



GATE Center for Automotive Fuel Cell Systems at Virginia Tech

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28 February 2008

2008 DoE Merit Review Presentation

**This presentation does not contain any
proprietary or confidential information**

- Purpose of work
- Response to June 2007 review comments
- Barriers
- Approach
- Performance Measures and Accomplishments
- Technology Transfer
- Plans for 2008-2009
- Summary
- Publications

Mission

The mission of the GATE Center for Automotive Fuel Cell Systems is to develop new science and technology to help overcome technical barriers for hydrogen and fuel cell vehicles and to provide the next generation of engineering professionals to implement these technologies in the U.S. automotive industry.

- Educate and develop engineers with knowledge and capabilities in high efficiency vehicles and clean domestic fuels to reduce petroleum consumption and GHG emissions
- Improve transportation energy security and maintain a globally competitive automotive manufacturing industry

Much of the work undertaken by OEMs and their suppliers to improve transportation energy security and to remain globally competitive is conducted by in-house teams....they need engineers that have advanced degrees in hydrogen, fuel cell, and advanced vehicle technologies and that have an interdisciplinary perspective

Purpose of the VT GATE Center

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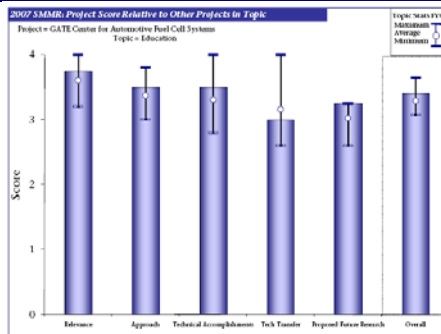
- Provide multidisciplinary learning opportunities through courses, interactive projects, and simulations to prepare graduate students to contribute to fuel cell and hydrogen technology development
- Engage graduate students in Virginia Tech's basic and applied research programs for fuel cell, hydrogen, and vehicle technology
- Provide the automotive industry with
 - *Technical resources* in the form of presentation and publication of research results
 - *Human resources* in the form of graduate students who are educated in the development, application, and deployment of hydrogen and fuel cell vehicle technology

5

Response to 2007 Review Comments

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- **Relevance to DOE Objectives**
 - Fuel cells are critical to DOE goals and mission is well aligned with OEM needs
 - Continue providing interdisciplinary research and education
 - Fuel cells remains our focus and we continue to interact with OEMs through research and student hires.
 - Continuing interdisciplinary efforts through GATE and affiliated programs (e.g. REU)
- **Approach to research and development**
 - Education and research are well integrated (e.g. synergy with Challenge X)
 - Program addresses industry needs through curriculum, student recruiting, dissemination, interaction
 - Integrative activities continue to be pursued on multiple levels – interdisciplinary, undergrad/grad, research/education
 - Increased focus on dissemination
- **Technical accomplishment**
 - Commended for high student count, number of publications, course development, tuition cost share, recent hires
 - Future reports should elaborate on curriculum development
 - Efforts continued in each of the noted areas
 - Curriculum development continued –details reported here
- **Technology transfer**
 - Signs of industry interaction – publications, industry visits, hires
 - Degree of industry interaction could be clearer; perhaps increase
 - Continued publication, industry visits, additional hires
 - Currently establishing a formal industry advisory board
- **Approach and relevance of proposed future research**
 - On a good path – continue curriculum development, labs, recruiting and industry interaction
 - Hands-on labs spring 2006; plans for additional FC course



- **Strengths**
 - Good established program with good industry hires
 - Working to maintain strengths
- **Weaknesses**
 - Clarify role of students in GATE publications
 - Revised reporting to clarify
- **Place fuel cells in global context**
 - Strengthened environmental impact sections of class
- **Clarify student participation and track hires**
 - Revised tracking and reporting to clarify

6

Barriers

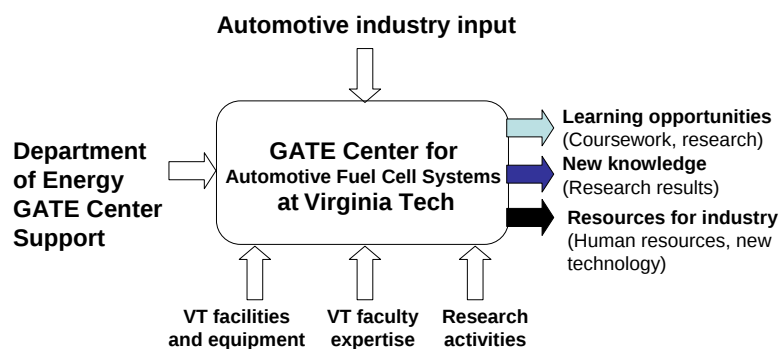
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- Automotive OEMs and suppliers need to develop cost effective technologies to reduce petroleum consumption and GHG emissions
- There is an insufficient supply of experienced industry professionals and graduate degree engineers with the background to help solve these problems
- There is a need for new knowledge and understanding in critical technology areas (e.g. fuel cell durability, water management, system modeling)

7

Concept for DOE/VT/Industry Interaction

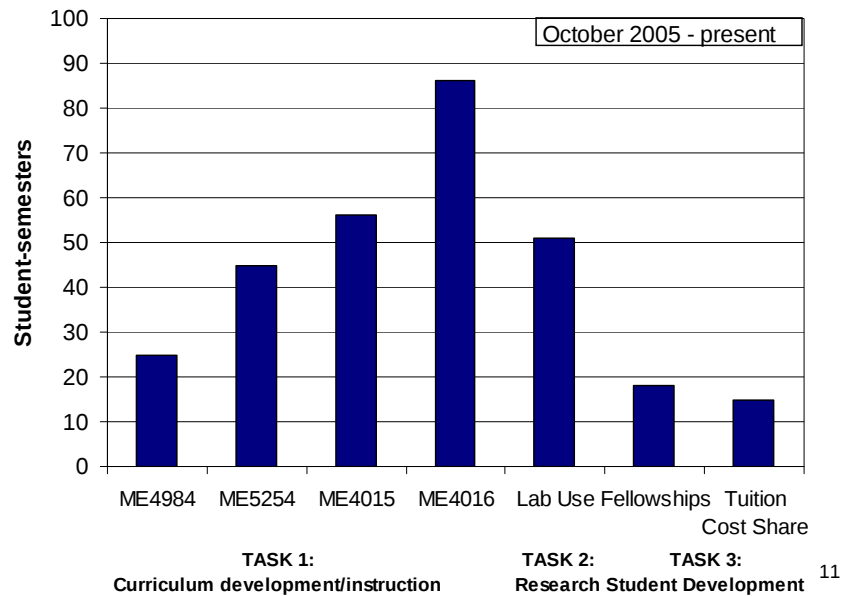
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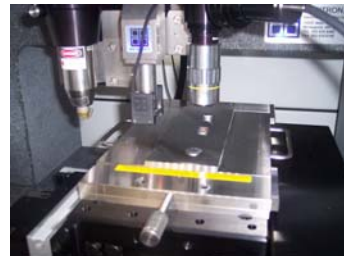
8

- Task 1 – Curriculum development
 - Develop new materials and enhance existing courses for a fuel cell and hydrogen systems curriculum
- Task 2 - Engage students in research
 - Provide research opportunities for students that support the goals of the GATE Center
- Task 3 – Recruit students for GATE Fellowships
- Task 4 – Dissemination and scholarship
- Task 5 – Industry interaction

- Research collaboration among academic departments
 - Mechanical Engineering – system modeling, testing and materials character.
 - Material Science and Engineering Department - mesoscopic modeling and material characterization related to fuel cell electrodes
 - Engineering Science and Mechanics Department – durability modeling and membrane characterization
- Research collaboration with undergraduate researchers
 - NSF Research Experience for Undergraduates (REU)
 - 10 summer students working with faculty and graduate mentors on various aspects of fuel cell materials and processes (ME, MSE, ESM, ChE, Chemistry)
- Educational collaboration across departments and academic levels for student projects and classes
 - Mechanical engineering, electrical engineering, MSE
 - Graduates, seniors, juniors

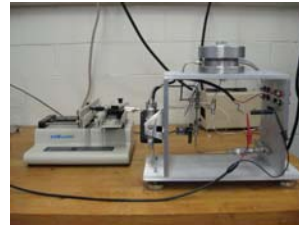


- Improvement of membrane durability requires an understanding of membrane mechanical properties and their relationship to membrane failure
- Research by students that have completed GATE center coursework, used GATE labs, or received GATE center funding (denoted by *) has addressed
 - Characterization of the viscoelastic properties of PFSA membranes
 - Development of a constitutive model for PFSA viscoelastic properties
 - Characterization of the fracture energy of PFSA membranes using a knife slit test
 - Evaluation of the biaxial strength of PFSA membranes using pressure-loaded blister tests
 - Simultaneous measurement of water uptake and strain in PFSA membranes*
 - Development of techniques for evaluation of the resistance of PFSA membranes to shorting*
- Research has been conducted in conjunction with industrial sponsorship
- Dissemination
 - 5th International Conf. on Fuel Cell Science, Engineering, and Technology, June 2007
 - 6th International Conf. on Fuel Cell Science, Engineering, and Technology, June 2008



Nano-indenter used for measurement of out-of-plane membrane properties

- Improvement of fuel cell performance, particularly at high current density, requires an understanding of liquid water transport in gas diffusion media
- Research by students that have completed GATE center coursework, used GATE labs, or received GATE center funding (denoted by *):
 - Development of characterization techniques for capillary pressure – saturation curves for materials of mixed wettability (i.e. GDLs)*
 - Development of characterization techniques for relative permeability in gas diffusion media*
 - Development of analytical models of the GDL that incorporate experimentally determined liquid transport characteristics*
- Research has been conducted in conjunction with industrial sponsorship
- Dissemination
 - 6th International Conf. on Fuel Cell Science, Engineering, and Technology, June 2007



Apparatus for measuring saturation pressure curves for PEMFC GDL's

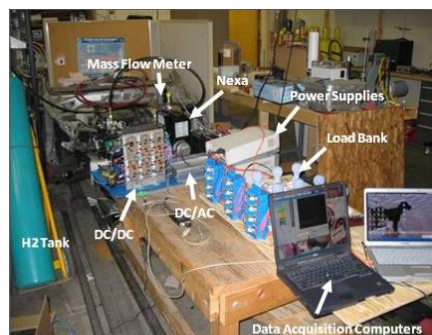


Apparatus for measuring relative permeability of PEMFC GDL's

13

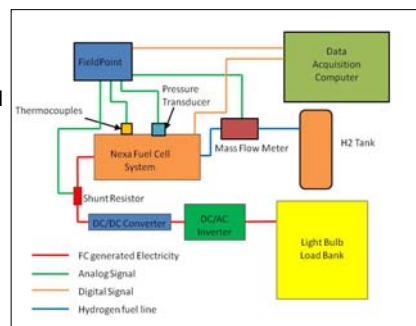
Systems Level Transient Modeling of a Fuel Cell Auxiliary Power Unit*

On-Board and external data acquisition was used to validate the Simulink model



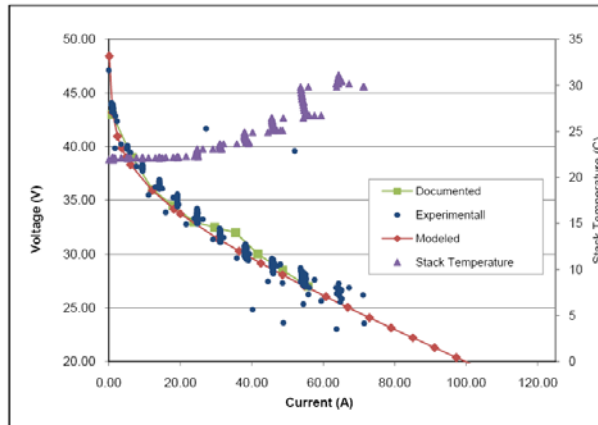
A bank of individually switched light bulbs was built for a test load for the Nexa fuel cell

* Work conducted by GATE funded student



14

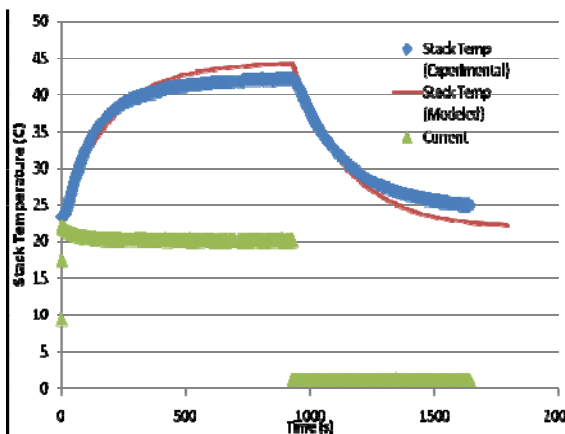
Transient Model Validation



- Experimental data was used to determine the coefficients in the empirical polarization curve
- The polarization curve is very sensitive to changes in stack temperature

15

Comparison of Steady State and Transient Data



- Steady state temperatures were validated first. The model agreement to experimental data is good.
- The transient characteristics of the model were then compared to experimental data in a warm up and cool down cycle

Gross Current	Cooling Speed (m/s)	Stack Temp C	T predicted C	Error in T C
5.47	2.2	22.69	21.3	-1.39
10.1	2.2	28.32	26.3	-2.02
15.6	2.2	34.12	32	-2.12
20.59	2.2	39.72	38.4	-1.32
26.17	2.3	44.56	44.5	-0.06
32.75	2.4	51.19	51.8	0.61
40.27	2.6	56.19	59.8	3.61

16

- The synthesis, design, operation, and control of PEMFC, DMFC, and SOFC cells, stacks, and systems as well as fuel storage devices:
 - Development of detailed dynamic and stationary non-linear models
 - Multi-scale and multi-physics (e.g., lumped parameter, continuum, kinetic theory, and quantum thermodynamic) techniques at the nano-, meso-, and macro-scales
 - Effective techniques for analysis and large-scale optimization (e.g., multi-objective as well as decomposition strategies)
 - Development of uncertainty techniques applicable to already burdened dynamic synthesis/design and operational control optimizations and analyses
- Research by students that have completed GATE center coursework, used GATE labs, or received GATE center funding include the following:
 - Development and application of quantum thermodynamic techniques (as a replacement of and correction to the traditional approach of linear and non-linear molecular dynamics) to the storage of H₂ on carbon nanotubes
 - Integration of MIMO state space control into the dynamic optimal synthesis/design and operation/control of PEMFC systems
 - Dynamic PEMFC system synthesis/design and operation/control under uncertainty
 - Transformation from a deterministic to a probabilistic problem
 - Development and application of probabilistic techniques for large-scale optimizations

17

- Demonstration of significance of load and cost uncertainties on meeting critical constraints (e.g., < 10 ppm of CO with a 95% confidence level)
 - Study of the feasibility of replacing the best battery technology with fuel cells in micro-air vehicles
 - Design, construction and testing of micro-tubular H₂ and MeOH fuel cells and stacks
 - Development and application of 3D reconstruction techniques for porous SOFC and PEMFC electrodes using SEM and TEM images
 - Development and implementation of kinetic theory models to the mesoscopic 3D modeling of reacting mixture flows with and without phase change in porous SOFC and PEMFC electrodes
 - Development and implementation of 2D macroscopic durability models of SOFC electrodes
 - Development of modeling optimization and control strategies for SOFC APUs
- Research has been conducted in conjunction with both industrial and government agency sponsorship
- Dissemination
 - 5th International Conf. on Fuel Cell Science, Engineering, and Technology, June 2007
 - ASME IMECE in Seattle, WA, November 2007
 - J. of Power Sources and ASME J. of Fuel Cell Science and Technology
 - 2 Ph.D. dissertations and 2 M.S. theses

18

Students that have received one or more semesters of GATE support

Bryan Shevock: completed MS thesis on "System Level Modeling of Thermal Transients in PEMFC Systems", Jan 2008.

Josh Sole: completing PhD dissertation "Investigation of Water Transport Parameters and Processes in the Gas Diffusion Layer of PEM Fuel Cells" expected completion May 2008.

Kurt Johnson: completing MS thesis on "Energy and greenhouse gas emissions comparison for hydrogen and grid electricity fueled vehicles", expected completion June, 2008.

Chris Fox: completing MS thesis "Evaluation of Penetration Shorting in PEM Fuel Cells", expected completion August 2008

Charles Smith: continuing Ph.D. on "Hydrogen storage on carbon nanotubes using quantum thermodynamics".

Students that have completed (or are currently enrolled in) GATE center classes and that have conducted fuel cell research

B. Vikram Kasula: completing Ph.D. on "Kinetic Modeling of Reacting 2-Phase Mixture Flows in PEMFC Electrode-Catalyst Layers".

Richard Evans: completed M.S. on "Modeling and Testing of a Micro-Tubular Low-Temperature Fuel Cell for use in a Micro Air Vehicle", Dec 2007.

Matt Miller: beginning M.S. on "Modeling and Testing of a Micro-Tubular Low-Temperature Fuel Cell for use in a Micro Air Vehicle".

Kihyung Kim: completed Ph.D. on "Dynamic Proton Exchange Membrane Fuel Cell System Synthesis/Design and Operation/Control Optimization under Uncertainty", Jan. 2008.

Meng Wang: completed Ph.D. on "The Integration of State Space into the Dynamic Synthesis/Design and Operational/Control Optimization of a PEMFC System", Jan. 2008.

Sigrður Gudmundsdóttir: completing M.S. on a "Parametric Study of the Design and Performance of SOFC Auxiliary Power Systems".

Yongqiang Li: completing Ph.D. on "Characterizing the Mechanical Durability of Proton Exchange Membranes",¹⁹ expected completion, December 2008.

- Students recently hired in fuel cell and automotive fields
 - Bryan Shevock (MS): GM, HEV integration, February 2008
 - Meng Wang (Ph.D.): GM, FCA, December 2007
 - Kurt Johnson (MS in progress): GM, June 2008
 - Will Smith (MS in progress): ETEK, June 2007

- Industry forums attended by GATE students and faculty
 - 2007 ASME IMECE
 - 2007 Challenge Bibendum, Shanghai, China
 - 2007 EVS-23 , Anaheim, California
- Interactions with industry
 - Luna Innovations, Inc.
 - Research on materials development for micro-tubular fuel cells for micro-air vehicles
 - Mr. Charles Strickler, Ecoelectrix, LLC
 - Research collaboration
 - Dr. Ann Norris, Dow Corning Corporation
 - Discussion of possible collaborative research projects related to PEMFC's
- Professional Development
 - SAE course, "Automotive Fuel Cell Systems", 3 days, offered two times per year to approximately 30 industry professionals.
 - Short course on "Techniques for the Modeling, Analysis, and Optimization of High and Low Temperature Fuel Cells: From the Microscopic Level to the System Level"; taught in Naples, Italy and Zaragoza, Spain as a 2-day course

21

Technology Transfer

- Our "products" are graduating students with advanced degrees and experience in fuel cell, hydrogen and vehicle research, along with research results and publications
- These students and publications are the main form of Technology Transfer from our work to industry and the marketplace
- Specific research projects funded by industry also target materials, processes and technologies that will impact transportation energy use; e.g.,
 - Techniques for the construction and testing of H₂ and MeOH micro-tubular fuel cells and stacks being transferred to Luna Innovations, Inc.
 - Techniques for PEMFC state space MIMO control strategies as well as decomposition strategies for large-scale optimization being transferred to GM via the hire of Dr. Meng Wang (former VT graduate student)

22

Activities Planned for 2008 - 2009

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- Task 1 – Curriculum development
 - Continue to offer and update courses for fuel cell systems, hydrogen energy technologies, vehicle technologies
 - Add laboratory experience to courses
 - Develop doctoral level course in fuel cell materials and processes
- Task 2 - Engage students in research
 - Provide research opportunities for students
 - Complete 2 more MS and 1 more PhD degrees
- Task 3 – Recruit 2 more students for GATE Fellowships
- Task 4 – Dissemination and Scholarship
 - Publications, conferences, short courses
- Task 5 – Industry Interaction
 - Shared research projects, visits, graduating student hires, industrial advisory board

23

Summary: GATE Center for Automotive Fuel Cell Systems at Virginia Tech

2008 DoE GATE
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- DoE objectives – Produce graduate degree engineers for industry with background in fuel cell, hydrogen and vehicle technologies research
- Approach – Develop courses and research projects to benefit students and industry needs
- Accomplishments – Courses, fellowships, projects and publications
- Collaborations – Industry projects, student hires
- Plan for 2008-09 – Progress on goals and tasks

24

Publications

2008 DoE GATE
Merit Review

- David A. Dillard, Yongqiang Li, Jacob R. Grohs, Scott W. Case, Michael W. Ellis, Yeh-Hung Lai, Michael Budinski, and Craig Gittleman, "On the use of pressure-loaded blister tests to characterize the strength and durability of proton exchange membranes" *ASME Journal of Fuel Cell Science and Technology*, submitted October 2007.
- Jacob R. Grohs, Yongqiang Li, David A. Dillard, Scott W. Case, Michael W. Ellis, Yeh-Hung Lai, Michael Budinski, Craig Gittleman, "Evaluating the time and temperature dependent biaxial strength of Gore-Select® series 57 proton exchange membrane using a pressure loaded blister test," *ASME Journal of Fuel Cell Science and Technology*, submitted October, 2007.
- Joshua D. Sole, Michael W. Ellis, David A. Dillard, "Experimental and analytical study of gas diffusion layer materials for ribbon fuel cells," *ASME Journal of Fuel Cell Science and Technology*, accepted November 2007.
- Bryan Shevock and Douglas J. Nelson, 2008, "System Level Transient Model of a Fuel Cell System", SAE paper 2008-01-0636, accepted for publication at the 2008 SAE *International World Congress*, April 14-17, 2008, Detroit, Mi, 17 pgs.
- Steven Boyd, and Douglas J. Nelson, 2008, "Hybrid Electric Vehicle Control Strategy Based on Power Loss Calculations", SAE paper 2008-01-0084, accepted for publication at the 2008 SAE *International World Congress*, April 14-17, 2008, Detroit, Mi, 15 pgs.
- Arsalis, A., Calise, F., von Spakovsky, M.R., 2007, "Thermoeconomic Modeling and Parametric Study of Hybrid Solid Oxide Fuel Cell – Gas Turbine – Steam Turbine Power Plants Ranging from 1.5 MWe to 10 MWe," *Journal of Fuel Cell Science and Technology*, ASME, N.Y., N.Y., accepted for publication.
- Verda, V., von Spakovsky, M.R., 2007, "2D Detailed Planar SOFC CFD Model for Predicting the Effects of Cell Performance Degradation," *Journal of Fuel Cell Science and Technology*, ASME, N.Y., N.Y., accepted for publication.

25

Publications...continued

2008 DoE GATE
Merit Review

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- Mazumder, S.K., Pradhan, S., Hartvigsen, J., von Spakovsky, M. R., Rancruel, D., 2007, Effects of Battery Buffering and Inverter Modulation on the Post Load-Transient Performance of a Planar Solid-Oxide Fuel Cell, *IEEE Transactions on Energy Conversion*, IEEE, vol. 22, issue 2.
- Pradhan, S., Mazumder, S.K., Rancruel, D., von Spakovsky, M.R., Hollist, M., Hartvigsen, J., Kahleel, M., 2007, A Modeling Framework for Planar Solid Oxide Fuel Cell based Power Conditioning System for Vehicular APUs, *IEEE Transactions on Power Electronics*, IEEE Power Electronics Society, special issue on Automotive Power Electronics & Motor Drives, in press.
- Calise, F., d' Accadia, M.D., Vanoli, L., von Spakovsky, M. R., 2007, Full Load Synthesis/Design Optimization of a Hybrid SOFC-GT Power Plant, *Energy: The International Journal*, vol. 32, no. 4, p 446-458.
- Calise, F., d' Accadia, M.D., Vanoli, L., von Spakovsky, M. R., 2006, Single-Level Optimization of a Hybrid SOFC-GT Power Plant, *Journal of Power Sources*, vol. 159, no. 2, Sept. 22, p 1169-1185 (not reported in the 2006 report).
- Coppo, M., Siegel, N. P., von Spakovsky, M.R., 2007, On the Influence of Temperature on PEM Fuel Cell Operation, *Journal of Power Sources*, Elsevier Press, Vol. 159/1, pp 560-569.
- Kasula, B. V., Mercado, L., Asinari, P., and von Spakovsky, M. R., 2007, "3D Microstructure Reconstructions of Solid Oxide and Proton Exchange Membrane Fuel Cell Electrodes with Applications to Numerical Simulations of Reacting Mixture Flows Using LBM," *International Mechanical Engineering Congress and Exposition – IMECE'2007*, 26 ASME Paper No. IMECE2007-42937, N.Y., N.Y., November.

- S. Cano-Andrade, A. Hernandez-Guerrero; M. von Spakovsky; C. Rubio-Arana, 2007, "Effect of Radial Plate Flow Field Distribution on Current Density in a Proton Exchange Membrane (PEM) Fuel Cell," *International Mechanical Engineering Congress and Exposition – IMECE'2007*, ASME Paper No. IMECE2007-42429, N.Y., N.Y., November.
- Arsalis, A., Calise, F., von Spakovsky, M.R., 2007, "Thermoeconomic Modeling and Parametric Study of Hybrid Solid Oxide Fuel Cell – Gas Turbine – Steam Turbine Power Plants Ranging from 1.5 MWe to 10 MWe," *Fourth International Conference on Fuel Cell Science, Engineering and Technology*, ASME, paper number: FUELCELL2007-25207, N.Y., N.Y., June.
- Smith, C. E., von Spakovsky, M.R., 2007, "Time Evolution of Entropy in a System Comprised of a Boltzmann Type Gas: An Application of the Beretta Equation of Motion," *International Mechanical Engineering Congress and Exposition – IMECE'2007*, ASME Paper No. IMECE2007-42933, N.Y., N.Y., November.