TASK IV-C. HYDROGEN POWERED AEROPROPULSION
Modeling and optimization of fuel cell systems for aircraft applications

Principal Investigator: J.C. Ordonez, Dept. of Mechanical Eng.

Organization: Florida Agricultural & Mechanical University

Start Date = 01 Jan 2005
Planned Completion = 31 Dec 2005

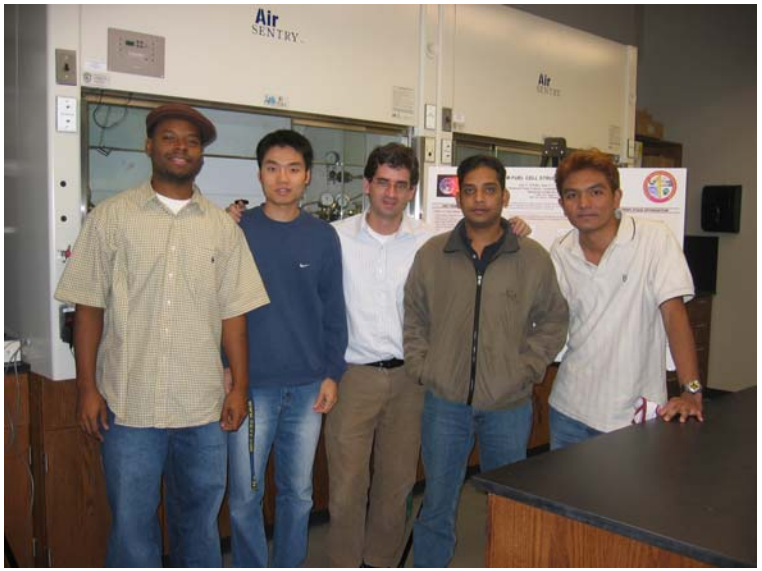
Research Goals and Objectives

Project Summary:

We propose to carry out four studies aimed at modeling and optimizing fuel cell integration to aircraft:

Proposed Studies:

1. Model for a Solid Oxide Fuel Cell (SOFC) with a recuperator for a hybrid gas turbine/SOFC system
2. System level and component level analysis to investigate optimal on-board fuel cell system size for a given mission.
3. Optimization of fuel cell architecture (geometry).
4. Implementation of Fuel Cell based Aeropropulsion systems into Advanced Power Simulation Environments.



FAMU FC Team: T. Brinson, S. Chen, J.C. Ordonez, N. Srivastava, W. Wechsatol (missing :Dr. Luongo, A. Lazic, S. Credle).

Awareness of and advance to current state-of-the-art

NASA has identified as current needs:

"Development of SOFC/GT alternative configurations, Optimization over entire mission, Dynamic/transient modeling" (J.Freeh, NASA-GRC)

Contributions to the current state-of the-art:

- New methodology for fuel cell internal and external geometry optimization (PEM and SOFC).
- We have reported on the effects of internal geometry of PEMFC on transient response.
- Developed a high efficiency APU configuration based on SOFC/GT

Tools developed:

- Implementation of hybrid system models in Matlab-Simulink
- Implementation of PEM and SOFC models integrated with power electronics into electrical network simulators

Relevance to overall NASA goals

- Fuel cells have been present on every NASA manned space mission
- Increase fuel cell power density
- Tools for APU system design and integration
- Noise reduction
- Pollution reduction

- Contribution to strategic programs:
  - More electric aircraft
  - Regenerative FC systems
  - Hydrogen powered aeropropulsion

Budget, Schedule and Deliverables

- Budget: 120K (84K direct). **On schedule, on Budget**

Products and Deliverables

- 1st Quarter: Quarterly report with initial implementation of SOFC model for the hybrid system.
- 2nd Quarter: Quarterly report with description of models and computational tools developed (studies 1, 3, 4).
- 3rd Quarter: Quarterly report focusing on studies 2 and 3.
- 4th Quarter: Final report covering all four studies and copies of all resulting publications.

Resources:

2 part-time faculty, 1 postdoctoral researcher (6 months), 2 PhD students (6 months), 2 MS student (6 and 3 months), 3 undergraduates (3 months).

Schedule

Milestone Description	Quarter (2005) 1	2	3	4
1. Implement SOFC model into Simulink. (Study 1) 2.Literature search (size vs efficiency) SOFC/PEM (study 2)	1	2		
3. Complete initial control volume model for SOFC (study 3) 4. Couple recuperator model with SOFC model (study 1)		4	3	
5. Implement improved PEM model into EMTDC (study 4) 6. SOFC model implemented into EMTDC (study 4) 7. Size optimization completed (study 2)		5	6	7
8. Optimized SOFC geometry 9. SOFC/ recuperator model coupled to turbine model 10. EMTDC simulations completed		9	8	10

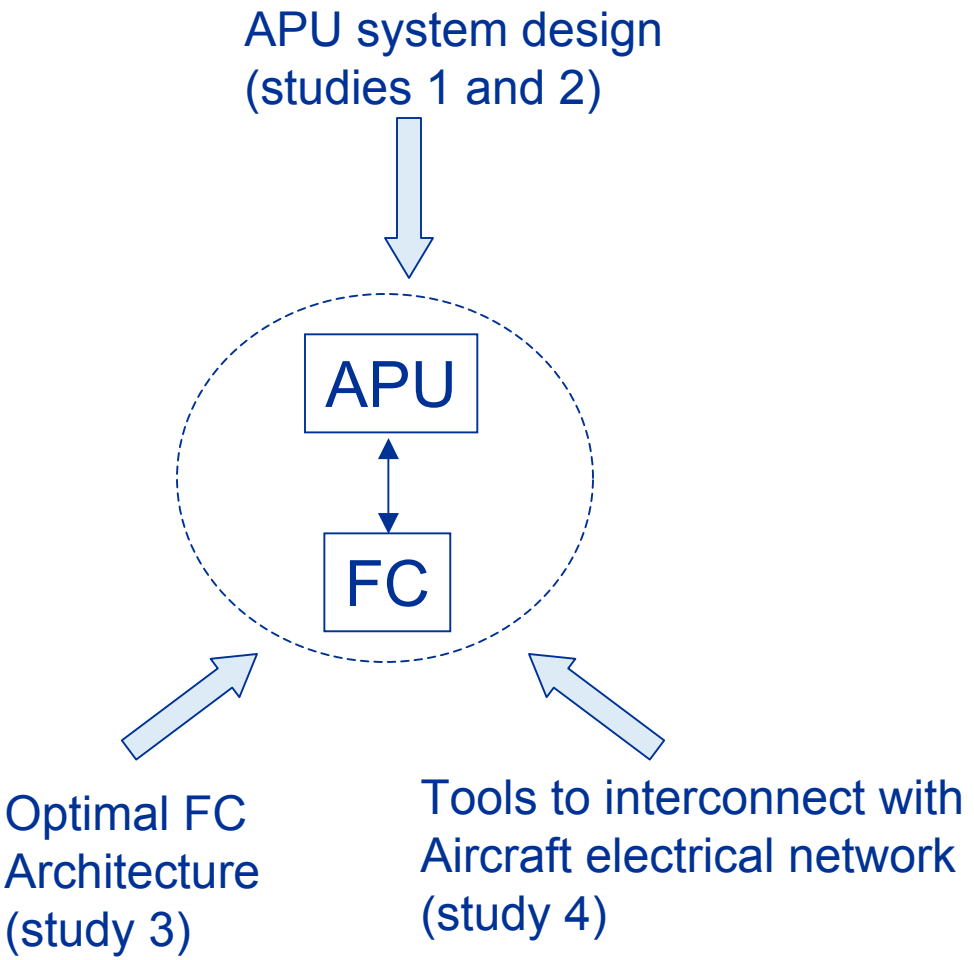
1Jan 2005

On schedule

This is FAMU's first year in the program

Anticipated Technology End Use

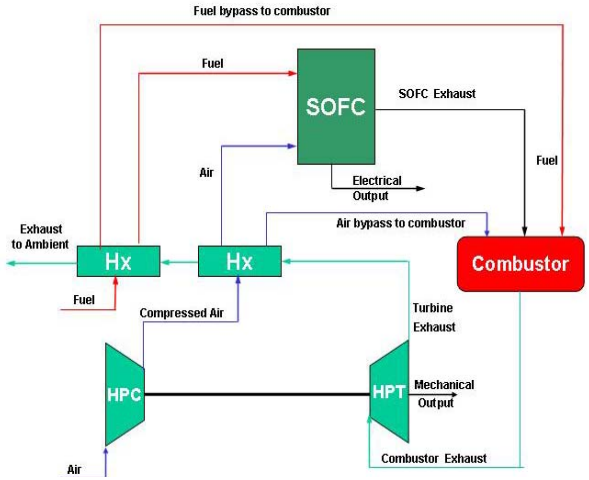
- Aircraft APU will be the first system to incorporate fuel cells. The four studies in this project contribute to the design and optimization of both the FC components and the APU overall system and its integration to the power network
- More Electric Aircraft
- Hydrogen powered aircraft



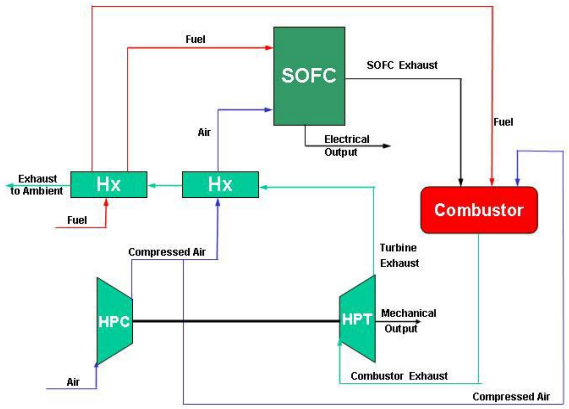
Accomplishments and Results

Comparison Among Candidate Hybrid SOFC/GT APU Configurations

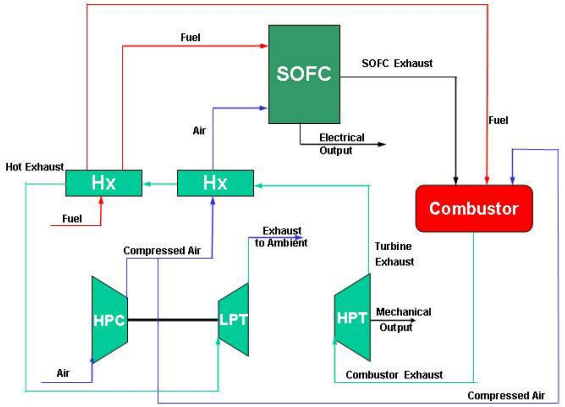
More efficient systems



Config-1



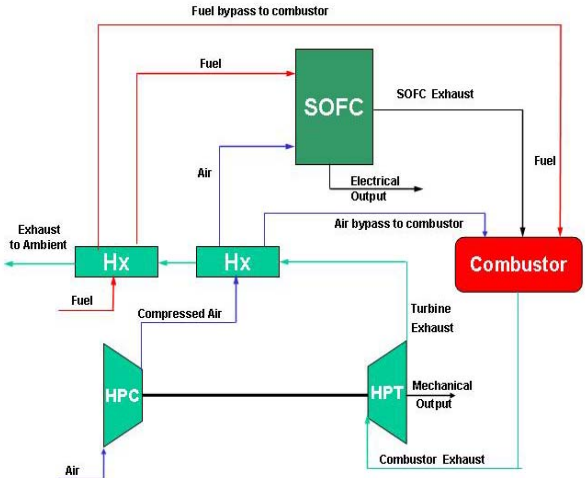
Config-2

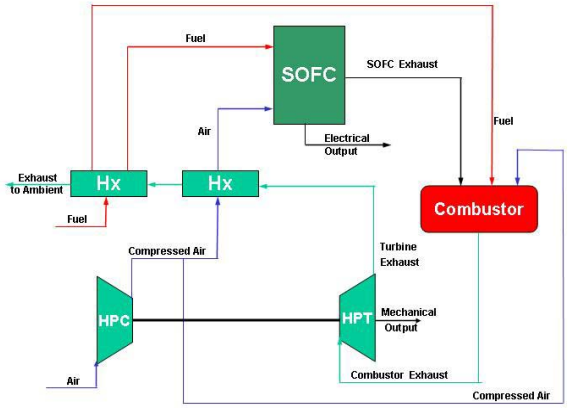


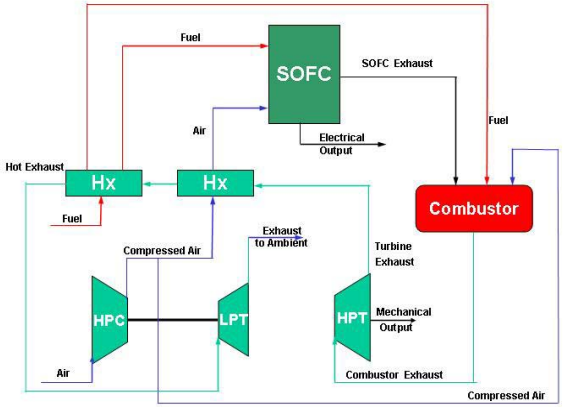
Config-3.

Comparison Among Candidate Hybrid SOFC/GT APU Configurations

conventional system → Improvements on conventional system







Config-1:Main Features

- All air and fuel are preheated.i.e. no bypassing before heat exchangers.
- All air is preheated.
- Fully expanded turbine

Config-2:Main Features

- All the fuel is preheated but only air going to the SOFC is preheated.
- Part of the air stream goes directly to the combustor w/o preheating.
- Fully expanded turbine.

Config-3:Main Features

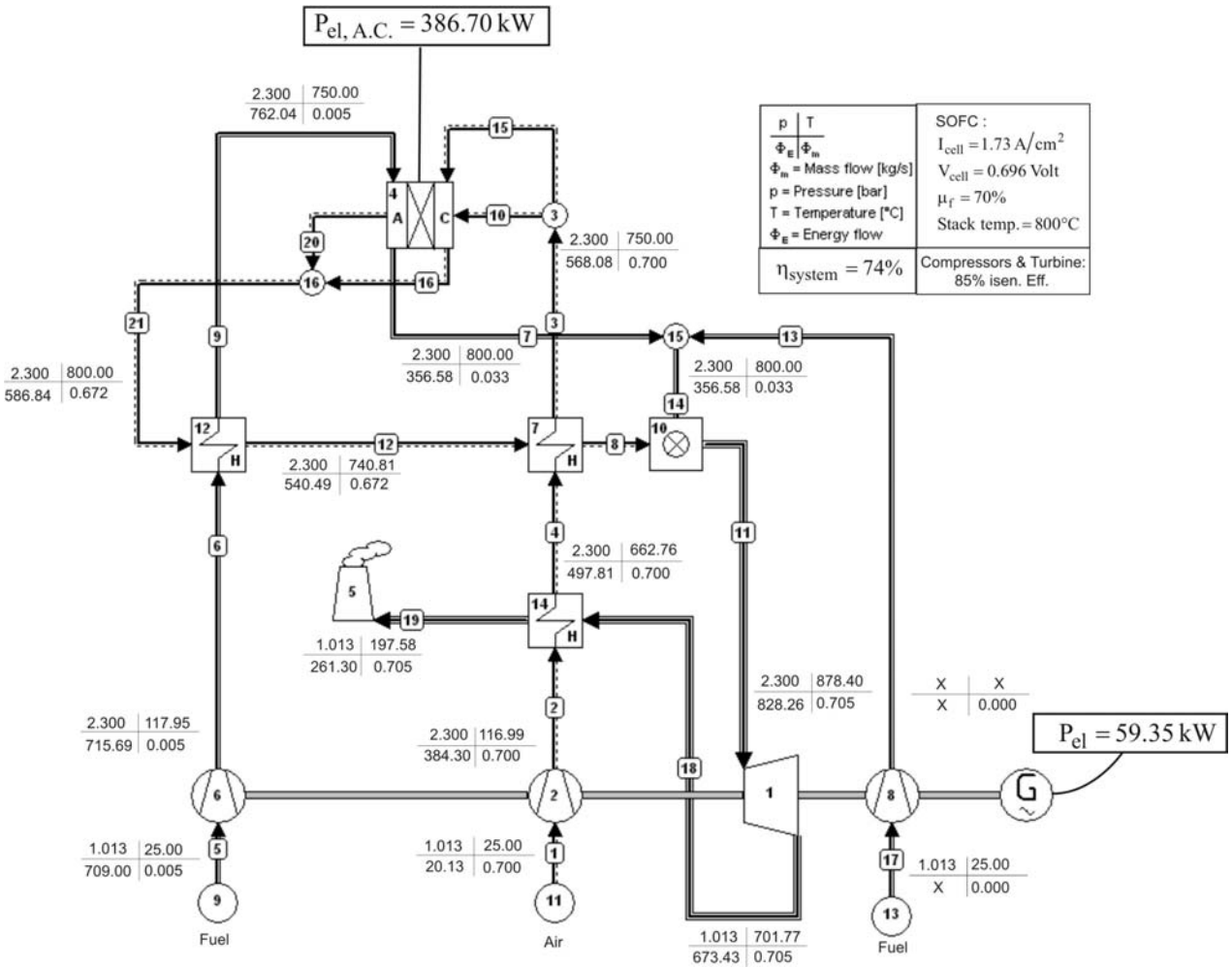
- All the fuel is preheated but only air going to the SOFC is preheated.
- Part of the air stream is preheated.
- Partially expanded HPT (high pressure turbine)
- Full expansion of heat exchanger exhaust in LPT . LPT drives the compressor.

Study 1

Optimized APU Configuration

Employing Entropy Generation Minimization techniques, an optimized SOFC/GT system for aircraft APU has been designed

$\eta_{system} = 74\%$ (LHV)

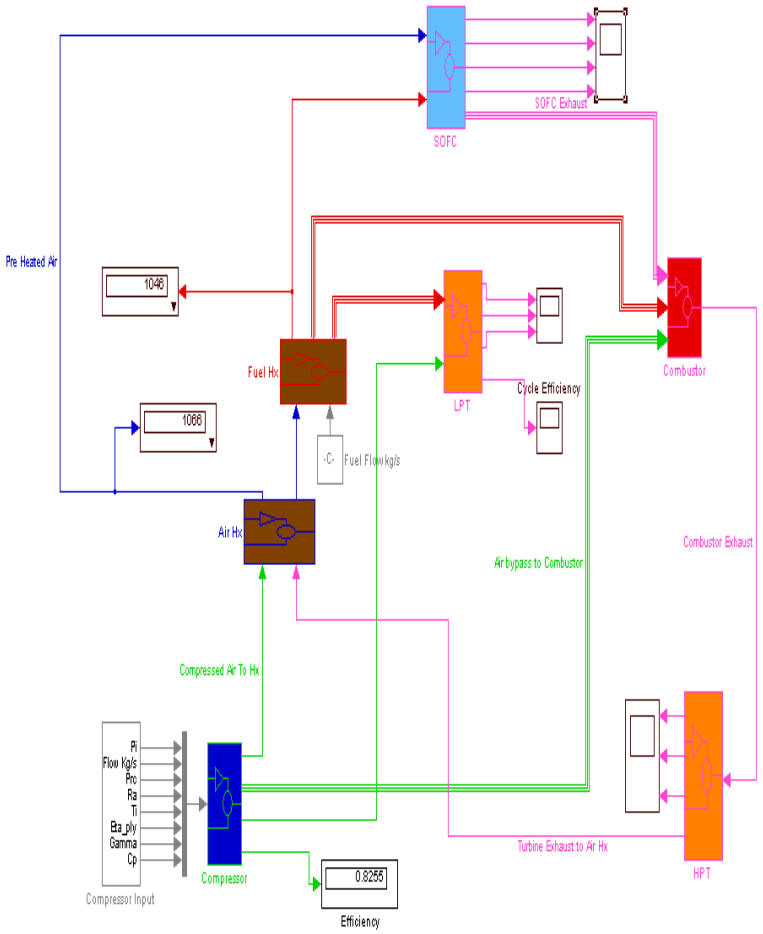


Config-4

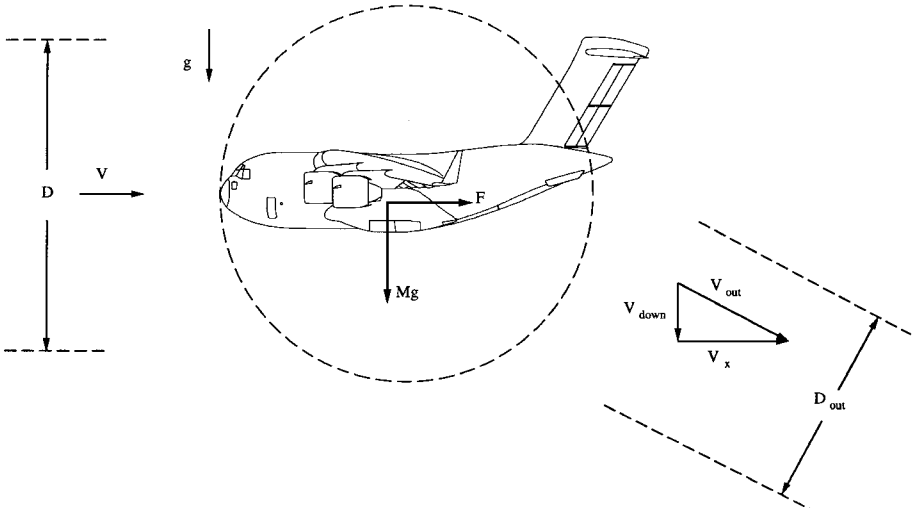
Decision Matrix

	Config-1	Config-2	Config-3	Config-4
Fuel flow(g/s)	9.62	9.62	9.62	5
Air flow(g/s)	464	342	342	700
SOFC Temp(^{0}C)	574	761	870	800
Turbine inlet Temp (^{0}C)	1442	1366	1371	878
SOFC power(kW)	12	260	312	387
Net Turbine Power (kW)	157	114	102	59
Total power (kW)	169	374	414	446
System efficiency (LHV)	14.7%	32.5%	46%	74%
Exhaust Temp (^{0}C)	779	734	734	197

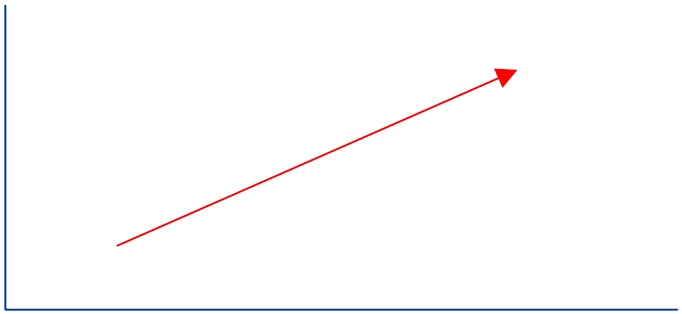
Design Tool: MATLAB-Simulink Implementation of SOFC/GT



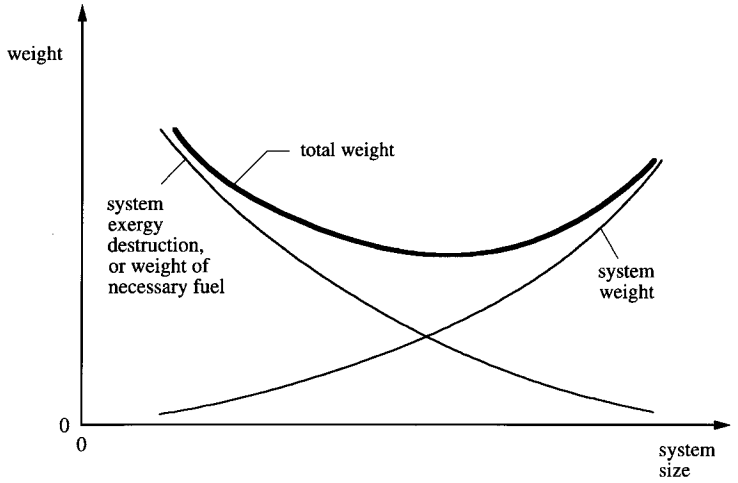
System level and component level analysis to investigate optimal on-board fuel cell system size for a given mission.



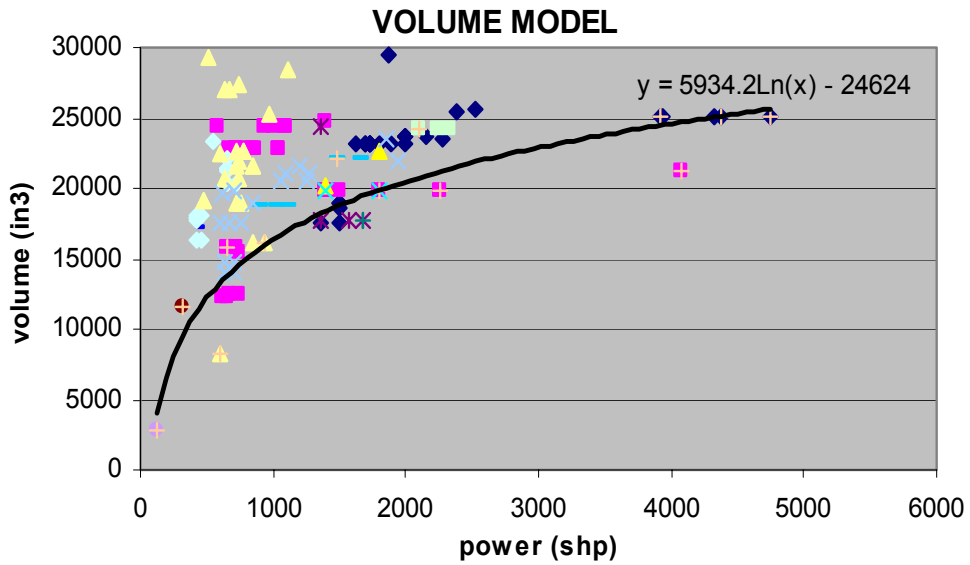
power required to flight

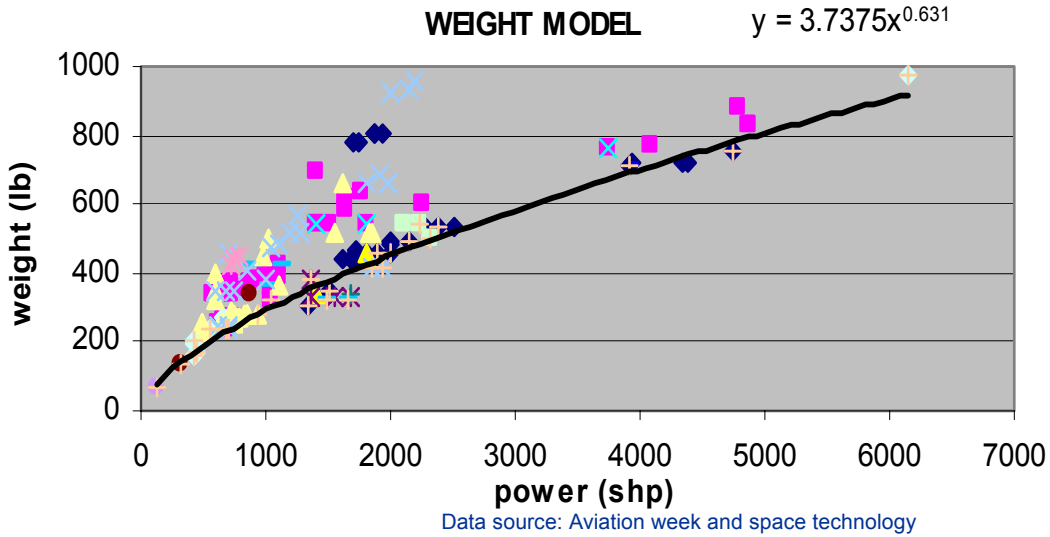


size / mass of the system



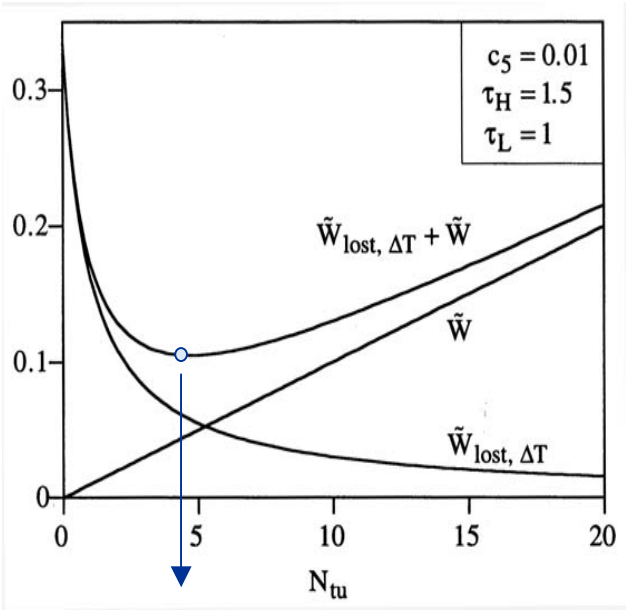
Effects of size - gas turbine





Data source: Aviation week and space technology

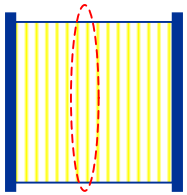
Effects of size - HX



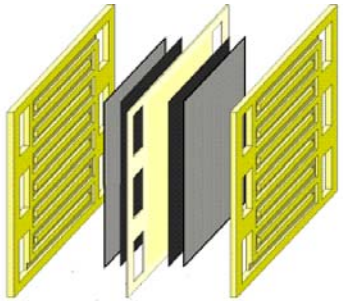
optimal size for an ON BOARD heat exchanger

Objective: Generate weight estimations for different SOFC/GT configurations

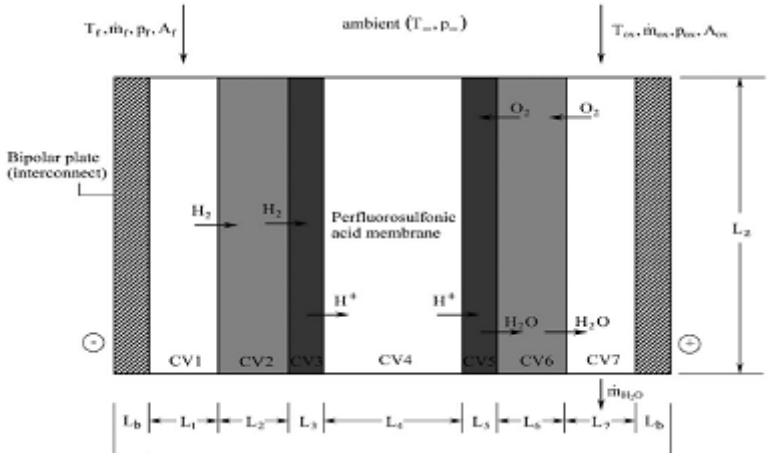
Optimization of fuel cell architecture



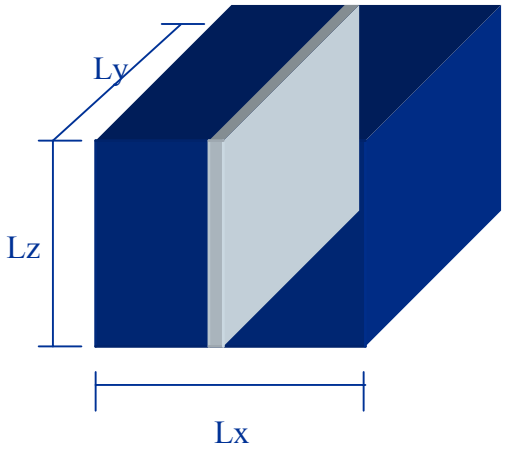
stack



Unit cell



Control volume modeling (Internal Shape)



(External shape)

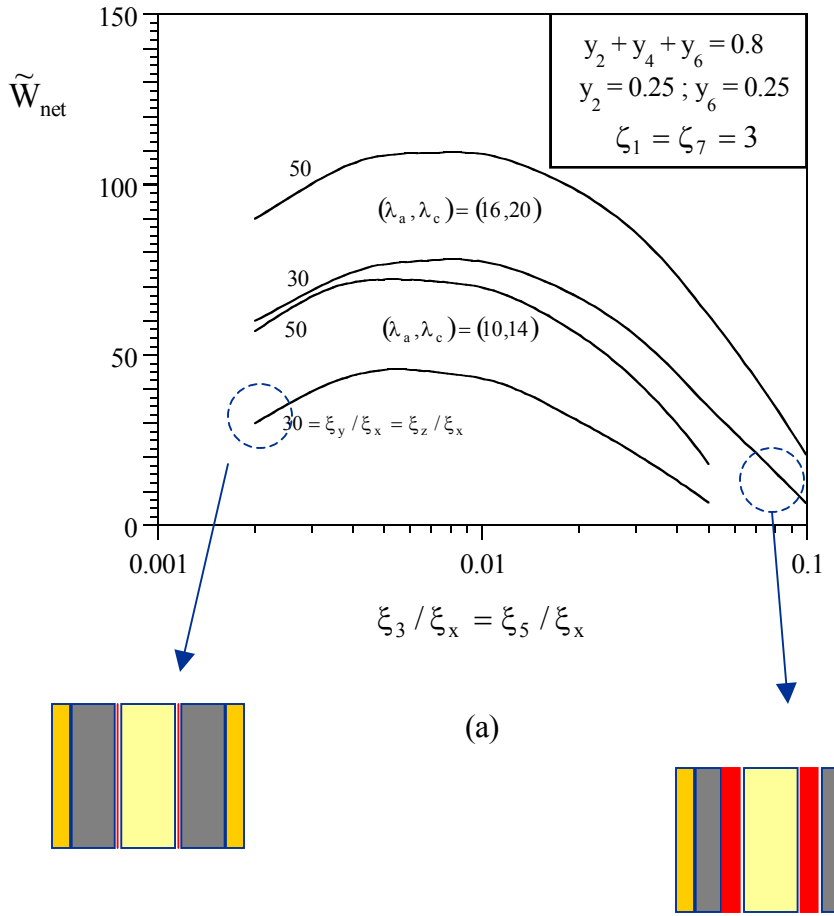
Our approach to FC geometry optimization is at two levels:

- Internal geometry (optimal relative thickness)
- External geometry (optimal aspect ratio)

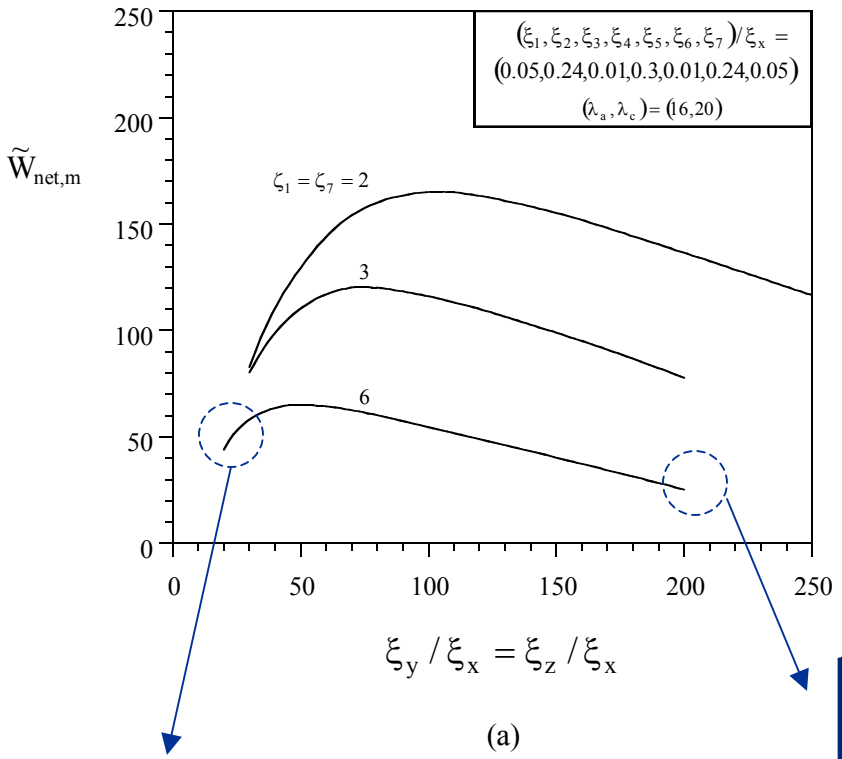
Objective: maximize power density

Optimization of fuel cell architecture (PEM-Unit cell)

Optimal electrode relative thickness

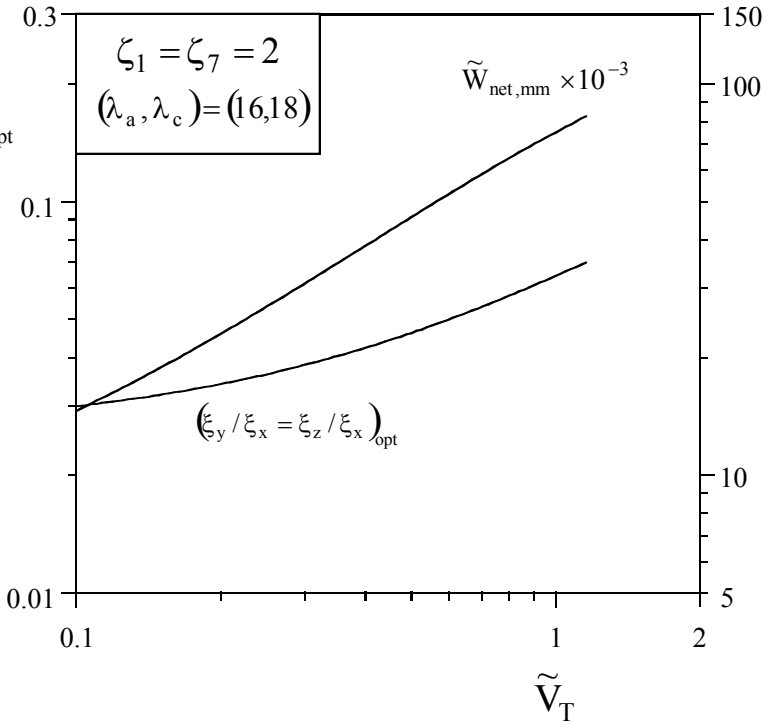


Optimal External Aspect Ratio

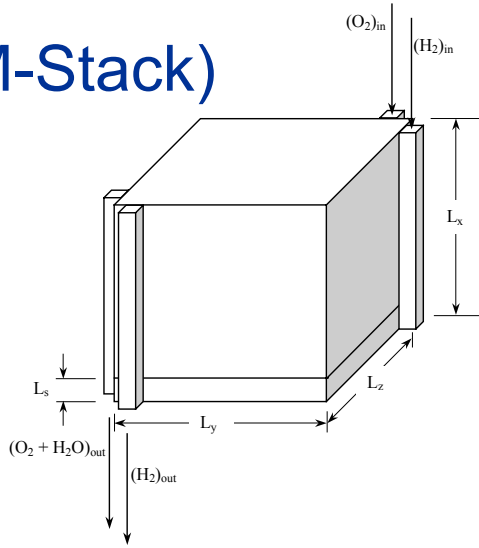


Optimization of fuel cell architecture (PEM-Stack)

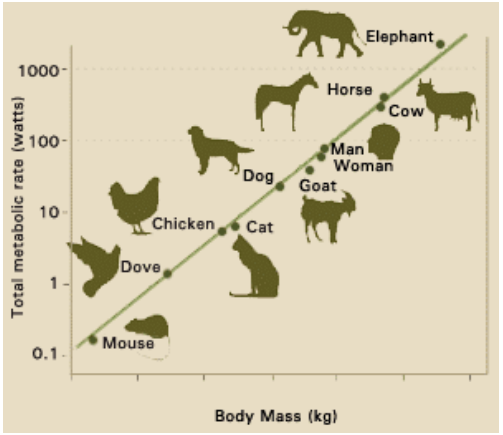
$\left(\xi_y/\xi_x = \xi_z/\xi_x\right)_{opt}$



$\tilde{W}_{net,mm} \times 10^{-3}$

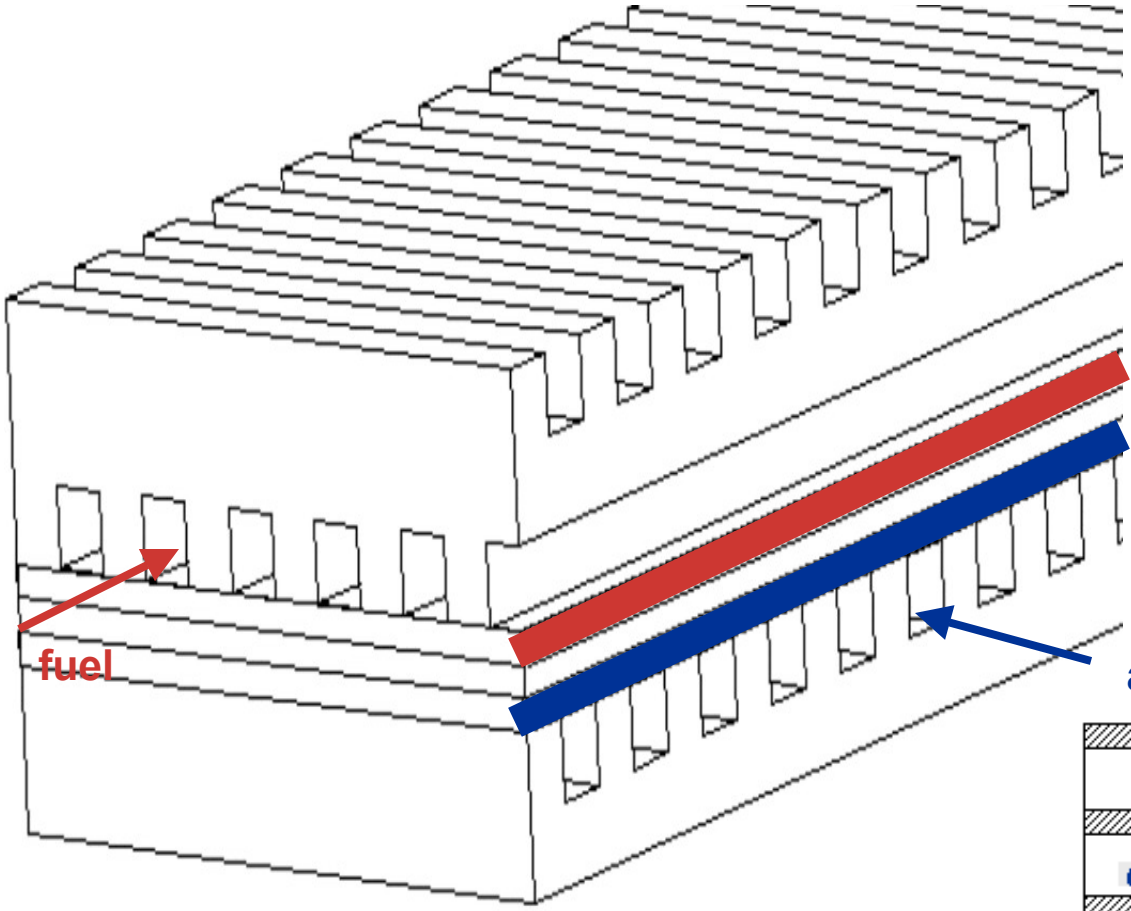


Slope ~ $\frac{3}{4}$ in both cases



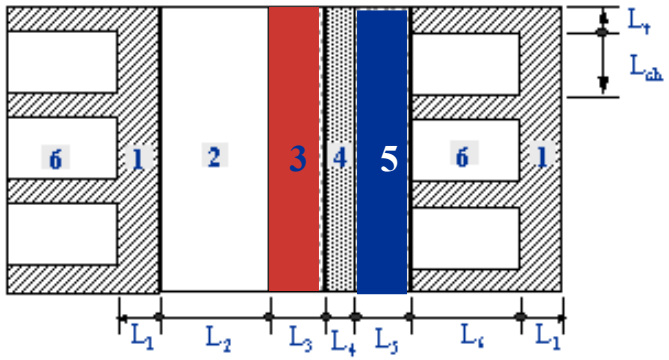
Scaling of a PEM stack: optimal stack aspect ratios for maximum power density

Optimization of fuel cell architecture (SOFC)

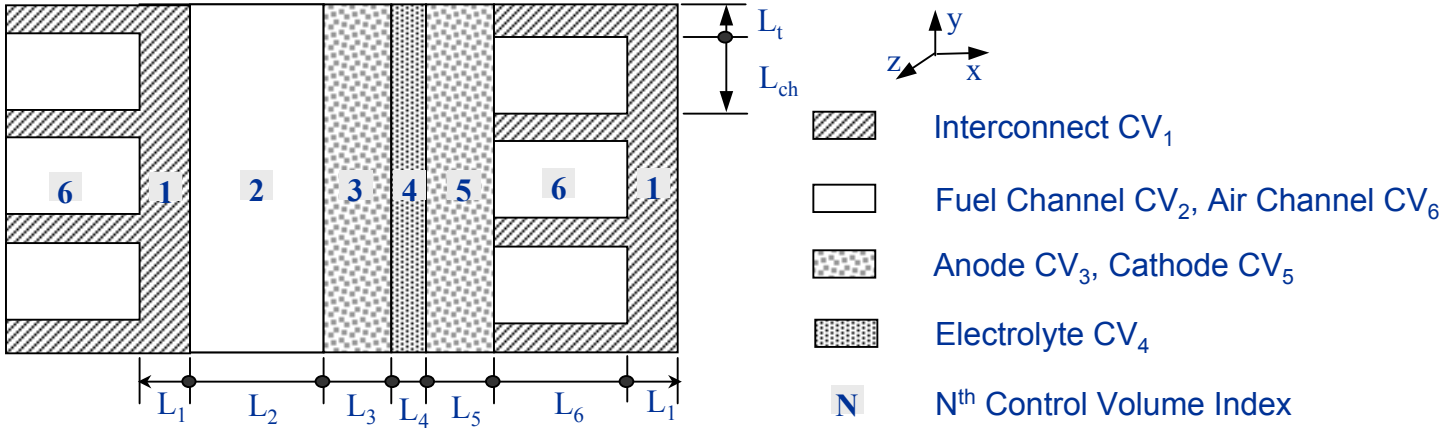


SOFC internal structure

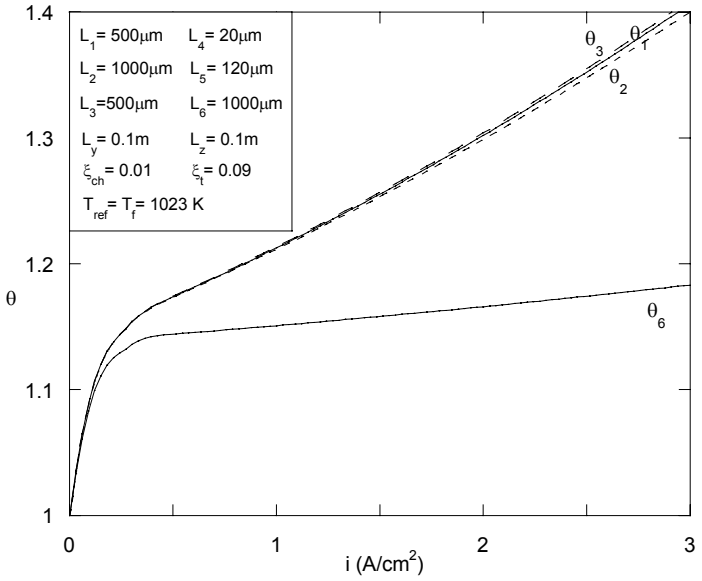
C.V	Description
1	Interconnect
2	Fuel Channel
3	Anode
4	Electrolyte
5	Cathode
6	Air Channel



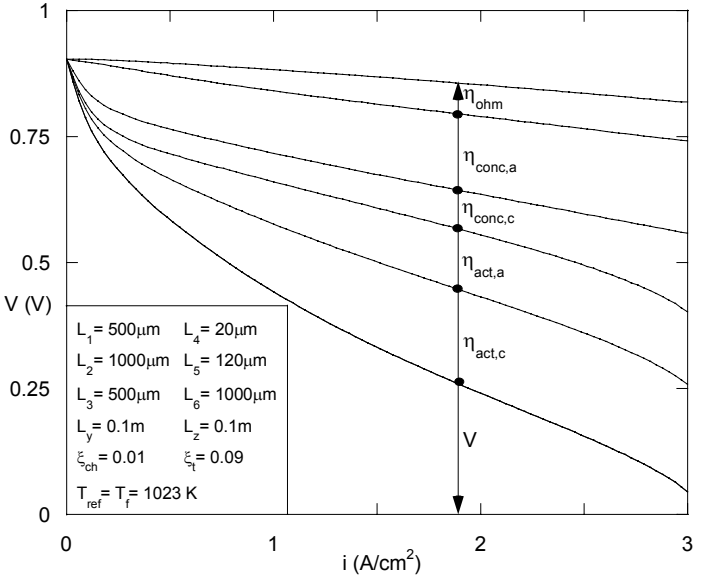
Internal Geometry Optimization (SOFC)



SOFC cross-section

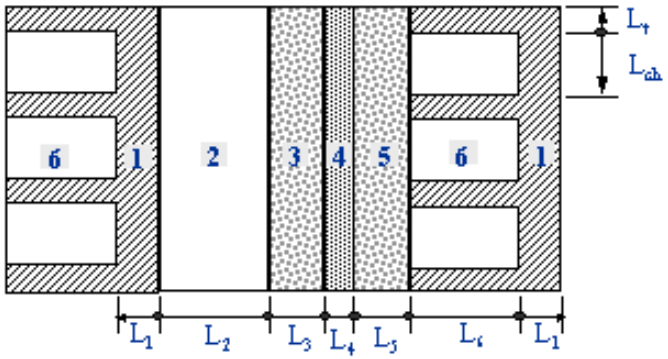


Anode Supported SOFC Temperature Profile

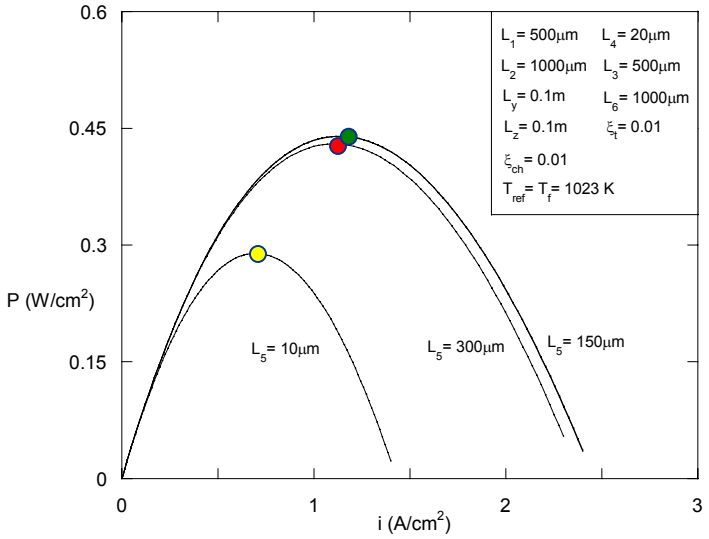


Anode Supported SOFC Polarization

Internal Geometry Optimization (SOFC)

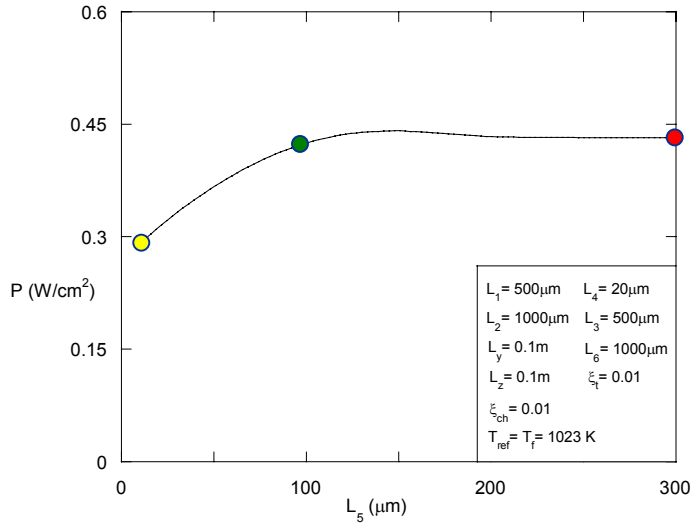


Thin electrode (not enough reaction area)
Thick electrode (high concentration overpotential)



Anode Supported SOFC Power Density

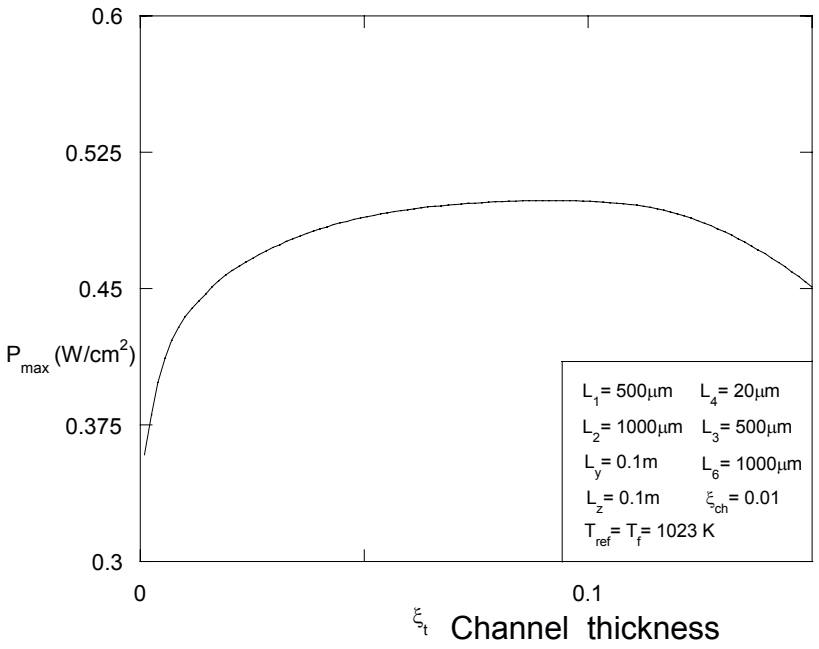
Optimal Electrode Thickness



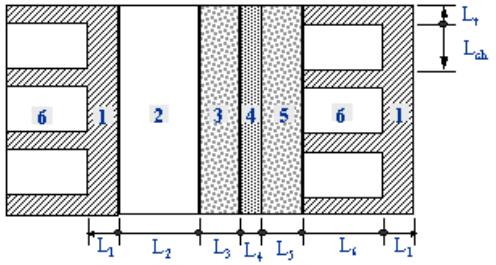
Cathode Thickness Effect on the Power Density

Optimal Electrode Thickness

Internal Geometry Optimization (SOFC)



Optimized Channel Geometry

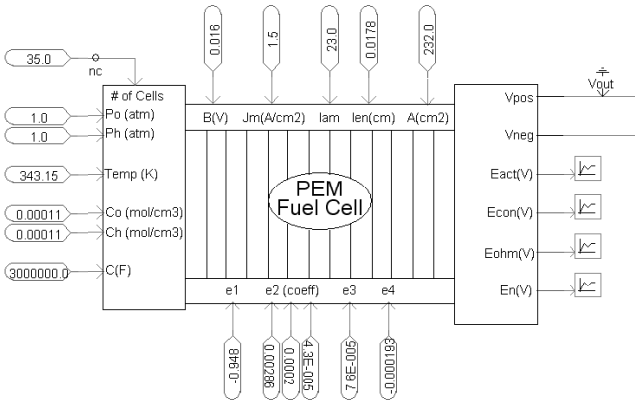


- Optimal electrode thickness
- Optimal channel geometry
- Maximized power density

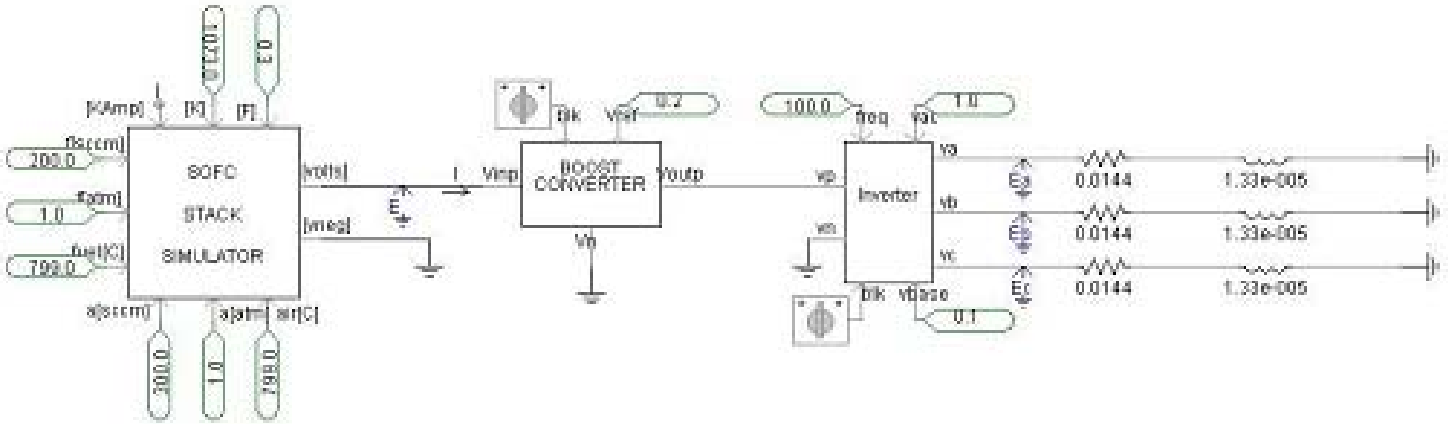
Guidelines for Fuel Cell Design and Manufacturing

Fuel Cell-Based Power System and Electrical Network Modeling In EMTDC

PEM model implementation into EMTDC



SOFC and associated power electronics implementation:



EMTDC is a good tool to study the coupling with the necessary power electronics, however, we are now migrating to MATLAB based tools (Simulink)

Accomplishments and Results

- Optimized configuration of a hybrid SOFC system for APU
- Optimized internal and external structure of PEM unit cells and stacks
- Optimized internal structure of SOFC unit cells
- Description of internal structure effects on PEM transient behavior
- Implementation of PEM and SOFC models with integrated power electronics into electrical network simulator

NASA Interns:

- Two graduate summer interns at NASA-GRC: Thomas Brinson and Sydni Credle working on fuel cell-related topics.

Other related activities:

- Boeing Seminar on More Electric Aircraft.

Accomplishments and Results

Publications:

- George Kopasakis (NASA-GRC) Thomas Brinson & Sydni Credle (FAMU) Ming Xu (Virginia P&S Univ). "A Theoretical Solid Oxide Fuel Cell Model for System Controls and Stability Design" Submitted to ASME Turbo Expo 2006.
- J.V.C. Vargas, J.C. Ordóñez, and A. Bejan, Constructal PEM fuel cell stack design. International Journal of Heat and Mass Transfer, Volume 48, Issues 21-22, October 2005, Pages 4410-4427.
- J.V.C. Vargas, J.C. Ordonez, A. Bejan and S.C. Amico. The Optimal Shape for a Unit PEM Fuel Cell. ASME. Third International Conference on Fuel Cell Science, Engineering and Technology, Ypsilanti, MI, 2005.
- N. Srivastava, J.C. Ordóñez and T. Brinson. "SOFC-Gas Turbine Hybrid System for Aircraft Applications: Modeling and Performance Analysis". 2005 58th Annual Meeting of the Division of Fluid Dynamics, APS, Chicago, Nov. 2005.

In preparation:

- S. Chen, J.C. Ordóñez, and J.V.C. Vargas. "Shape And Structure Optimization of a Unit Pem Fuel Cell For Transient Operation" (in preparation).
- S. Chen, J.C. Ordóñez, and J.V.C. Vargas. " Internal Geometry Optimization of a unit SOFC for maximum power density" (in preparation).
- J.C. Ordóñez, S. Chen and J.V.C. Vargas ASME-FC 2006 (invited by Josh Freeh NASA-GRC)

Future Plans

- Continue on the optimization of on-board FC systems weight
- Optimization of planar FC assemblies.
- Transient analysis of hybrid FC APU systems
- Optimization of fuel channels geometry
- Regenerative FC systems (collaboration with Georgia Tech)
- Bipolar plate design: jet impingement and constructal flow network
- Hardware in the loop experiment (NASA-URETI).

Thank you