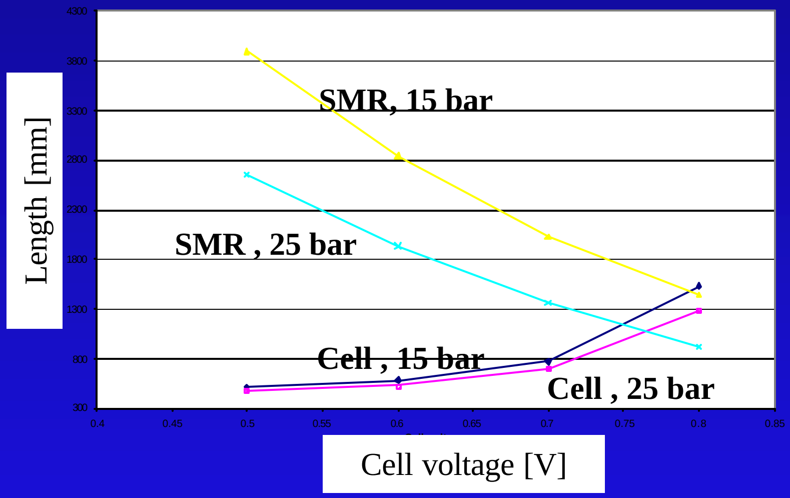
- **High methane conversion during pre-reforming is not recommended**
- **There is a cell voltage where the total cost of the cell and the SMR is a minimum**

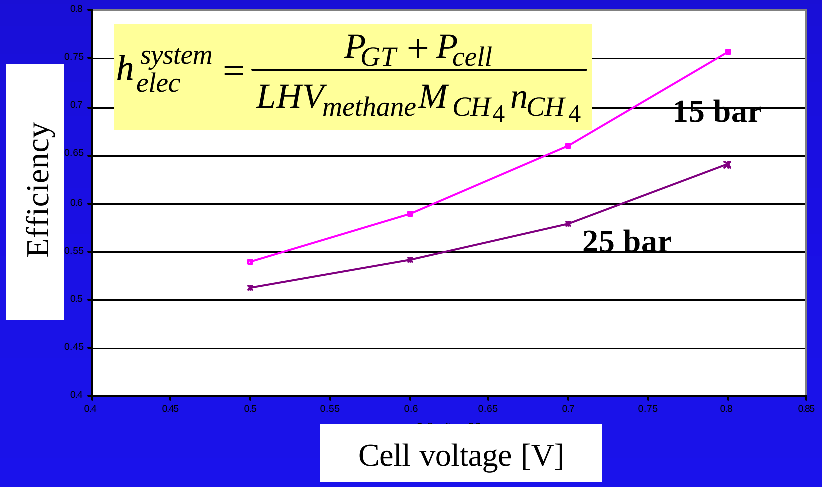
Previous Work: System (SOFCSS/BOPS) Results

Influence of the steam to carbon ratio



Influence of the cell pressure



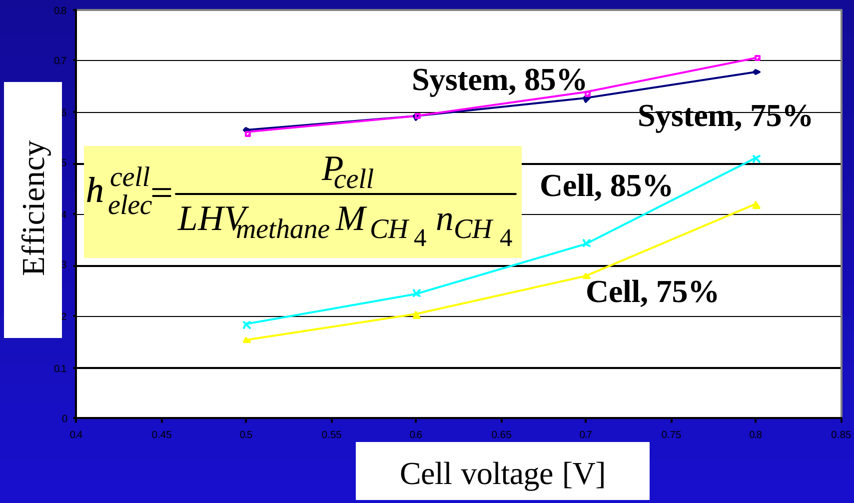


$$h^{system}_{elec} = \frac{P_{GT} + P_{cell}}{LHV_{methane} M_{CH_4} n_{CH_4}}$$

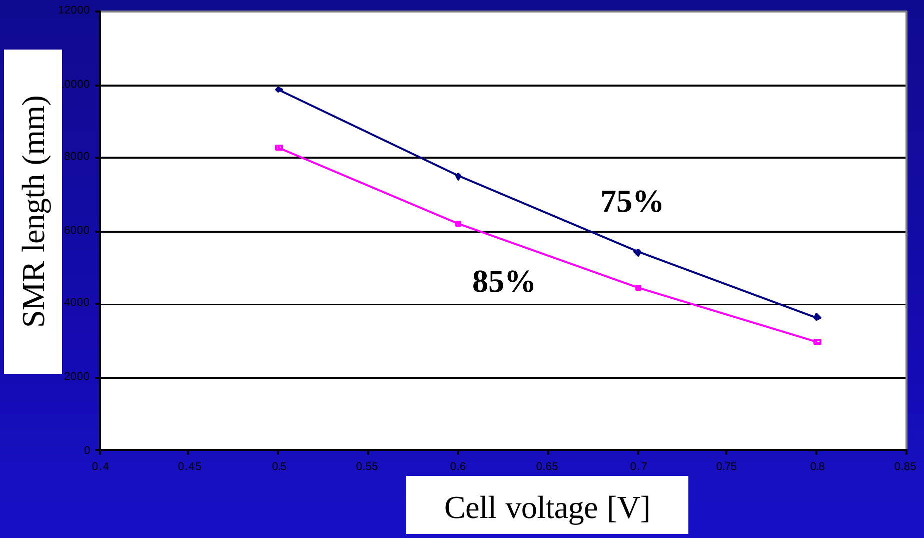
- Better to work at a low steam to carbon ratio
- However, lower limit of the steam to carbon ratio exists because of carbon deposition
- At higher pressure, equipment cost decreases
- At higher pressure, system efficiency decreases

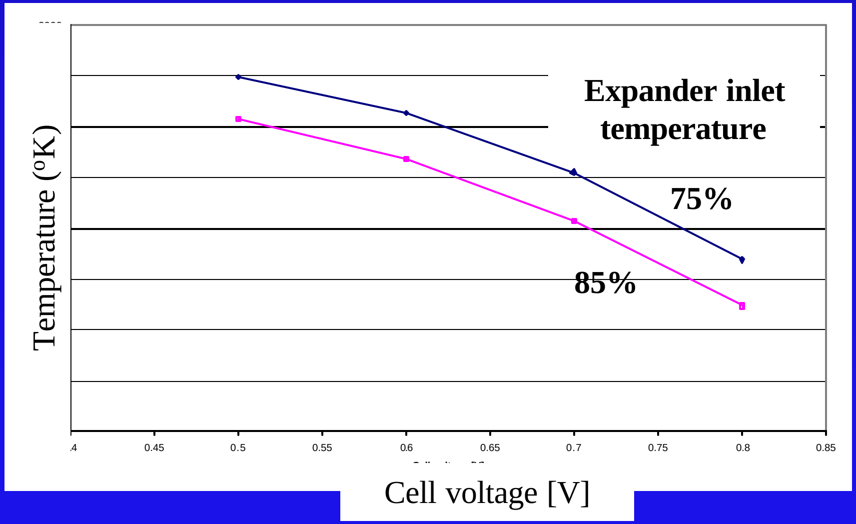
Previous Work: System (SOFCSS/BOPS) Results

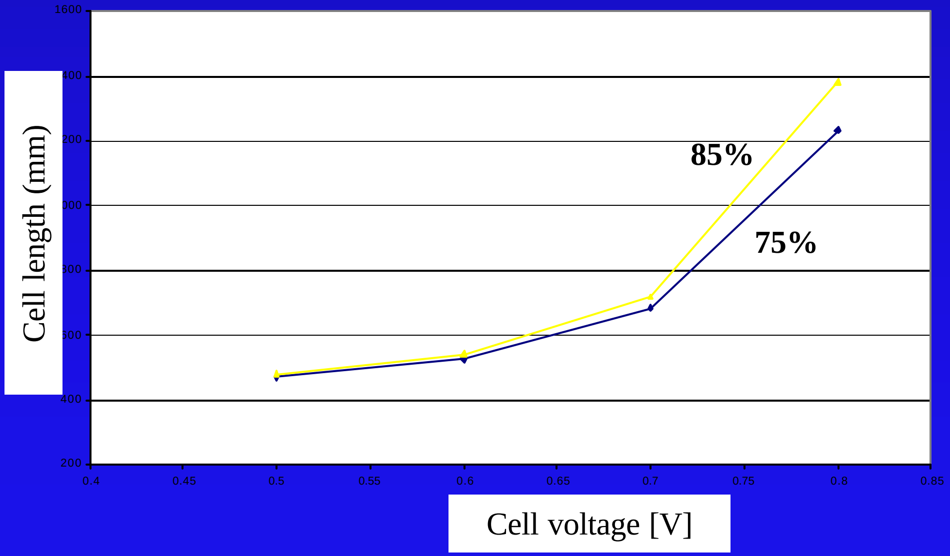
Influence of fuel utilization



$$h^{cell}_{elec}=\frac{P_{cell}}{LHV_{methane}\,M_{CH_4}\,n_{CH_4}}$$

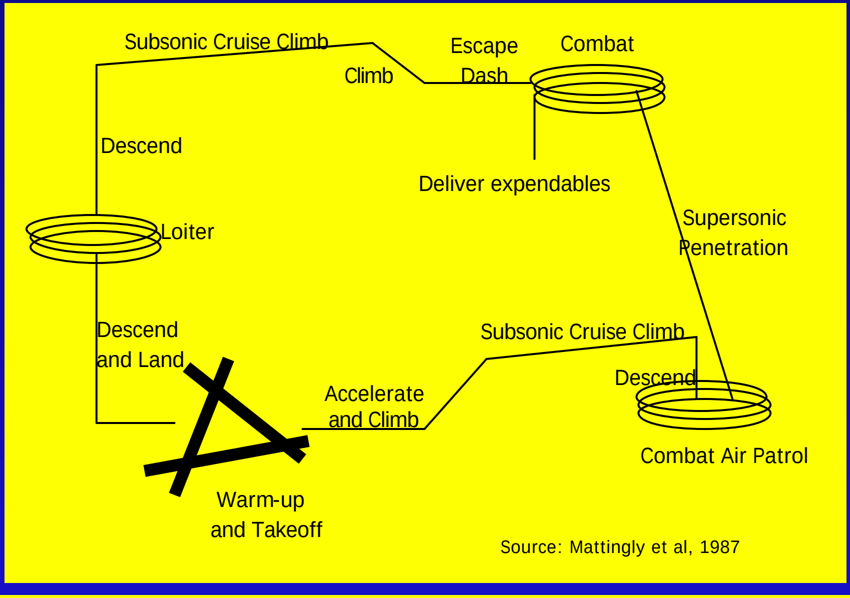






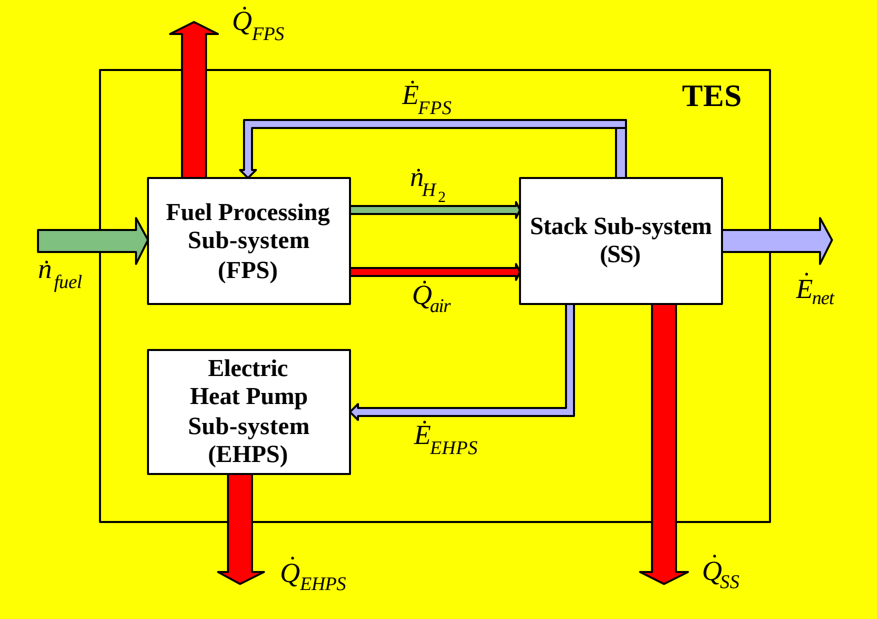
Previous Work: Integrated System-level Synthesis / Design Optimization - ILGO

- System: Advanced Air-to-Air Fighter (PS-ECS-FLS-VC/PAOS-AFS) – Synthesis/design optimized with 553 degrees of freedom



Source: Mattingly et al, 1987

- System: Fuel Cell Based Total Energy System (SS-FPS-EHPS) – Synthesis/design optimized with 39 degrees of freedom



R&D Approach: Phase I Tasks

Phase I:

- Planar SOFCSS model development, implementation and validation
- Characterization of the PES interface with the SOFCSS
- Load profile development
- BOPS model development, implementation and validation
- Integration of the PES, SOFCSS, and BOPS models
- Analysis of system stability and dynamics
- Parametric studies of best-practice control strategies

Phase II:

- Refine models and couple with ILGO; determine optimal control strategies and analyze load profile variations on reliability, performance, and response

R&D Approach

- Integration within (i.e. UIC, Va. Tech and Ga. Tech)
- Integration without (i.e. SECA teammates)

Collaboration with DOE Labs and SECA partners is critical to an effective Phase I !!!