Developing a National Strategy for High-Volume Manufacture of P.E.M. and Solid Oxide Fuel Cells Workshop

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Executive Summary

This report presents the results of a workshop sponsored by the National Institute of Standards and Technology (NIST) that took place on December 8, 2003, in Dearborn, Michigan. The purpose of the workshop was to bring together a broad national audience to identify critical manufacturing issues associated with the high volume production of fuel cells and to explore the development of a national strategy for fuel cell manufacturability (NSFCM). The workshop technology focus was on polymer electrolyte membrane (PEM) fuel cells and solid oxide fuel cells (SOFC), as these two technologies are closest to high volume, commercial application. In scope, fuel cell applications included the U.S. transportation sector (especially the automotive industry) as well as stationary and portable power generation. There were approximately 50 attendees from a diverse cross-section of stakeholder organizations, including PEM and SOFC manufacturers and suppliers, relevant government agencies, organizations, and academic institutions (see Appendix B).

The workshop opened with four presentations:

- David Stieren, Strategic Relations Manager, NIST Manufacturing Engineering Laboratory (MEL), and the host of the workshop;
- Patrick B. Davis, Fuel Cell Team Leader, U.S. Department of Energy (DOE) Hydrogen, Fuel Cells, and Infrastructure Technologies Program;
- Jean Botti, Chief Technologist, Delphi Corporation, an SOFC manufacturer; and
- Chris DiLello, Director of Fuel Cell Stack Manufacturing, Ballard Power Systems, a PEM cell manufacturer.

Instead of having preset workshop topics to discuss, the workshop organizers decided to conduct an affinity grouping diagram exercise. The affinity grouping exercise is a process by which the attendees determine the important issues and how to organize them. Attendees were asked to write down the five greatest technical barriers to full cell manufacturing on adhesive note slips; one barrier per adhesive slip. Once they had completed the notes, the participants placed the notes on a wall resulting in approximately 250 notes that needed to be organized. The participants then had to read the notes and sort them into coherent groupings. The session organizers then reviewed the wall and identified four themes for the breakout groups based on the topics organized on the wall.

There were four breakout groups, each led by a facilitator and provided with a scribe to take notes:

Group A. Metrology and Standards
Group B. Fabrication and Assembly
Group C. Simulation and Modeling and
Group D. Materials and Sealants

The Metrology and Standards Group discussed the need for metrology standards across the fuel cell industry and across markets to improve developer/supplier relationships. It was determined that NIST (with participation from industry, professional societies, and academia) could help define the important product performance metrics and characterization methodologies, define testing protocols and their limitations, and also define standard reference materials. NIST could also set up testbeds for industry to take measurements under controlled conditions. Professional societies are well suited to distribute the standards. Another step is to help understand the relationships between the significant product performance metrics and generic manufacturing and design parameters. Assuming sufficient industrial interest, such an effort could be funded through a consortium, the U.S. Fuel Cell Council, and/or FreedomCAR.

The Fabrication and Assembly Group felt the move to high-volume production, e.g., automotive levels, is premature. Better fuel cell designs, the application of well-known design-for-manufacturing methodologies, and the evolution of production engineering techniques are sufficient to scale up to high volume production. The group identified a number of needs in the area of Design for Manufacturability (DFM) and production engineering. To address the issues the group proposed a roadmapping exercise to compile a list of non-competitive best manufacturing processes, identify the obstacles to realizing high-volume fuel cell production, and propose projects on an ad-hoc basis through the usual funding channels (grants from the National Science Foundation (NSF), the DOE or Department of Defense (DOD)) or a consortium.

The Simulation and Modeling group discussed the application of computer modeling and simulation to the development and optimization of fuel cells, which heretofore has focused on the basic physical processes and control of fuel cells, but not on fuel cell manufacturing. While the variability in fuel cell designs, the competitive nature of the industry, the variety of technical domains involved in fuel cell manufacturing, and the fundamental novelty of the technology are obstacles to the direct application of generic simulation models, the group believed an NSFCM could provide a framework for a staged development of modeling tools, as described below.

- Near-term: facilitate access to existing simulation tools and processes to accelerate manufacturing development and efficiency
- Medium term: define and support enhancements to modeling and simulation tools to address increased fabrication tolerances and new materials.
- Long term: define a strategy for model and simulation development to optimize the efficiency of the fuel cell manufacturing process.

The Materials and Sealants workgroup felt it was too early in the developmental stage of fuel cells to talk about an NSFCM, and therefore, did not endorse such an action. However, selected technical areas in membrane electrode assembly (MEA) and bi-polar plate technology would benefit from NIST assistance in developing industry standards and providing metrology development support. Also, because other national governments have proactively addressed the development of the fuel cell, the United States is at risk of losing leadership in this technology. The group believes there is a role for NIST to drive for standards—both within the United States and between countries and regions—in selected areas of fuel cell material and sealing development. The group also acknowledged that it may be beneficial if there were an effort to increase sharing of pre-competitive information on research and development (R&D),

measurement, and standards; and suggested that NIST could play a role in this ‘learning to share’ effort.

After the four breakout groups reconvened and presented their results, workshop participants came to the following general consensus. There is a need in the industry to develop a common set of fuel cell performance metrics and measurement protocols. There is a need to compile a list of simulation models and make them available to industry and researchers alike. There is a need to integrate these models to better understand system interactions and to understand the effects of manufacturing process parameters and their variation on fuel cell system performance. One proposed funding strategy was through the creation of a consortium, similar to Sematech. Any fuel cell strategy would have to include working with other federal and state government agencies, professional societies and fuel cell organizations, and the fuel cell and automotive industry.

1. Background

During 2003, the Manufacturing Engineering Laboratory (MEL) at the National Institute of Standards and Technology (NIST) set out to identify critical manufacturing issues associated with the high volume production of fuel cells, and to investigate if there is the need for a National Strategy on Fuel Cell Manufacturability (NSFCM). Toward this end, NIST hosted a workshop on December 8th, 2003 in Dearborn, Michigan that explored technical challenges, barriers and opportunities for the development of fuel cell manufacturing technologies. These technologies will enable the high volume manufacture of fuel cells (both PEM and SOFC) for application to the U.S. transportation sector (especially the automotive industry), as well as to stationary and portable power generation. An important first step was to initiate a dialogue between NIST and the automotive fuel cell industry. To accomplish this task, the Center for Automotive Research (CAR) and Altarum were contracted by NIST to identify stakeholders in the automotive fuel cell manufacturing industry, and to arrange and participate with NIST in interviews of these companies. The results of the interviews are reported in Appendix A.

This report presents the results of the workshop. The workshop's primary purpose was to bring together a broad national audience to identify critical manufacturing issues associated with the high volume production of fuel cells and to explore the development of an NSFCM. This workshop was a focused event attended by personnel (knowledgeable in manufacturing areas) from stakeholder organizations. The primary focus of the workshop was on polymer electrolyte membrane (PEM) fuel cells and solid oxide fuel cells (SOFC), as these two technologies are closest to high volume, commercial application. There were approximately 50 attendees from a diverse cross-section of stakeholder organizations, including PEM and SOFC manufacturers and suppliers, relevant government agencies, and academic institutions. A complete attendee list is provided in Appendix B.

This report is organized according to the workshop agenda, which is presented in Appendix C. The workshop opened with presentations, followed by an affinity grouping exercise which determined the topics for the breakout sessions. The majority of the time was then spent in these breakout sessions, where panelists identified manufacturing issues and discussed the implications of an NSFCM and how it might help the industry. Finally, the participants convened at the end of the day to hear summary presentations from each of the breakout groups and make overall comments on their views of an NSFCM.

2. Presentations

The workshop began with four presentations that set the stage for the proceedings:

- NIST, the host of the workshop;
- the Department of Energy (DOE), the government agency that funds a significant amount of the research being applied to the hydrogen economy;,
- Delphi, an SOFC manufacturer; and
- Ballard Power Systems, a PEM cell manufacturer.

The first presentation was by David Stieren, the Strategic Relations Manager of the NIST MEL and the host of the workshop. He welcomed the participants, gave a brief informational talk on NIST, and provided background on the workshop (see Appendix D.1)

The second presentation was by Patrick Davis, the Fuel Cells Team Leader in the Hydrogen, Fuel Cells, and Infrastructure Technologies Program at the DOE Office of Energy Efficiency and Renewable Energy (see Appendix D.2). After presenting the benefits of moving to a hydrogen economy, he discussed three areas of DOE-funded projects:

- A lower cost bipolar plate manufacturing process from Porvair Fuel Cell Technologies;
- Multiple projects in membrane and membrane electrode assemblies (MEAs); and
- Two cost studies that show system cost is dominated by the fuel cell stack, which is dominated by the MEA, which is dominated by platinum cost.

The third presentation was by Jean Botti, Chief Technologist of Delphi Corporation, on the Challenges in High Volume SOFC Manufacturing (see Appendix D.3). Delphi is pursuing SOFCs as auxiliary power units (APUs) for the automotive market and expects they will enter the high end niche vehicles in the 2010 time frame. Current challenges include:

- Reducing the material cost of the cell stack by 70% (80% of the cell cost is in the stack and 70% of the stack cost is materials)
- Reducing the cost of cell fabrication processes by 60% (reducing incoming material costs is key, as well as eliminating manufacturing steps)
- Improving the quality control of cells by 50% (sealing the stack to withstand repeated thermal cycling during operation is a major technical barrier)
- Increasing cell throughput by 70% (eliminating the number of sintering steps, possibly through alternative manufacturing processes, such as vacuum plasma spraying)
- Lowering the cost of metal components by 60% (lowering the operating temperature will help in developing lower cost metallic interconnects that can be manufactured by precision, high volume, lower cost processes).

(Unfortunately, due to other commitments, Mr. Botti could not stay for the breakout sessions.)

The final presentation was by Chris DiLello, Director of Fuel Cell Stack Manufacturing at Ballard Power Systems, on the Challenges in High Volume PEM Manufacturing (see Appendix D.4). He presented a number of challenges and activities at Ballard, including:

- Cost reduction activities (lower cost gas diffusion layer (GDL) and flow field design, lower cost bipolar plate material, and research in lower and non-platinum based catalysts)
- Unit cell component technologies (cold start, water freeze damage, low humidification)
- PEM fuel cell FC operational functionality and modeling (large measurement effort to validate complex fluid dynamics models).

3. Affinity Grouping Exercise

Instead of having preset workshop topics to discuss, the workshop organizers conducted an affinity grouping exercise. The affinity grouping exercise is a process by which the attendees determine the important issues and how to organize them (see Appendix E for the instructions that were presented to the attendees). There are two major advantages of the affinity grouping process over fixed topics. First, the organizers learn how the attendees think of the problem space, i.e., which topics they deem important and how they might be structured. The second advantage is that the working groups usually have a much better understanding of their discussion topics before they convene into their breakout sessions, since they participated in the creation of the topics.

The attendees were asked to write down the five greatest technical barriers to full cell manufacturing on adhesive note slips; one barrier per adhesive slip. Since the workshop focused on fuel cell manufacturing, technical barriers within the scope of the workshop included

- Fabrication processes (chemical or mechanical)
- Manufacturing control issues
- Assembly techniques, including automation issues
- Systems integration and interoperability
- Software issues
- Metrology (hardware)
- Measurement technology, procedures, and protocols
- Technical, non-regulatory standards

Conversely, examples of topics beyond the scope of the workshop were

- H_2 Generation
- H_2 Distribution
- H_2 Storage
- Education
- Regulatory codes and standards
- Any proprietary information

Topics related to product innovation became a grey area, as they often affect manufacturing (e.g., product architecture, materials development, product durability, etc.). The criteria applied here was whether the innovation was directed more toward product performance or more toward manufacturing. For example, if a material was developed to make manufacturing easier or cheaper (e.g. materials that are easier to manufacture and assemble) then it was considered in scope. However, a material developed to increase PEM fuel cell durability was considered out of scope.

Attendees also had to identify whether the barriers applied to PEM cells, SOFCs or both; they also were asked to identify themselves as being industrial, government or academic participants. Once they had completed the notes, the participants placed the notes on a wall that was divided into three areas: PEM on the right, SOFC on the left, and both in the middle. This exercise resulted in approximately 250 notes on the wall that needed to be organized. The participants had to read the notes and sort them into coherent groupings (see Appendix F for the final organization of the wall). Once the participants were satisfied with the groupings, they could sit down or take a break. The session organizers then reviewed the wall and identified four themes for the breakout groups, based on the topics created on the wall.

One of the difficulties encountered was that a significant number of notes focused on product issues, which were clearly stated as being beyond the scope of the workshop. For example, participants listed “lower temperature for SOFC” (a product issue) as a technical barrier, although the instructions clearly stated that the barriers should be focused on manufacturing issues. This is interpreted as an indication of product maturity. There are still many product issues that must be resolved before high-volume manufacturing takes a higher priority for these participants.

Another difficulty was that, while the participants wrote the notes and placed them on the walls, they (as a whole) did not spend much time organizing the wall. Some would try to organize one section of the wall, while others simply went on break to talk to other attendees. This resulted in approximately 40 groupings, instead of the expected 5 to 10 groupings.

After the break, the attendees reconvened and discussed the scope and content of the four breakout groups:

- Group A. Metrology and Standards
- Group B. Fabrication and Assembly
- Group C. Modeling and Simulation
- Group D. Materials and Sealants

Each breakout group was led by a facilitator, who was given a copy of the instructions on how to direct and focus the group discussions (see Appendix G). The facilitator also presented the group’s findings. In addition, each group had a scribe to take notes. The notes are presented verbatim in appendix H. Each group’s presentation had to address the following issues

1. Summarize/articulate the area, its issues, and its fuel cell applications.
2. What are the pre-competitive technical issues that need to be addressed relating to this area?
3. What are the critical measurement and standards issues associated with the area?
4. What roles should stakeholder groups (government – DOE, DOD, NIST, other; industry; academia) play in addressing the area?
5. How would an NSFCM impact this area?

The following sections are the summaries of the breakout groups.

4. Workgroup A: Metrology and Standards

The Metrology and Standards group focused primarily on standardization issues ranging from manufacturing process environment to supplier relationships.

On the manufacturing process side, the goal is to improve in-line sensing of parameters to ensure the manufactured product will meet design specifications. The issue then becomes identifying the relevant performance and process parameters and their interaction. Thus, it is necessary to develop testing procedures to measure and control the parameters, resulting in test protocols and acceptable limits of testing. As an example: one person raised the question "how clean does the manufacturing environment have to be?" Different manufacturers believe different levels of clean room environments are necessary, but no one really knows the impact of being more or less clean on fuel cell performance or life. Some believe this would be useful information to share at the industry level as it would ensure companies do not invest unnecessary resources into manufacturing processes without sacrificing competitive capabilities.

Another issue raised was that there are no performance standards between fuel cell developers and suppliers. Thus, it is difficult for suppliers to meet the varying demands of customers for the same basic service, and it is difficult for customers to compare different suppliers. Indeed, without standards for measuring performance it is difficult to conduct any kind of benchmarking, be it for components or the final assembled product. Developing component performance standards would lower costs and increase quality within the industry.

Related issues include the need for standard measurement protocols that would identify acceptable limits of precision and accuracy of techniques and equipment, the need to align techniques with design criteria, and the need to establish guidelines for best practices for manufacturing process quality. However, questions remain as to the depth to which such measurement protocol standards should go and whether industry would adopt such standards.

The group also discussed existing bodies with special committees dedicated to discussing fuel cell and hydrogen issues at a national and international level. If standards can be agreed upon internationally, it would make it easier to do business in international markets.

In summary, metrology standards ensure quality in the supply chain and lower costs, enhance international trade, and improve the quality of the end product. However, the relationship between process parameters and product performance are not fully understood at this time. The time is right to discuss metrology standards across the fuel cell industry and across markets to improve developer/supplier relationships.

NIST, in cooperation with industry, professional societies, and academia could help define the important product performance metrics, testing protocols, limitations of the protocols, and standard reference materials. NIST could also help by setting up testbeds for industry to take measurements under controlled conditions. The professional societies are well suited to distribute the standards.

Another step would be to help understand the relationships between the significant product performance metrics and generic manufacturing and design parameters. However, this is a much more difficult task, in part, because one must be very sensitive to generic versus proprietary parameters. Assuming that such generic factors exist and that there is an interest on the part of industry (as expressed in the workshop), the question was raised about how such an effort could be funded. Suggestions included a consortium or approaching the U.S. Fuel Cell Council.

5. Workgroup B: Fabrication and Assembly

In the areas of fuel cell fabrication and assembly, the group generally believed that process evolution would handle the move to high-volume production, and that no revolutionary fabrication or assembly processes need to be developed. That does not mean that current processes are sufficient, only that there are no foreseen fabrication and assembly processes of such difficulty that significant R&D efforts are needed to overcome them.

The group also believed that the move to high-volume production, e.g., automotive levels, is premature. Fuel cell penetration is likely to begin in niche applications, such as premium power, proceed through adoption in areas such as defense and mobile applications, and finally into automotive. This follows the DOE scenario. In order to displace the internal combustion engine, better fuel cell designs are necessary. It is unclear whether winning designs will necessitate revolutionary fabrication and assembly processes, but at this point the group could not identify any. The hesitancy of suppliers to commit to component production in the face of uncertain near-term volumes is complicating the move to high-volume production.. Several suppliers have pulled out of the market since promised order quantities have not materialized.

Manufacturers in the group stressed three points on the topic of design. First, designers often change fuel cell designs, so large capitalization now for current designs is ill-advised. The use of flexible production equipment that can be quickly retooled for modest design changes A better choice. Second, designers are not following design-for-manufacturing (DFM) methodologies, making cost-effective production impossible. Third, designs need to work repeatably on the test bench and in customer environments, and need to be scalable to high-volume production.

Summarizing the above points: better fuel cell designs, the application of well-known DFM methodologies and the evolution of production engineering techniques are sufficient to scale up to high-volume production. Specific needs are detailed below.

The topic of better fuel cell design was out of scope for this group, although it crept in during the discussion on DFM. In DFM, the group identified these needs:

- Component selection that is more conducive to manufacturing
- Reduced parts count
- Designs that can be produced consistently at both low and high volumes
- Realistic tolerance specifications, varying during phases of design and production
- Designs that can be manufactured on current production equipment
- Involvement of high-volume production manufacturing engineers at the early stages of product development

In the area of production engineering, the group identified these needs:

- Better supply chain management
- Scalability of processes from low to high volumes
- In-process inspection (geometric and functional)
- Fully automated systems
- High-volume sealing
- High-volume plate manufacturing
- Robust processes, e.g., better optical alignment
- High-speed alignment and assembly
- Flexible manufacturing that works with a broad range of materials
- Simulation without substantial empirical studies
- Better process measurement, i.e., what is important to measure and how to use measurements

To address these issues, the group discussed the need for a roadmapping exercise. This exercise would begin with the compilation of non-competitive best manufacturing practices, possibly stemming from analyses of the manufacture of comparable products (like flexible circuits or photocopiers). Obstacles to realizing high-volume fuel cell production would then be enumerated, and specific projects to overcome these obstacles could be undertaken. These projects could take place on an ad-hoc basis (e.g., between a supplier and an OEM), through the usual funding channels (grants from the National Science Foundation (NSF), Department of Energy (DOE) or DOD) or as part of a possible consortium.

6. Workgroup C: Simulation and Modeling

The Simulation and Modeling group discussed the application of computer modeling and simulation to the development and optimization of fuel cell manufacturing processes. While there are efforts underway in industry, academia, and government labs to model the basic physical processes and control of fuel cells, the group was not aware of efforts focused on modeling and/or simulating fuel cell manufacturing. On the other hand, the group felt modeling and simulation could significantly advance the development and optimization of manufacturing processes, and thus is a key element in the development of a viable fuel cell industry.

In principle, modeling and simulation could specifically aid fuel cell manufacturing in the following ways:

- Models for basic material fabrication and assembly, such as stamping or deposition, can be used to virtually develop processes for fabricating basic fuel cell elements.
- Models for fuel cell fabrication and assembly can be used to optimize the efficiency of the overall manufacturing process, and thus reduce the cost of fuel cells. Models can be used to optimize both physical plant and supply chain components.
- Models that relate changes or variability in manufacturing parameters to variability in fuel cell performance, such as robustness, durability, and mean time to failure, can significantly accelerate the development of manufacturing processes. Currently, the impact of small changes in manufacturing processes are assessed using time-consuming empirical testing.
- Virtual prototyping/testing simulations can be used for design intent verification.

Even though modeling and simulation of manufacturing processes is a relatively mature field, the group recognized there are several unique issues with respect to fuel cell manufacturing that either complicate the direct application of existing techniques or limit the applicability of generic models. Specifically:

- The emerging nature of the industry results in a large variability in fuel cell designs and fabrication processes─even within a specific fuel cell type, across manufacturers and over time. Thus, it is difficult to develop process models that are generically applicable until the technology converges to more standard designs.
- The highly competitive nature of the industry results in most manufacturers treating technical data relevant to the manufacturing process, e.g., product design and fabrication process, as proprietary. Thus, it is difficult for external sources, such as academia and/or government labs, to develop widely applicable models or software tools.
- Fuel cell manufacturing spans a wide variety of technical domains, including materials science, electrical engineering, and others. Thus, multi-disciplinary expertise is required to develop models and simulation tools.

- Since certain aspects of fuel cell manufacturing are fundamentally new, models and simulations will have to be refined and validated using extensive experimental data.

The group did identify some pre-competitive technical issues that could be addressed to advance modeling and simulation of fuel cell manufacturing:

- Some processes in fuel cell fabrication, such as stamping, deposition, and molding, are generic manufacturing processes. Models and/or virtual prototyping tools for these generic processes have been developed in the context of other industries. Developing consolidated access to these models and software tools is possible and would prevent the emergent fuel cell industry from re-inventing available technology.
- Certain fuel cell manufacturing processes are likely to require much tighter tolerances than comparable processes in other applications. Existing models and software tools for generic manufacturing processes may need to be altered to address the tolerances in fuel cell manufacturing.
- Virtual test procedures and standards can be developed to evaluate fuel cell performance, independent of fuel cell design specifics.
- The fundamental linkage between material performance and process change can be studied for materials that are generically applicable to fuel cell technology.

The critical measurement and standards issues associated with modeling and simulation primarily relate to defining parameters or to data collection for model validation. Development of new process models will require collection of baseline data for model validation. Virtual testing will require the specification and development of standard fuel cell performance requirements in many areas, such as electrical performance and safety.

Government, industry, and academia can all play roles to advance modeling and simulation of fuel cell manufacturing, and thus advance the development of a viable industry.

- NIST could serve as the focal point for assembling relevant generic modeling, simulation, and measurement technology to advance the development of fuel cell manufacturing technology. As the technology matures, NIST laboratories could develop modeling tools to improve specific manufacturing processes.
- Government agencies focused on advancing fuel cell technology and supporting the development of a viable industry (e.g., DOE and DOD) can identify and support the development and improvement of modeling and simulation tools for generic manufacturing processes.
- Regulatory agencies, such as the Department of Transportation and the Environmental Protection Agency, could provide standards that would be used in virtual testing procedures.
- Industry can identify generic modeling and simulation needs and support their development through consortia and cooperative agreements. Industry groups can support the development of virtual testing procedures and standards.

- Academia can advance basic modeling and simulation technologies for fuel cell manufacturing processes, and educate the future fuel cell workforce in their use.

A National Strategy for Fuel Cell Manufacturing (NSFCM) could impact modeling and simulation of fuel cell manufacturing by defining a framework for developing useful tools that advance (in a staged manner) as the fuel cell industry matures. Specifically:

- In the near-term, the NSFCM could facilitate access to existing simulation tools and processes to accelerate development and improve efficiency in the manufacturing of fuel cells.
- As fuel cell technology develops, the NSFCM could define and support enhancements to modeling and simulation tools that are required to meet the increased fabrication tolerances and new materials of fuel cell designs. Further, a procedure for developing virtual testing standards for emerging designs and applications could be defined.
- As fuel cell technology matures, the NSFCM could define a strategy for developing models and simulations that could be used to optimize the efficiency of the fuel cell manufacturing process, and thus increase the competitiveness of the U.S. industry.

7. Workgroup D: Materials and Sealants

It was generally agreed that because basic fuel cell materials are not yet well-defined, fuel cell performance, durability and manufacturing are still highly uncertain. Although the Materials and Sealants workgroup indicated they believe it is too early to pursue an NSFCM in general, and specifically the materials and sealants used for fuel cells, the group offered many material-related technology and process issues that NIST could begin to investigate.

There is still much developmental work for both the PEM membranes and the catalyst materials. The workgroup suggested that NIST consider investigating approaches to developing standard tests on membranes for key attributes (e.g., tensile, cycling, conductivity, etc.). However, the group offered the caveat that it still needs to determine which attributes need to be measured. One area of concentration could be to work to create uniformity (defect) measures for PEM membranes. Another area of interest is the loading, dispersion and durability of the platinum catalyst. According to the workgroup, industry needs to develop standards and test protocols for materials and components

Another area of development is the robustness of the catalyst. Current catalyst strategies and materials are not capable of lasting, given hydrogen purity variations. This is an important materials issue. One participant indicated that there might be an opportunity for NIST to assist in developing the purity standards and measurement systems for hydrogen.

<u>Membrane Electrode Assembly (MEA) and bipolar plate technology</u>:
The group discussed processes for the manufacture of MEAs and plates. It was suggested that although there have been thousands of MEA and plate designs investigated, the prominent designs need to standardized. At least one participant questioned whether it was possible to develop an industry standard for flow fields. There is a poor correlation between current cost and performance targets. The ability to better understand the connection between these two variables would be helpful.

Because the stamping of plate components requires large-scale (high volume) tolerances and uniformity standards, one participant suggested it might be valuable to pursue strategies that either avoid the need for such tight tolerances, or that better allow for the exacting standards. There is also a need for the development of large-scale materials and process development for the welding and joining of plates to seals and manifolds for SOFCs.

The measurement of series conductivity of plates offers another area of potential NIST action. The group felt there is too much variation using the current methods. There was a suggestion for NIST to lead an effort, leveraging the work of others, including the U.S. Fuel Cell Council, the American Society of Testing and Materials, the National Center for Manufacturing Sciences, and others to establish standards for conductivity measurement. Finally, the group also supported standardized conductivity (ionic, bulk, proton) tests for completed PEM fuel cells. The bulk molding of composite plates so that the thickness, flatness, parallelism, and molded net shape for flow fields can be controlled was mentioned by one participant as an area NIST could investigate.

Fuel Cell Sealing Technology

There was agreement that it was too early in the development of the fuel cell to discuss the standardization of sealing technology—or even materials. The options for the high volume manufacture of seals are still not fully understood. This is in large part due to a great uncertainty regarding the seal material required. Questions such as the long term durability (i.e. 10 years) and high volume manufacture of seals were identified as areas of concern. However, it was noted that current seal materials last longer than the current fuel cells.

There was an acknowledgement that the fuel cell industry lacks an 'openness' that makes the sharing of pre-competitive knowledge difficult. The group also recognized that it may be beneficial to the industry if there were an effort to increase sharing of pre-competitive information on R&D, measurement, and standards. NIST could play a role in this 'learning to share' effort.

An example of this problem is the industry's relative sluggishness with regard to testing and establishing a database of knowledge about the robustness of fuel cell components. There is a substantial amount of system level interactions that need to be better tracked and documented. According to individuals in the workgroup, the industry is still early in the learning curve to really determine correlations. Currently individual developers are performing many of these tests, but because of intellectual property concerns, the industry has been unwilling to create a database of such results. Such a database would offer the opportunity to build on previous work and could lead to rapid advances.

In summary, the workgroup felt it was too early in the developmental stage of the product (fuel cell) to talk about an NSFCM. Therefore, the group did not endorse such an action. However, they did agree that other national governments and regional coalitions have proactively addressed the development of the fuel cell. The United States and North America are therefore at risk of losing leadership in this technology. The group believes that there is a role for NIST to drive for standards—both within the United States and between countries and region—in selected areas of fuel cell material and sealing development.

8. Conclusions and Recommendations

After the breakout groups reconvened and presented their results, there was discussion regarding the path forward. There was clearly a division among the participants about the need for an NSFCM. Some believe it is simply premature, due to the lack of a stable product and stable demand. However, there was also a general consensus that there are several issues, specifically involving metrology standards and simulation, where collaboration between industry and government could lead to benefits that would drive fuel cells more rapidly toward commercial viability.

There is a need in the industry to develop a common set of fuel cell performance metrics, standards, and measurement protocols. Although current metrics tend to be indirect measures of fuel cell performance, they are useful and, with proper protocols, could be used to benchmark fuel cell performance, providing the customers a means by which they can compare alternative fuel cells. Similarly, measurement standards need to be established for fuel cell components to enable suppliers and customers to work more cost-effectively with one another. Finally, there is a need to understand the underlying parameters that affect each of the component and performance metrics, including the effects of manufacturing process variation on fuel cell system performance.

Numerous simulation models have been developed— both under DOE contracts as well as by industry. The time has come to compile a list of these simulation models and make them available to industry and researchers alike. Further, an effort should be undertaken to integrate these models to better understand system interactions. Typically, the individual models have a fair degree of fidelity and detail, as they were designed to understand specific relationships. It is believed that it is possible to combine simulation models to create a larger system-level simulation with a fair degree of fidelity. The model could then be used to better understand the relationship between manufacturing parameters and fuel cell performance metrics.

While manufacturing has not been a major focal point of research for many funding agencies, it is clear that manufacturing plays an important role in making fuel cells more affordable and, hence, is on the critical path to commercialization. Some believe that manufacturing issues will be addressed when the market demand rises and the need for higher volume processes is evident. However, others believe that novel manufacturing methods can be developed or adapted from non-automotive industries to dramatically reduce the cost of current fuel cell manufacturing.

To address the specific manufacturing issues identified previously in this report, it is recommended that a consortium or several consortia (e.g., one for PEM and another for SOFC) be created with very narrowly focused mission purposes. It is believed that, given the broad areas of fuel cell research, consortial activities with a broad mandate have too great a probability of duplicating other efforts or disintegrating due to lack of focus and disparate activities and interests on the part of the participants.

The group discussed the Sematech consortium as an example. It too was a consortium with a very narrowly focused mission. However, questions arose as to the general issue of government supported initiatives: “Why should public funds be used to seed a consortium? If venture capital can't be found, isn't this an indication that the problem is not worthy of funding?” The group believed that there are national interests in fuel cell development citing President Bush's endorsement of a Hydrogen Economy. Reduction of reliance on foreign oil (a national security issue) and improving the environment (a quality of life issue) are both justifications for public spending to seed a fuel cell consortium. During the wrap-up session, participants listed a number of fuel cell consortia already in existence, such as the U.S. Fuel Cell Council and FreedomCAR.

If another consortium is created, it should:

- consist of industry participants as well as national labs;
- be created with coordination and collaboration with other existing organizations, such as the Fuel Cell Council, Solid State Energy Conversion Alliance (SECA), and the Society of Automotive Engineers (SAE);.and
- have a focused, non-overlapping purpose.

It was also suggested that the consortium participants should contribute funds and in-kind support. It is anticipated that universities would participate as knowledge and research resources on an as-needed basis.

The topics defined above are two high impact areas where a consortial approach could have a large impact. They appear to be under-funded and/or unaddressed.

9. Appendix

A : Preconference report

B : Attendee Roster

C : Workshop Agenda

D: Presentations

- NIST
- DOE
- Delphi
- Ballard

E : Affinity Grouping Exercise

- Instructions
- Affinity Grouping Results

F : Workgroup Notes

- Facilitator Instructions
- Workgroup A: Metrology and Standards
- Workgroup B: Fabrication and Assembly
- Workgroup C: Simulation and Modeling
- Workgroup D: Materials and Sealants

A : Preconference report

Issues in High Volume PEM and SOFC Fuel Cell Manufacturing

Center for Automotive Research
November, 2003

Introduction

The National Institute of Standards and Technology (NIST) is investigating the need for a National Strategy on Fuel Cell Manufacturing. Towards this end, NIST intends to host a workshop that explores challenges, barriers and opportunities for the development of fuel cell manufacturing technologies. These technologies will enable the high volume manufacture of fuel cells (both PEM and SOFC) for application to the U.S. transportation sector (especially the automotive industry), as well as to stationary and portable power generation. An important first step is to initiate a dialogue between NIST and the automotive fuel cell industry. To accomplish this task, the Center for Automotive Research (CAR) was contracted by NIST to identify stakeholders in the automotive fuel cell manufacturing industry, and to arrange and participate with NIST in interviews of these companies.

During the third quarter of 2003, CAR partnered with the Manufacturing Engineering Laboratory (MEL) at NIST to interview representatives from five organizations: two fuel cell manufacturers, two fuel cell component manufacturers, and one government research organization. These interviews were designed to accomplish three tasks. First, they were to identify barriers to the high volume manufacture of fuel cells. Second, they were to determine the need for a NIST sponsored workshop to develop a roadmap for a national strategy to facilitate such manufacture—as well as identify potential roles that NIST and other governmental agencies might play in such a strategy. The third task was to initiate a dialogue between NIST researchers and the automotive fuel cell industry.

Three of the participating companies became involved in fuel cell development because they are concerned that the internal combustion engine (ICE) could become obsolete at some point in the coming decades. They perceive their company's expertise as a natural 'fit' with the fuel cells, and as such presents opportunity. The fourth company was incorporated solely for the purpose of developing fuel cell technology for a variety of applications. The government research organization identified the desire to gain synergies from the automotive fuel cell industry and United States Department of Defense directives.

The research team realizes that the high volume manufacture of fuel cells is merely one small part in the overall challenge to reach the 'hydrogen economy'. However, this effort is intended to investigate only the high volume manufacture of fuel cells. As such we have intentionally reserved the discussion of such critical issues as infrastructure, hydrogen storage and creation, and well-to-wheel (-to-grave) energy analysis for other forums.

We have also chosen to investigate only the fuel cell stack. While there are manufacturing issues involving the balance of plant and power electronics, many suggest that those appear to be solvable via continuous improvement of known manufacturing processes. However, the development of high volume manufacturing processes for the fuel cell stack appears to offer the greatest challenge and uncertainty.

This white paper describes the information gathered in the interview process and serves as a planning tool for NIST to develop a workshop that will identify collaborative opportunities for fuel cell manufacturing research with automotive and fuel cell industry stakeholders. As with many CAR projects—and in deference to the highly confidential nature of the topic—company representatives were given assurance of confidentiality. They were also asked to review a draft of the white paper, with the opportunity to delete any information that they felt was confidential in nature and to comment for clarification. The Center for Automotive Research and the NIST Manufacturing Engineering Laboratory would like to thank those company representatives. The manufacture of fuel cells is a highly competitive and confidential issue. The willingness of these individuals to openly share their knowledge, insights and, of course, their valuable time made this project possible. Commitment to collaboration such as this should stand as an example for future work in this area.

Project Background

Fuel cell manufacturing cost has consistently stood as one of the major barriers to wide-use automotive applications. Polymer electrolyte membrane (PEM) technology is widely recognized as the most suitable technology for mobile applications, but the current production cost (dollars per kilowatt) exceeds the internal combustion engine cost by at least a factor of ten, thus relegating it to very low-volume prototype use. Solid oxide fuel cells (SOFC) present an alternative in the form of auxiliary power units, but are currently far too expensive. While there is significant research underway to advance fuel cell technologies, rapid developments and future product uncertainty have limited the attention given to high volume manufacturing processes and associated costs; an issue of profound importance to the mass-automotive market. The complexity of overlaying the incumbent and prospective manufacturing processes (current and new) stems from the concurrent technology development and resulting future uncertainty of the precise PEM or SOFC architecture, and future projections must consider at least a ten-year horizon. Any proposed roadmap cannot lay out conclusive manufacturing requirements over this timeframe. However, it can outline appropriate strategic approaches to accelerate mass-market usage while assessing technological manufacturing capabilities, economic soundness, and future uncertainty.

Within the automobile market, evolutions will likely progress from prototype (experimental volumes) to niche vehicle (10,000-25,000 units/year per model), to large-volume models (250,000 or more units/year per model)—with each progression requiring a new set of manufacturing scalability requirements. The manufacturing attributes for the auto industry include: low unit cost, process reliability, supply reliability (e.g., materials and components), operating safety, and high quality. The necessary manufacturing processes and technologies do not exist today—or have not been refined to adequately meet these requirements. Furthermore, incremental improvements with prevailing technologies will likely not achieve these objectives.

The critical need is to identify manufacturing technology evolutionary scenarios that most quickly lead to the mass automotive market with minimal economic or technological risk. New fuel cell applications (specialty, commercial, and consumer) will develop in route to high-volume mobile markets, stimulating capital investment and energizing new research to apply to the subsequent application and process development, typically resulting in lower cost and broader demand. Figure 1 presents a stylized developmental curve for fuel cell manufacturing technology. Increasing fuel cell manufacturing scalability will be a consistent theme over time. Lead-time based estimates may be developed for the amount of “contribution” needed to achieve mass-mobile applications broken down by: product and technology improvements, new materials, manufacturing refinement, and new manufacturing scale-up technologies. Mitigating capital investment risk and accelerating the lead-time to mass automotive applications will be significant contributions of this proposed roadmap. A probabilistic perspective on evolutionary scenarios may be appropriate, with an assessment of the likelihood of success/failure at critical path-changing nodes that identify alternative directions in manufacturing process evolution. The roadmap will undoubtedly be refined during the evolution as new information becomes available.

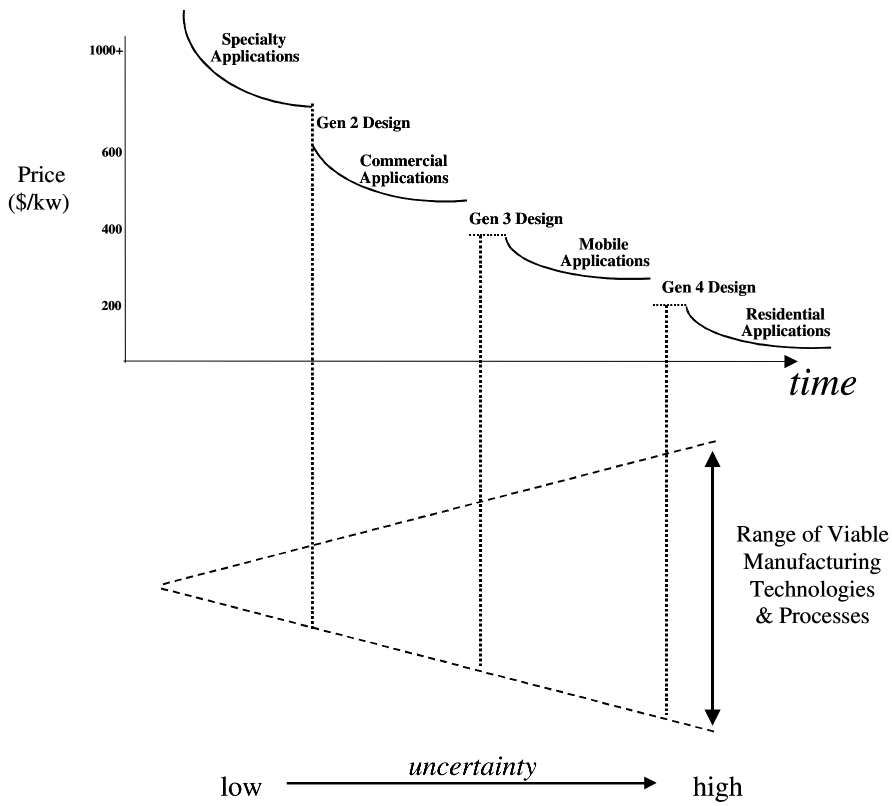


Figure 1. A stylized developmental curve for fuel cell manufacturing technology

Opening Remarks from Interviewees

All respondents believed that the internal combustion engine was likely to be the most viable power source for the coming decade—or possibly much longer. However, each respondent indicated a strong belief that the fuel cell offered the potential to replace the internal combustion engine eventually. Several respondents also cautioned that the fuel cell industry—either as a source of mobile power or for auxiliary power unit applications—is far from having a real product to manufacture. According to these respondents, the exact specifications of a salable high volume product—either PEM or SOFC are far from defined. However, the respondents felt that it was not too early to begin to assess manufacturing issues. As one said, "the design for manufacturability time is now."

Other respondents did not necessarily agree that the fuel cell was far from production. One representative believed that direct methanol systems (used primarily in batteries) are moving to significant volumes in the next 5 years and that transportation applications (PEM in this case) would follow some time after that.

All company representatives concurred that manufacturing was a significant challenge in the effort to successfully capture the automotive market—for either PEM or SOFC. Most participants agreed that there is the likelihood that new manufacturing processes must be adopted to meet the cost requirements associated with automotive application. Several also indicated that there was opportunity for NIST, or other agencies, to be a catalyst in the push to develop 'leapfrog' technologies.

For these reasons, all interview participants expressed interest in a National Fuel Cell Manufacturing Strategy and agreed to participate in the NIST workshop.

Process-related issues being encountered, including those associated with materials and raw materials

All participants agreed that manufacturing and assembly present a critical barrier to the success of fuel cells for transportation applications. The fuel cell industry is just now moving from the hand built paradigm through low volume manufacturing, and then possibly to the high volume paradigm. They felt that it was essential to ensure that manufacturing and assembly were important criteria in the product development process.

Manufacturing processes for the SOFC include stamping, co-firing ceramics, and (potentially) vacuum plasma spraying. For SOFC assembly, sealing and brazing were identified as critical processes. Although some processes are currently automated, and appear to be scalable, there are a number that are not. Brazing and vacuum plasma spraying were identified as two processes that present significant challenges with respect to high volume production. Brazing presents a particular scalability challenge because of the arc time, while cycle time also presents a challenge for vacuum plasma spraying. There is also difficulty—both material and process—in sealing the SOFC stack. The elastomeric material, commonly used for sealing PEM fuel cells, cannot withstand the temperatures associated with SOFC.

With regard to PEM fuel cell manufacturing, the respondents highlighted several high volume process issues. For this discussion, we have chosen to divide them into five main critical elements: membrane, membrane electrode assembly, seals, bipolar plates, and the final assembly of the stack.

Several respondents indicated concern over the capability of current membrane manufacturing processes. The exceptionally high volume required of the production process makes it a significant challenge. However, a representative whose company has experience in membrane manufacturing stated that his company believes their manufacturing process is fairly mature compared to industry demand and that reaching increased demand volume levels would be relatively easy.

There was also some concern regarding the viability of current membrane technology. Several participants suggested that membrane development was still far from close to meeting product requirements. Thus, they were concerned about whether the manufacturing processes for current membrane technology would be transferable to future product specifications. Other participants felt that current membrane technology would, through reasonable continuous improvement, meet the required performance needs.

Most respondents felt that the MEA assembly process was not as advanced as the membrane process, yet did show 'promise'. One MEA assembly process was described as semi-automated, with the 'front-end' processes automated and the later, more customer specific processes, still done manually. The representative for this company suggested that MEA assembly was not necessarily a process issue, but instead one of standardization. He felt that, as the industry moved toward a more standardized end product, it may be possible to become entirely automated utilizing current manufacturing capabilities. A representative from another company stated that his company is moving from a manual MEA assembly system to a vision-based mechanical alignment system. The ability to apply coatings (spraying, rolling, layering, etc.) in this process would be an important step in achieving high-volume manufacture.

The application of the catalyst is a critical element of the MEA assembly. Aside from being centered on either the gas diffusion layer (GDL) or the membrane, the catalyst must be uniformly loaded over the entire contact area with micrometer level control. An ideal process for this has not been realized.

Currently the material of choice for PEM Fuel Cells is an elastomer (silicon). These seals are extremely thin—approximately 0.25 mm (for reference, a seal for an internal combustion engine is approximately 3.0 mm thick). A couple of participants indicated that because of the permeability of silicone, it will always present a seepage issue. That is, hydrogen can theoretically penetrate the materials' molecular structure and leak from the stack. Therefore, there is concern that silicon may not be the material that is used in a 'workable' high volume PEM fuel cell. According to these respondents, there is a need for an alternative with a high flow rate like silicon, however with a lower permeability. If silicone remains the only choice for PEM fuel cells, the current rolling equipment used for seal production is not capable of high volume production when coupled with the low delivery rates (grams/unit time) required for 0.25 mm thick seals. Such a process would need significant development.

Most bi-polar plate development is focused on graphite or composite (ceramic) materials however, there is work in conductive thermoplastic bi-polar plates. Although metallic and graphite plates have been the focus of much developmental effort, they still appear to present significant hurdles before high volume processes are finalized. One respondent indicated that they believed composite plates present a viable alternative. They also believe that these composite plates can benefit from existing manufacturing processes that can easily be applied to this application. The representative suggested, much like other material replacement opportunities, the end product can benefit greatly by designing for a specific material, instead of attempting to make new materials fit within the existing paradigm.

Respondents indicated that alignment is one of many important for assembly challenge for the stack assembly. There are two aspects to alignment. One is the horizontal alignment, i.e., the amount of surface area through which the hydrogen flows. The other is the vertical alignment of the various cells. The voltage is proportional to the number of cells in the stack. The current, however, is sensitive to horizontal variation between cells. This is related to the MEA alignment problem mentioned previously, namely the membrane area, GDL and catalyst must all be aligned to allow the maximum hydrogen flow through all layers (typically 5 or 7 layers per cell). Any misalignment is lost current performance; hence the alignment of the cells in the stack relative to each other is a critical control element.

The variation in vertical alignment is a problem of closing pressure and component variation stackup. A fuel cell stack typically needs a pressure of 2,627 N/m (15 lb/linear inch) to operate properly compared to an ICE, which has typically 10,500-17,500 N/m (60-100 lb/linear inch).

Each stack component varies in thickness across its surface. One respondent suggested that, MEAs vary by 50 microns with plate thickness variation an important element of that variation. This results in gaps and in uneven pressure distribution within the stack when the stack is closed (end plates are attached). The seals can compensate for small gaps, or only about 5% of the total variation in the stack. Larger gaps result in leakage which clearly degrades cell performance. The uneven pressure can cause individual bi-polar plates to crack (which are moving to becoming thinner to reduce weight and improve performance), thereby making the entire stack inoperable. Thus, sealing pressure is an important factor in fuel cell assembly.

Equipment-related issues manufacturing hardware and systems

With a few exceptions, respondents were unaware of significant equipment or controls-related issues. However, they warned that such issues would be likely as the processes moved to higher volume. In many respects, the respondents indicated that their biggest concern with regard to controls and equipment for high volume fuel cell manufacturing is that they do not necessarily know what the final solution will be. Therefore, they do not necessarily 'know what they do not know'. With the lack of standardized designs, the manufacturing processes have not evolved to a point where these types of problems can be identified.

An example of the challenge is illustrated by the rolling machinery for seal manufacture. The rolling equipment used for manufacturing internal combustion seals must be re-engineered in order to produce the much smaller fuel cell seals. While process results can likely be achieved, either through modification or redesign, users are in the very early in the learning process and not necessarily assured of meeting the required cost and cycle time requirements.

One glaring exception is that of the lack of 'referenceable' methodologies for testing and inspection. The fuel cell industry is, much like the product itself, in the developmental stage. There is opportunity for NIST to play an important role in assisting industry in developing and monitoring industry. These issues are further discussed in the section on metrology and standards issues.

Software issues, including systems integration, and data representation and exchange

The participants did not report any significant software issues. However, during the prototype build, there is the need to collect and analyze a substantial amount of data. One respondent stated that they collect approximately 100 times more data than for their traditional manufacturing processes. He explained that this was required for 'genealogy' and traceability. Several participants noted that there is still much to learn with regard to how the manufacturing processes affect product performance. For example, a respondent said they use as many as four process data streams as a proxy for a single product performance measure, and they are still learning what processing changes affect performance characteristics.

The companies are collecting data to understand the basic principles of the process so that they can learn the critical process control issues and ensure repeatability. Whether this could wait until product and process were stable was uncertain.

Metrology and standards issues (processes and product)

Participants indicated that possibly the most striking challenge for metrology can be attributed to the lack of maturity for the product. As a manufactured product, the fuel cell industry is truly in its infancy. As such there are few agreed upon standards for measure. There is also an exceptionally diverse group of companies and organizations working to develop the technology. With this diversity comes a wide range of technical capabilities. Some fuel cell developers have product expertise, but little or no manufacturing experience. Other industry participants have a longstanding history of manufacturing and standardization combined with product knowledge. While such a dissimilar mix of participants is commonplace for a new technology, it does produce uneven levels of technical capabilities.

Respondents believe that there would be a need for standardization of tests and measures for non-competitive elements. However, there was no consensus regarding the timing of such standards. The fuel cell is still, in many ways, a developmental product. Some participants felt that it may be too early for such actions. However, they did agree that there is (or will soon be) a need to develop clear functional test standards at the part level, and the need for a method of characterizing the duty cycle level of the system. One interviewee described an effort to develop a single cell performance curve and measurement protocol. Clearly, the statistical validity of any such protocol should be evaluated, and standardized testing practices developed and followed. Another highlighted challenge was the verification methodology in final assembly of SOFC. The final validation test cycle requires a heating of the unit to 900 degrees C, and back down. This test currently takes approximately an hour. This test cycle time would need to be greatly reduced to make high volume production feasible.

In what is indicative of the challenges faced by the participating companies in meeting the measurement requirements, one respondent company relayed their difficulty finding measurement equipment for on of their components. After a long search for an appropriate measuring device, they purchased from a supplier what they perceived to be the best available—but far less than optimal device. However, because of this company's in-house process engineering capabilities, it was able to alter the machine to fit their needs. After several iterations, the supplier used the company's changes to modify their product for other customers.

Several respondents indicated that they, or their supplies and or customers had difficulty consistently measuring bipolar plates, which micrometer variation in thickness, straightness of channels, and width of channels). These respondents indicated some industry participants did not have processes in place to assure consistent measurement quality. The material itself (graphite or composites), also presents a challenge for accurate measurement. There will also be a need for standards around the connections of the balance of plant and system interoperability, as well as voltage and impedance matching. One caveat offered was that any standards, especially regulatory standards, such as crash standards, be developed through industry and government collaboration.

Several respondents indicated that they, or their supplies and or customers had difficulty consistently measuring bipolar plates at the micron level (e.g., for variation in thickness, and the straightness and width of the channels). These respondents indicated some industry participants did not have processes in place to assure consistent measurement quality. The material itself (graphite or composites), also presents a challenge for accurate measurement. There will also be a need for standards around the connections of the balance of plant and system interoperability, as well as voltage and impedance matching. One caveat offered was that any standards, especially regulatory standards, such as crash standards, be developed through industry and government collaboration.

Conclusions

The interview participants offered important insights into the challenges and barriers to the high volume manufacture of PEM and SOFC technology. The interviews and the resultant white paper were intended to initiate the discussion of these hurdles. However, there were in no way intended identify all barriers. The interview process did however establish a need to proceed with the effort. To this end, the participants identified an opportunity for an opportunity for NIST and other federal agencies to further investigate the development of a strategy to address the challenges, barriers and opportunities for the development of fuel cell manufacturing technologies that will enable the high volume manufacture of fuel cells for automotive applications (both PEM and SOFC) for application to the U.S. transportation sector.

References:

[1] Mehta, V., Cooper, J.S. (2003) Review and Analysis of PEM Fuel Cell Design and Manufacturing, *Journal of Power Sources* (114):32-53.

[2] Tietz, F., Buchkremer, H.-P., Stöver, D. (2002) Components manufacturing for solid oxide fuel cells, *Solid State Ionics*, (152-153):373-381.

B : Attendee Roster

Altarum Institute

Ken Baker
President and Chief Executive Officer

Joe Burns
Senior Scientist

Greg Leonard *(did not attend)*
Business Director

Ballard Power Systems

Chris Di Lello
Director, Fuel Cell Stack Manufacturing

Joe Mitchell
Operations Director

Bulk Molding Compounds, Inc.

Wil Conner
Market Development

Center for Automotive Research

Dave Cole
Chairman

Rick Gerth
Assistant Director, Manufacturing Systems

Brett Smith
Senior Industry Analyst

ConocoPhillips Company

Jim Seaba *(did not attend)*
Director, Advanced Technology

DaimlerChrysler

Doanh Tran
Program Manager, Liberty and Technical Affairs

Delphi Corporation

Jean Botti
Chief Technologist, Innovation Center

Nabil Hakim *(did not attend)*

Kailash Jain
Staff Research Engineer

Delphi (continued)

Joseph Mantese
Group Manager - Materials

Su-Chee Wang
Senior Staff

Ford Motor Company

Alexander Bogicevic *(did not attend)*
Technical Expert Solid Oxide Fuel Cells

Shinichi Hirano
Principal Research Engineer

Bill Schank
Technical Specialist

Freudenburg NOK

Ted Duclos *(did not attend)*
Chief Technical Director

Steve Haycock *(did not attend)*
General Manager, Sales

Steve Koch
Director, Fuel Cell

General Motors

Mei Cai
Staff Research Engineer, GM Tech Center

Kettering University

K.J. Berry
Professor

Seth Lerner
Student

Los Alamos National Laboratory

Ken Stroh
Program Manager, Hydrogrn & Fuel Cells

National Center for Manufacturing Sciences

Manish Mehta
Director, Collaboration Programs

National Center for Manufacturing Sciences (continued)

Rebecca Taylor *(did not attend)*
Senior Vice President

National Institute of Standards & Technology

Gary Anderson
Economist

Muhammad Arif
Supervisory Physicist

Amit Bagchi
Program Manager

Gerald Ceasar
Program Manager, Energy Technology

Alkan Donmez
Group Leader

Dale Hall
Director

Fred Proctor
Electronics Engineer

Dave Stieren
Strategic Relations Manager

Terry Udovic
Chemical Engineer

National Science Foundation

Esin Gulari *(did not attend)*
Director, Chemical & Transport Systems

Nextech Materials

Jon Foreman
Manager, Sales & Marketing

Nuvera Fuel Cells

Robert Mulcahey
Manager, Manufacturing Group

Pacific NW National Laboratories

Prabhakar Singh
Fuel Cell Development Director

Plug Power

Paul Burton
Vice President of Manufacturing

Rensselaer Polytechnic Institute

Ray Puffer
Co-Director

Southwest Research Institute

Steve Wiedmann
Research Engineer

The United States Army

Erik Kallio
Deputy for Fuel Cell Development

The United States Department of Energy

Pat Davis
Fuel Cell Team Leader

Tiax LLC

Eric Carlson *(did not attend)*
Principal, Applied Chemistry & Materials

U.S. Fuel Cell Council

Bob Rose *(did not attend)*
Executive Director

University of Illinois

Edmund G. Seebauer
Professor

University of Michigan

John Halloran
Professor

Denise McKay
Student

Anna Stefanopoulou
Professor

UTC

Kevin Smith
Director, Supply Chain Management

W.L. Gore & Associates, Inc.

David Lane
Industry Liaison

C : Workshop Agenda

Developing a National Strategy for the
High Volume Manufacture of P.E.M and Solid Oxide Fuel Cells
A Workshop Sponsored by:
National Institute of Standards and Technology,
Manufacturing Engineering Laboratory

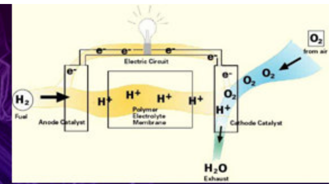
December 8, 2003
Dearborn, MI

7:00 - 8:00	Registration and continental breakfast
8:00 - 8:15	Welcome: NIST
8:15 - 8:40	Patrick Davis, D.O.E.
8:45 - 9:10	Jean Botti, Delphi Corporation: Challenges in High Volume SOFC Manufacturing
9:15 - 9:40	Chris DiLello, Ballard Power Systems: Challenges in High Volume PEM Manufacturing
9:45 -10:30	Affinity Diagram (Richard Gerth (CAR/David Stieren (NIST): Problem definition identification of important challenges
10:30-10:50	AM Break
10:50-11:15	Summary and workgroup 'assignment' (4-5 workgroups)
11:15 - 2:30	Parallel Workgroups: (12:30 - Working lunch)
2:30 - 2:45	PM Break
2:45 - 3:45	Reconvene with presentations from workgroups
3:45 - 4:30	Discussion
4:30 p.m.	Adjourn

D: Presentations

NIST

A National Strategy for Fuel Cell Manufacturability



Because:

- Manufacturability issues are generally recognized as being among the most significant contributors to the high cost of fuel cell technology today
- Manufacturability issues are critical to the widespread, economically viable mass production of fuel cell products
- Many manufacturability issues are infrastructural in nature

We are exploring the need for:

- A ***national strategy*** to address and solve manufacturability issues for fuel cells as they evolve to mass market applications.

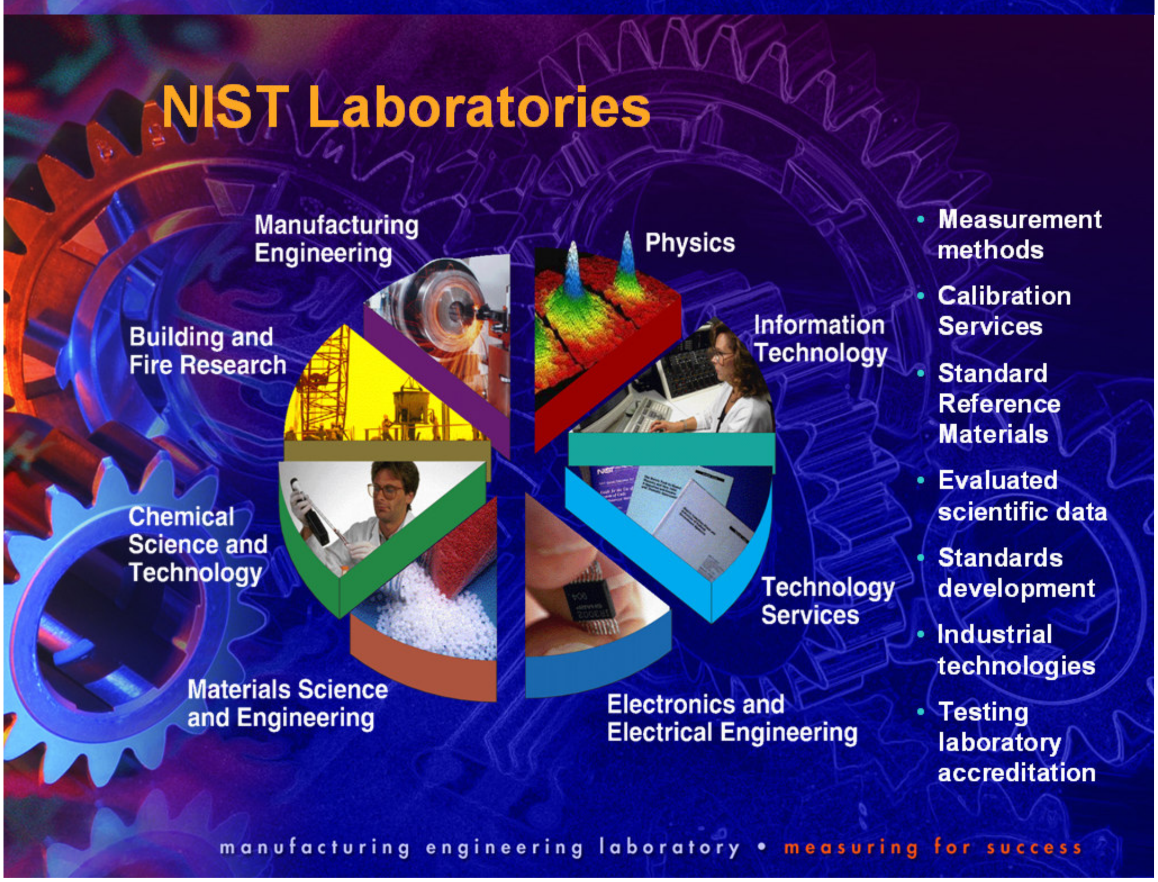
A National Strategy

A ***National Strategy for Fuel Cell Manufacturability*** should:

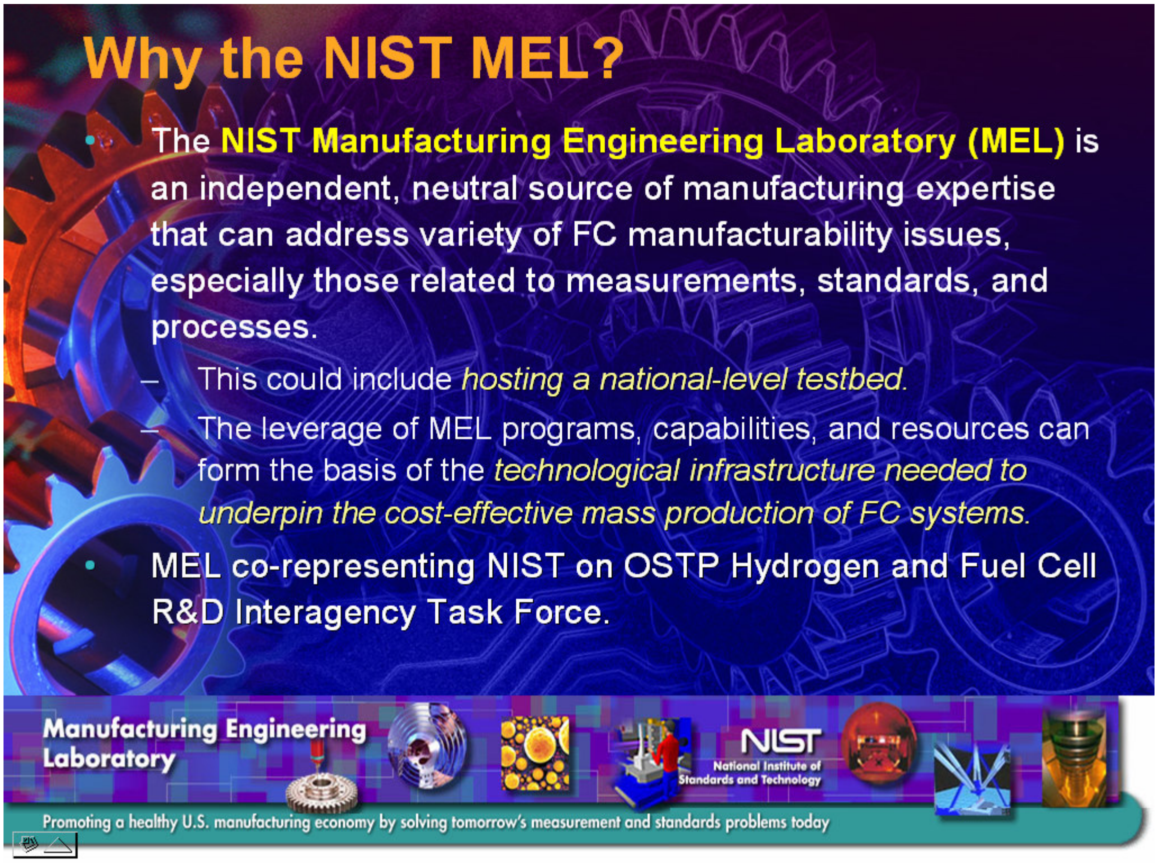
- ID specific needs in manufacturing technology development, including the requisite measurements and standards and other technical infrastructure issues to support high-volume production.
  - now and near-term future
- Address fuel cells for transportation sector (especially auto industry), as well as stationary and portable power apps.
- Address needs of industry and government agencies
- ID/clarify stakeholders, interest areas, and levels of commitment.

manufacturing engineering laboratory • measuring for success

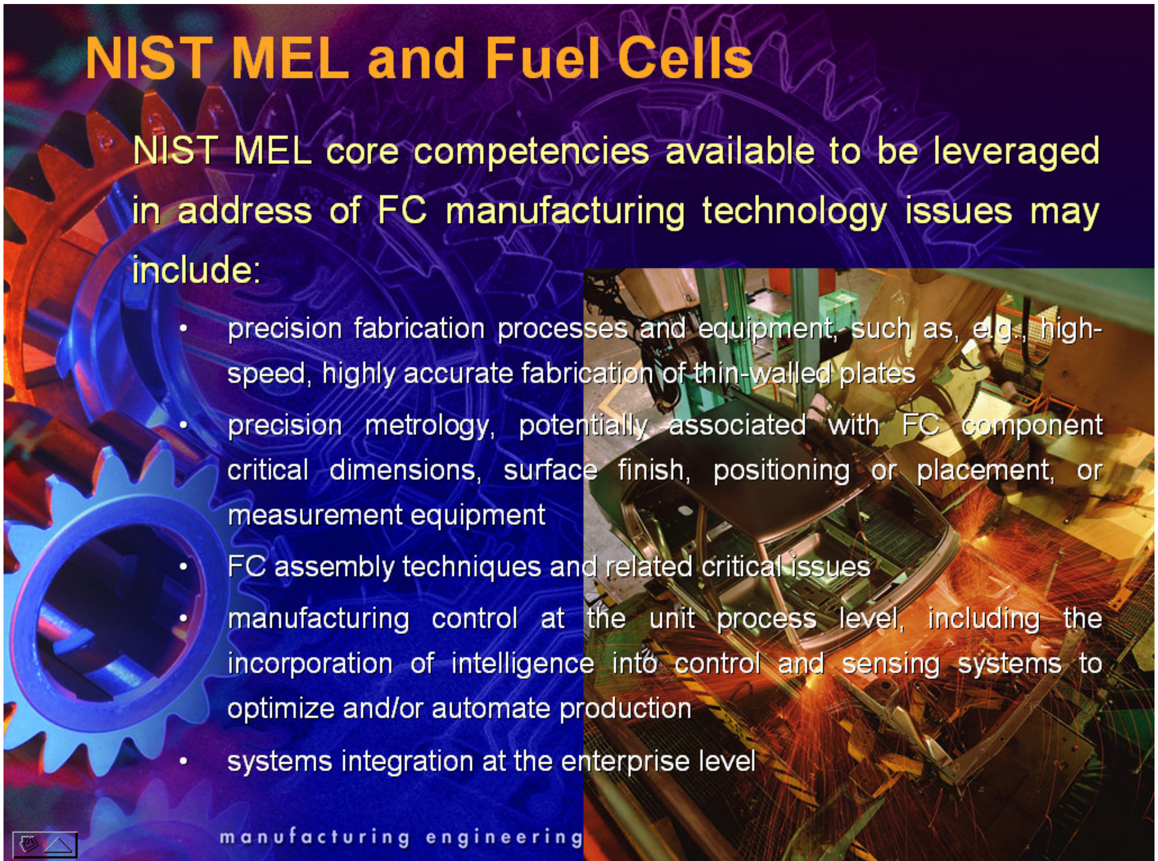
Why the National Institute of Standards and Technology (NIST)?
Develop and promote measurement, standards, and technology to enhance productivity, facilitate trade, and improve the quality of life.
NIST carries out its mission through a portfolio of four programs:
Laboratories
Advanced Technology Program
Manufacturing Extension Partnership
Baldrige National Quality
NIST can bring significant expertise and resources to bear through its Laboratories and the Advanced Technology Program
manufacturing engineering laboratory • measuring for success

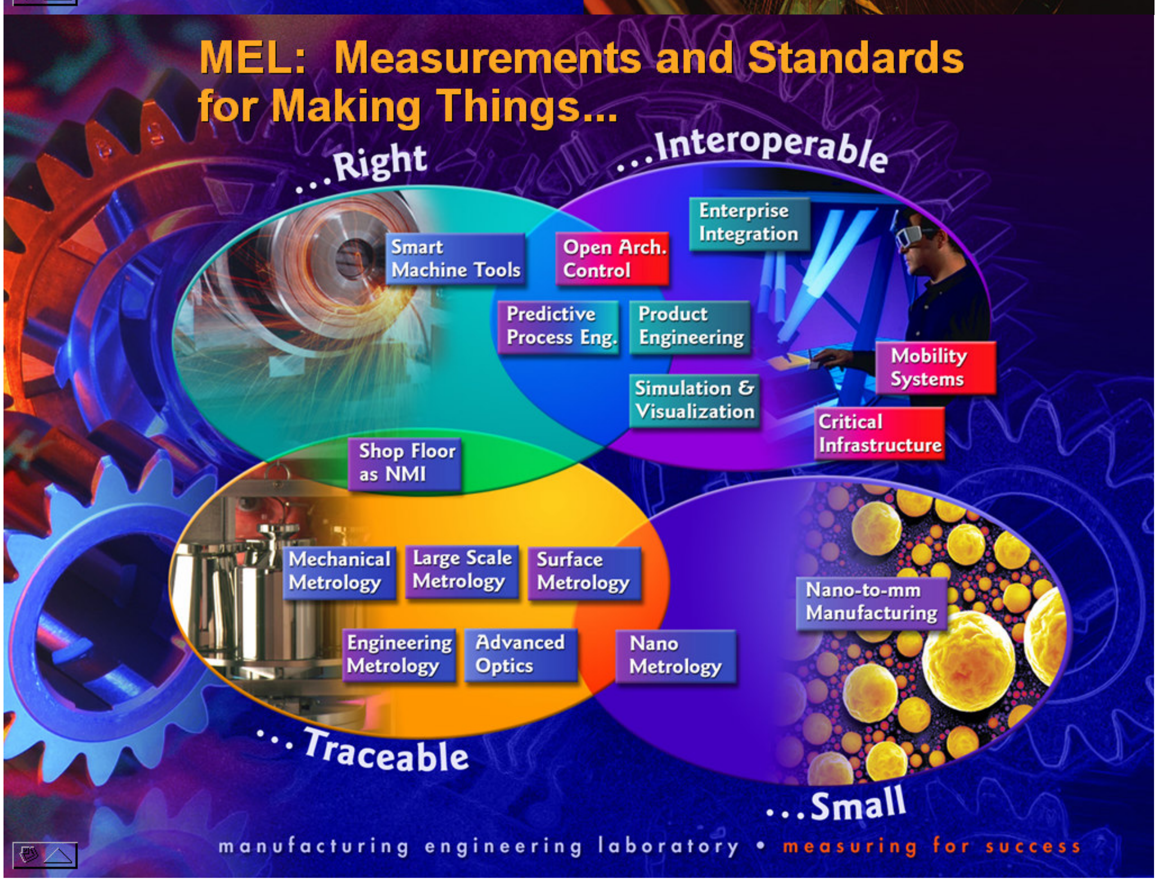


NIST Laboratories
Manufacturing Engineering
Physics
Building and Fire Research
Information Technology
Chemical Science and Technology
Technology Services
Materials Science and Engineering
Electronics and Electrical Engineering
• Measurement methods
• Calibration Services
• Standard Reference Materials
• Evaluated scientific data
• Standards development
• Industrial technologies
• Testing laboratory accreditation
manufacturing engineering laboratory • measuring for success


Why the NIST MEL?
The NIST Manufacturing Engineering Laboratory (MEL) is an independent, neutral source of manufacturing expertise that can address variety of FC manufacturability issues, especially those related to measurements, standards, and processes.
– This could include hosting a national-level testbed.
– The leverage of MEL programs, capabilities, and resources can form the basis of the technological infrastructure needed to underpin the cost-effective mass production of FC systems.
MEL co-representing NIST on OSTP Hydrogen and Fuel Cell R&D Interagency Task Force.
Manufacturing Engineering Laboratory
NIST
National Institute of Standards and Technology
Promoting a healthy U.S. manufacturing economy by solving tomorrow's measurement and standards problems today


The NIST Manufacturing Engineering Laboratory (MEL)
MISSION
To satisfy the measurements and standards needs of US manufacturers
in mechanical and dimensional metrology and in advanced manufacturing technology
by conducting research and development, providing services and participating in standards activities
CORE COMPETENCIES
• Dimensional and Mechanical Metrology
• Manufacturing Systems, Systems Integration, and Systems Interoperability
• Manufacturing Processes and Equipment
manufacturing engineering laboratory • measuring for success


NIST MEL and Fuel Cells
NIST MEL core competencies available to be leveraged in address of FC manufacturing technology issues may include:
• precision fabrication processes and equipment, such as, e.g., high-speed, highly accurate fabrication of thin-walled plates
• precision metrology, potentially associated with FC component critical dimensions, surface finish, positioning or placement, or measurement equipment
• FC assembly techniques and related critical issues
• manufacturing control at the unit process level, including the incorporation of intelligence into control and sensing systems to optimize and/or automate production
• systems integration at the enterprise level
manufacturing engineering


MEL: Measurements and Standards for Making Things...
...Right
...Interoperable
Smart Machine Tools
Open Arch. Control
Enterprise Integration
Predictive Process Eng.
Product Engineering
Simulation & Visualization
Mobility Systems
Critical Infrastructure
Shop Floor as NMI
Mechanical Metrology
Large Scale Metrology
Surface Metrology
Engineering Metrology
Advanced Optics
Nano Metrology
Nano-to-mm Manufacturing
...Traceable
...Small
manufacturing engineering laboratory • measuring for success

Partnering with MEL

- Major MEL focus on mechanical and electro-mechanical sectors, including automotive and aerospace
  - other sectors served include heavy equipt., machine tool mfrs., shipbuilders, semiconductor & microelectronics mfrs, instrument mfrs, optics, processing industries, …
- MEL partners with industrial consortia, individual companies, other government agencies, universities.
- MEL stake in partnerships focuses on issues that benefit industry sectors in a broad sense, typically relating to measurements and standards
- Partnership mechanisms include:
  - Cooperative Research and Development Agreements (CRADAs), Contracts, Guest Researchers, Memoranda of Understanding and Letters of Agreement, Grants, SBIR, National Research Council Post-Doctoral Research Associates, Summer Students, Summer Undergraduate Research Fellowships (SURF), Sabbatical, others

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NIST and Fuel Cells: Advanced Technology Program (ATP)

ADVANCED TECHNOLOGY PROGRAM

Mission: To accelerate the development of innovative technologies for broad national benefit through partnerships with the private sector.

http://atp.nist.gov/

- Co-funding of private-sector R&D to accelerate the development of high-risk, broadly enabling technologies
- Emphasis on innovation for broad national economic benefit
- Industry leadership in planning and implementing projects
- Project selection rigorously competitive, through peer review of technical and economic merit, and demonstrated need for ATP funding
- Requirement that projects have well-defined goals/sunset provisions

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ATP Fuel Cell Support

ADVANCED TECHNOLOGY PROGRAM

- 24 active or completed fuel cell technology projects
  - $58M ATP + $51M industry cost-share = $109M total
- $41.7M funding ($22.9M ATP + $18.8M industry cost-share) for micro-fuel cell development
  - Integrated FC Tech, Neah Power, PolyFuel, Motorola, Englehard, Virent Energy, Lilliputian Systems, NexTech Materials, Superior Micropowders, MTI MicrofuelCells, E/I duPont, T/J Technologies
- Pioneering in PEM and SOFC fuel cell technology for distributed power from 1997-2003
  - Avista Labs, Plug Power, Polyfuels, SRI, H Power, Nuvera, Materials and Systems Research, Superior MicroPowders, Babcock & Wilcox SOFCo, ECD Ovonics, Crucible Research, ITN Energy Systems, Blasch Precision Ceramics, Microcell, Plug Power, Technology Management Inc (TMI), Tiax

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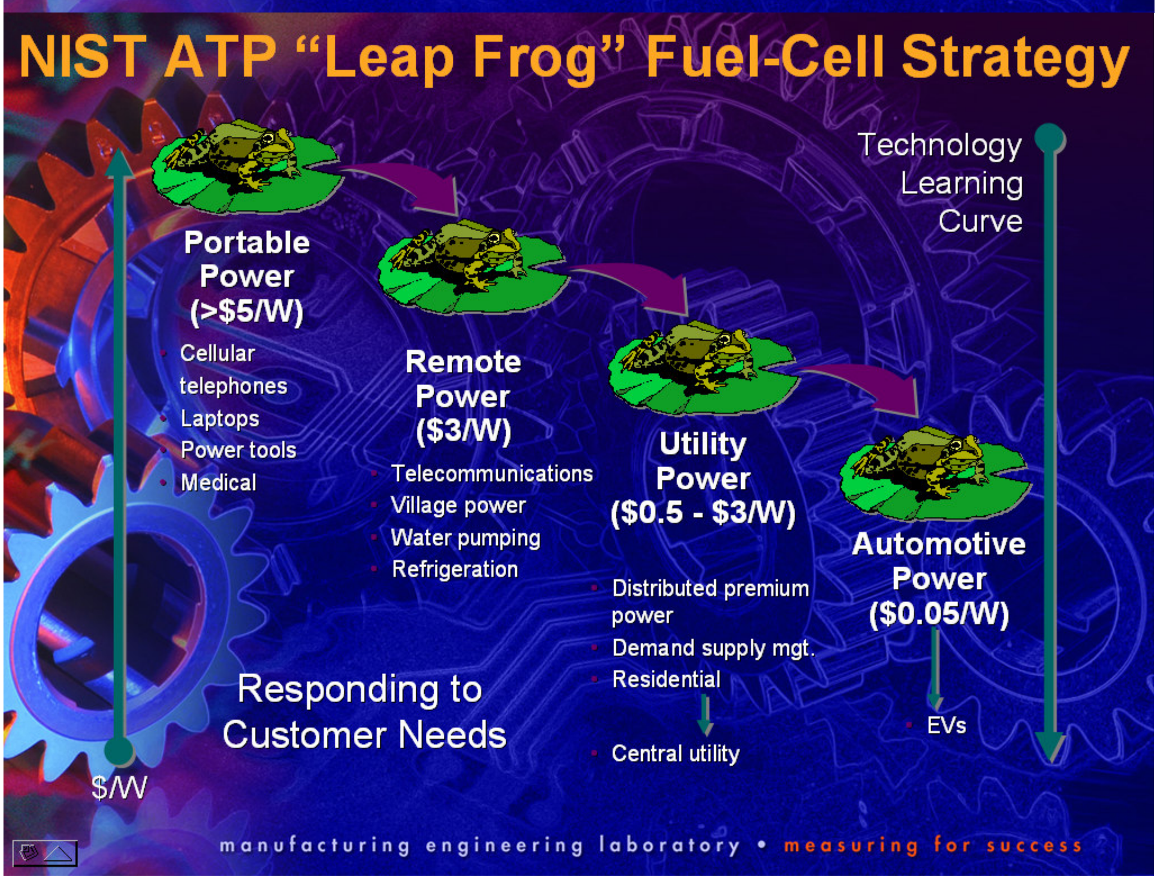
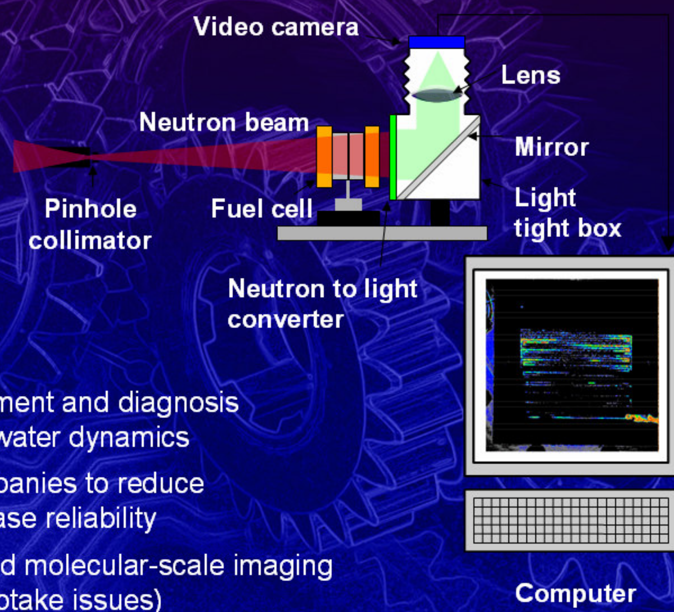


NIST Physics Lab: Neutron Imaging of Operational Fuel Cells

- X-rays are most affected by heavy elements (e.g., lead); Neutron rays are most affected by light elements (e.g., hydrogen)
- Provides unique means for 3-D tomographic imaging of *operating* fuel cells
- Provides essential measurement and diagnosis capability for hydrogen and water dynamics
- Used by major fuel-cell companies to reduce development time and increase reliability
- Future capabilities: nano- and molecular-scale imaging (membrane and hydrogen-uptake issues)



NIST Building and Fire Research Lab: Testing Methodology and Laboratory Facilities for Evaluating Fuel-Cell Systems

- Developing testing and rating methodologies for stationary fuel-cell units; instrumented, controlled-environment laboratory
- Objective: Consensus standards that capture and quantify overall performance
- Collaboration with ASHRAE
- Extends NIST-derived test methods for heat pumps, gas furnaces, water heaters, and other household appliances
- Specifically addresses energy cogeneration (capturing the heat byproduct of electricity output)


NISTIR 6848

Proposed Testing Methodology and Laboratory Facilities for Evaluating Residential Fuel Cell Systems

Mark W. Davis
Building Environment Division
Building and Fire Research Laboratory

January 2002

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary for Technology

National Institute of Standards and Technology
Arden L. Bement, Jr., Director

http://fire.nist.gov/bfrlpubs/build01/PDF/b01057.pdf

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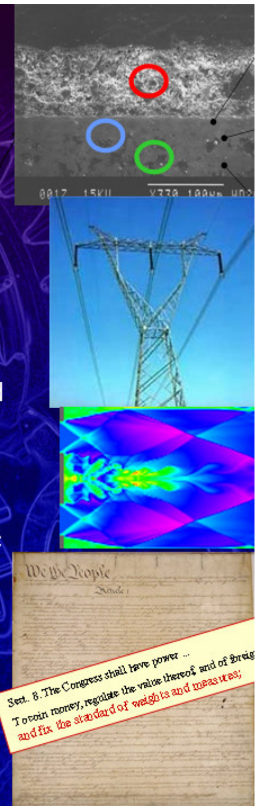
Other NIST Fuel Cells Support

- Materials Science and Engineering Lab
  - Studies of SOFC materials; Characterizations of void,phase microstructures for control and fuel-cell performance; Anode, cathode, electrolyte layers, and interfaces; Unique synchrotron-based x-ray facilities
- Electronics and Electrical Engineering Lab
  - test protocol for residential fuel-cell systems for EPRI covering efficiency, electrical performance, compatibility with the power grid
- Chemical Science and Technology Lab
  - Standards for mass-flow meters to measure, quantify flow and delivery of fuels (methane); physical measurement standards for H2 flow thru commerce interfaces; developing key thermodynamic eng. data for chemical processes involving supercritical steam, other fluids; experience in CO2 sequestration thru computational chemistry, kinetics, thermodynamics research.
- Technology Services
  - lead U.S. standards developing agency for weights and measures for vehicle systems and refueling facilities, fuel cells and on-site hydrogen generation, as designated by the DOE Codes and Standards Coordinating Committee



Why Altarum/CAR?

- **Altarum/CAR possesses extensive knowledge and history with many of the most critical stakeholders.**
  - The Center for Automotive Research, now an independent entity, has a long-standing relationship with the business and manufacturing policy makers throughout the international auto industry.
  - Possesses in-depth knowledge about the scalable manufacturing processes in body and power train processes.
  - Significant research is underway at the auto companies, and uncovering the state-of-the-art and identifying where there are areas of proprietary and non-proprietary knowledge will require close collaboration, which Altarum/CAR is skilled at creating.

CAR CENTER FOR AUTOMOTIVE RESEARCH

ALTARUM

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Why Industry, Other Government Agencies, and Academia?
• Development and coordination of a National Strategy for Fuel Cell Manufacturability with major stakeholders is the only way to ensure success and address the critical needs of manufacturers and users
• Each stakeholder group will have a distinct and complimentary function to play in the implementation of a national strategy
• A broadly encompassing, national strategy could have major impact on the widespread implementation of economically viable fuel cell technology.
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Today's Agenda
8:00 NIST Welcome, Dave Stieren
8:15 D.O.E. Programs and Perspectives, Patrick Davis
8:45 Challenges in High Volume SOFC Manufacturing, Jean Botti, Delphi Corp.
9:15 Challenges in High Volume PEM Manufacturing, Chris Di Lello, Ballard Power Sys
9:45 Affinity Diagram: Problem definition and Identification of the Priority Challenges, Rick Gerth, CAR / Dave Stieren, NIST
10:30 BREAK
10:50 Summary and Workgroup Assignment (4-5 workgroups)
11:15 Parallel Workgroups
12:30 Working Lunch
1:00 Continue Parallel Workgroups
2:30 BREAK
2:45 Reconvene with Presentations from Workgroups
3:45 Discussion
4:30 ADJOURN
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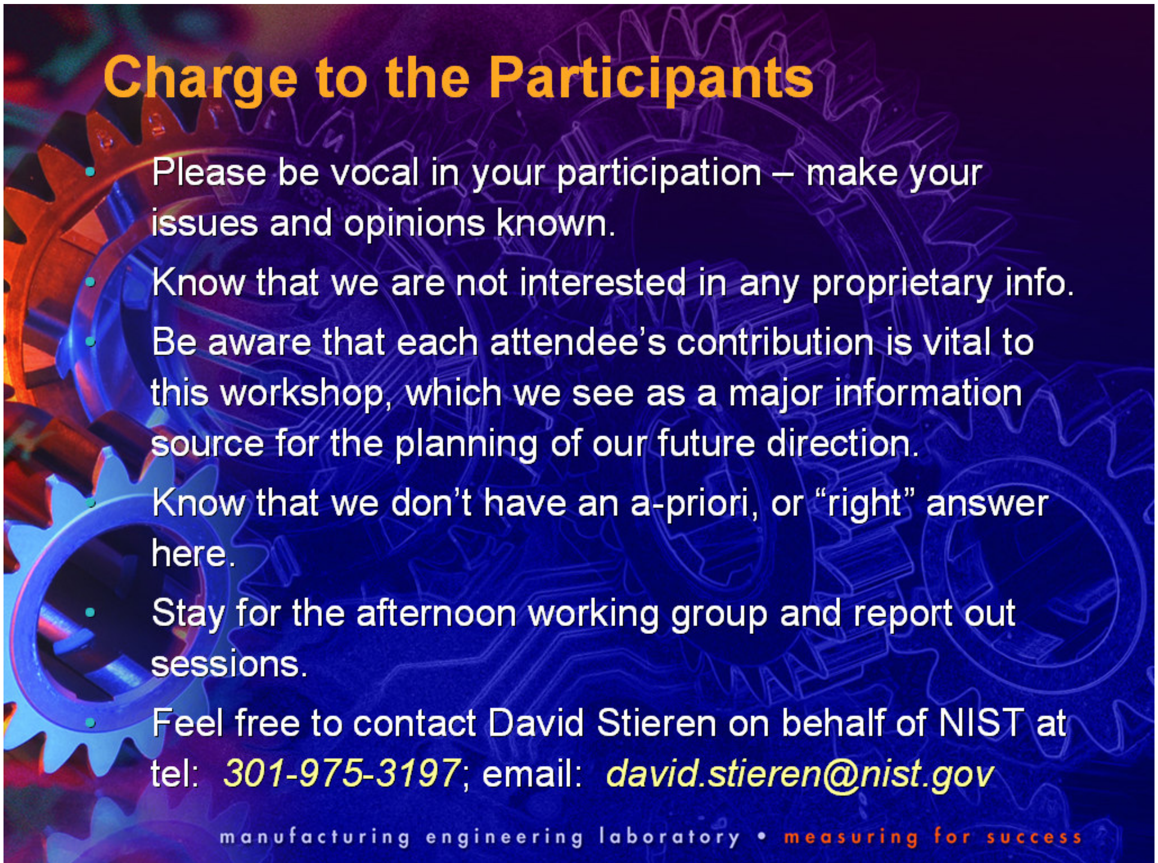
Charge to the Participants
Please be vocal in your participation – make your issues and opinions known.
Know that we are not interested in any proprietary info.
Be aware that each attendee's contribution is vital to this workshop, which we see as a major information source for the planning of our future direction.
Know that we don't have an a-priori, or "right" answer here.
Stay for the afternoon working group and report out sessions.
Feel free to contact David Stieren on behalf of NIST at tel: 301-975-3197; email: david.stieren@nist.gov
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DOE

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Fuel Cell Manufacturability Issues for Automotive Applications

Patrick B. Davis
Fuel Cells Team Leader
Office of Hydrogen, Fuel Cells, and Infrastructure Technologies
U.S. Department of Energy

November 8, 2003
Dearborn, MI

FreedomCAR and Fuel Initiative

H_2

U.S. Department of Energy
Energy Efficiency and Renewable Energy

DOE Fuel Cell Related Programs

Office of Energy Efficiency and Renewable Energy (EERE) ⇔ **Office of Fossil Energy (FE)**

Emphasis on low temperature fuel cells

- Transportation Applications
- Distributed Generation (Building Applications)
- Hydrogen Technologies

Emphasis on high temperature fuel cells

- Large Stationary Applications
- Distributed Generation (Grid)
- APUs

The Focus of the DOE Transportation Fuel Cell Activity is High Risk R&D to Remove Technical Barriers: FY04 Budget $65.6M

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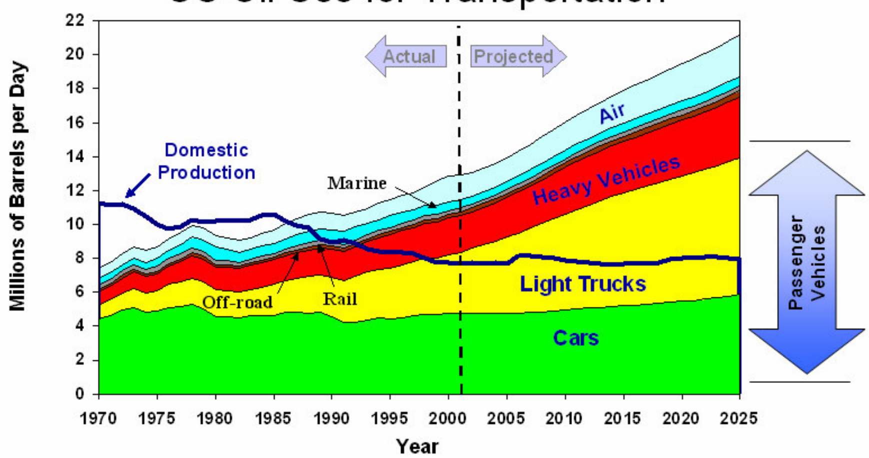
Oil Consumption Increasing: Energy Security and Emissions Issues

US Oil Use for Transportation



Source: Transportation Energy Data Book: Edition 22, September 2002, and EIA Annual Energy Outlook 2003, January 2003

- Transportation accounts for 2/3 of the 20 million barrels of oil our nation uses each day.
- The U.S. imports 55% of its oil, expected to grow to 68% by 2025 under the status quo.
- Nearly all of our cars and trucks currently run on either gasoline or diesel fuel.

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FreedomCAR and Hydrogen Fuel Initiatives

FreedomCAR Initiative – Launched in January 2002

Secretary Abraham joins with leaders of General Motors, DaimlerChrysler, and Ford in announcing FreedomCAR at the North American International Auto Show in Detroit.

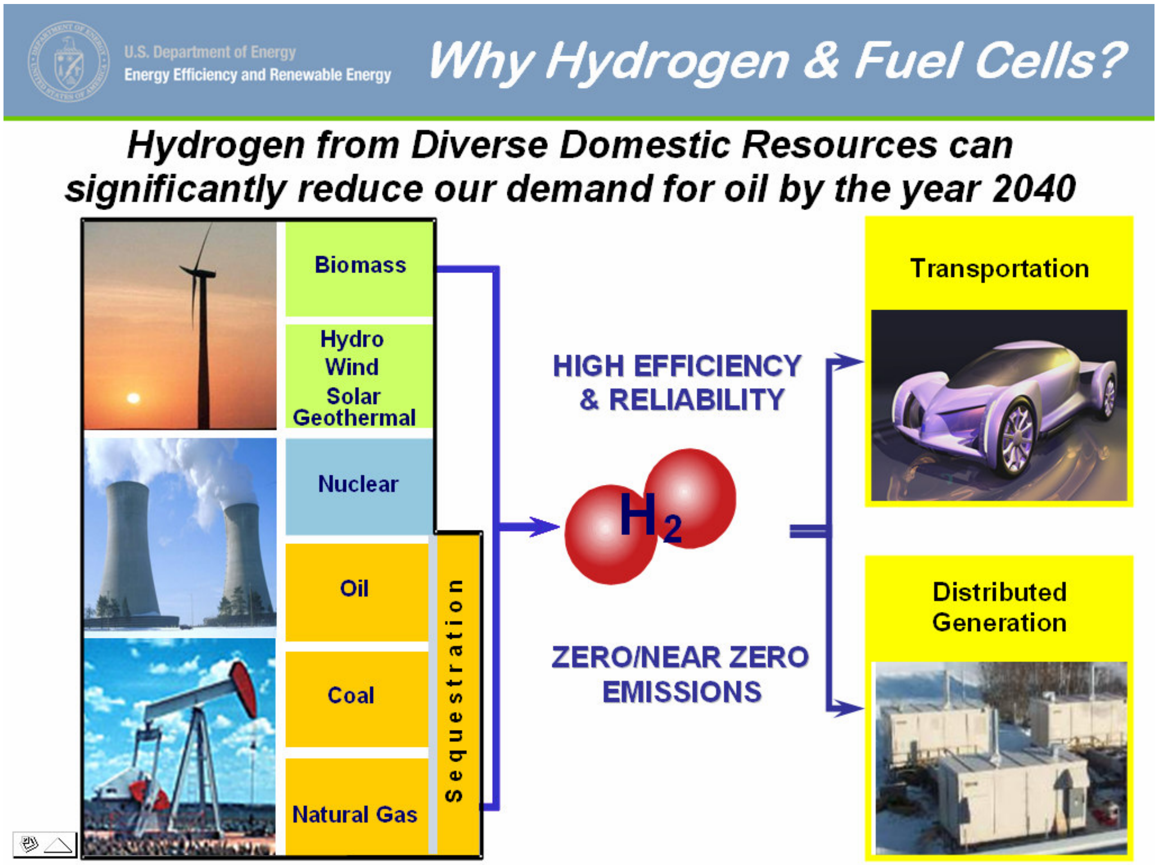
January 9, 2002

Hydrogen Fuel Initiative – Launched in January 2003

"Tonight I am proposing $1.2 billion in research funding ... so that the first car driven by a child born today could be powered by hydrogen, and pollution-free."

President George W. Bush
2003 State of the Union Address
January 28, 2003

Freedom from petroleum dependence, pollutant and carbon dioxide emissions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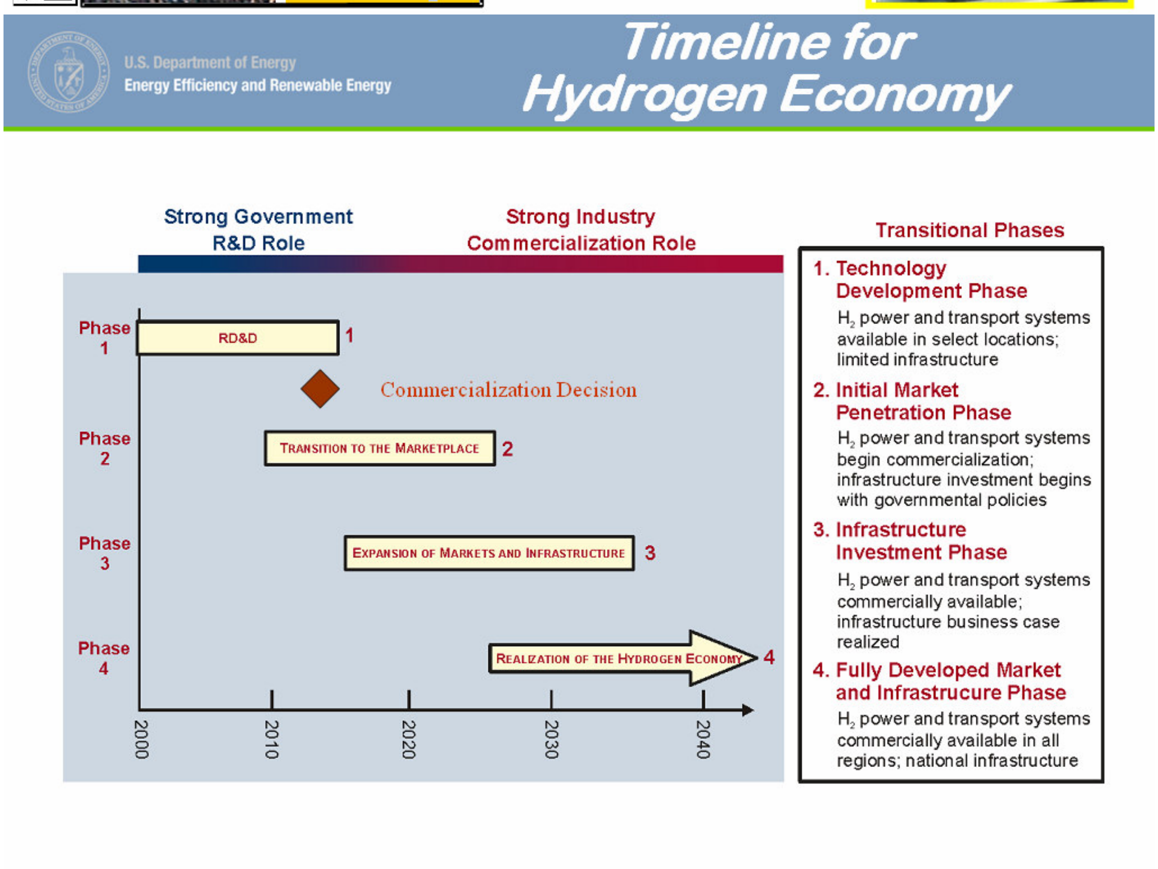
Why Hydrogen & Fuel Cells?
Hydrogen from Diverse Domestic Resources can significantly reduce our demand for oil by the year 2040
Biomass
Hydro
Wind
Solar
Geothermal
Nuclear
Oil
Coal
Natural Gas
Sequestration
HIGH EFFICIENCY & RELIABILITY
H2
ZERO/NEAR ZERO EMISSIONS
Transportation
Distributed Generation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Energy Efficiency and Renewable Energy
Timeline for Hydrogen Economy
Strong Government R&D Role
Strong Industry Commercialization Role
Phase 1
RD&D
1
Commercialization Decision
Phase 2
Transition to the Marketplace
2
Phase 3
Expansion of Markets and Infrastructure
3
Phase 4
Realization of the Hydrogen Economy
4
2000
2010
2020
2030
2040
Transitional Phases
1. Technology Development Phase
H2 power and transport systems available in select locations; limited infrastructure
2. Initial Market Penetration Phase
H2 power and transport systems begin commercialization; infrastructure investment begins with governmental policies
3. Infrastructure Investment Phase
H2 power and transport systems commercially available; infrastructure business case realized
4. Fully Developed Market and Infrastructure Phase
H2 power and transport systems commercially available in all regions; national infrastructure

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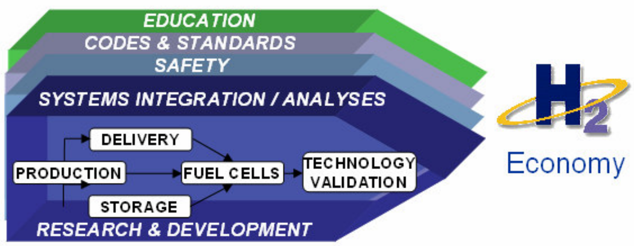
Barriers to a Hydrogen Economy

Critical Path Technology Barriers:

- Hydrogen Storage (>300 mile range)
- Hydrogen Production Cost ($1.50-2.00 per gge)
- Fuel Cell Cost ($30 per kW, automotive)

Economic/Institutional Barriers:

- Hydrogen Delivery (Investment for new Distribution Infrastructure)
- Codes and Standards (Safety, and Global Competitiveness)
- Education



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Fuel Cell Challenges

Transportation

- ✓ Cost ($30/kW automotive)
- ✓ Durability (5,000 hrs automotive)
- ✓ Fuel processing (30 sec start-up go/ no-go milestone)

Stationary

- ✓ Cost ($400-800/kW)
- ✓ Durability (40,000 hrs)
- ✓ Connectivity to grid
- ✓ Compatibility with CHP technologies

- ✓ Air/thermal/water management – air systems, HT membranes, heat rejection and humidification
- ✓ Supplier base

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Manufacturing Strategies

- Developing Manufacturing Technologies: When to Get Started?
  - In one sense, it is already late
  - But the technology needed for market introduction is not defined since current systems do not meet basic targets for cost, performance or packaging.
    - These issues impact every aspect of the system design.
    - How do you develop manufacturing technologies for an undefined product?
- Non-automotive applications very close to market, but orders of magnitude lower in volume

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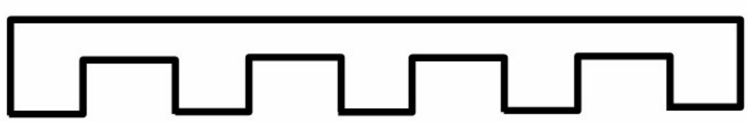
Manufacturing Issue: BiPolar Plates

Challenges:

Extreme Low Cost: ~$5/kW, <$1/Plate

Exacting Dimensional Requirements:



Specific Chemical,Electrical Performance:

H2 permeation <2x10-6cm^3/sec-cm^2, Corrosion <16microA/cm^2, Resistivity <0.02 Ohm-cm^2

Very High Volume: 800,000 plates per hour if every car sold in the U.S. today was a fuel cell vehicle (24 hours/day, 365 days per year)

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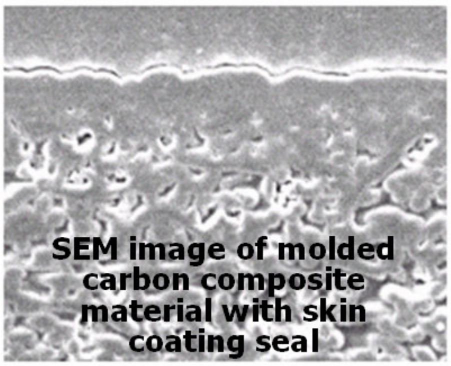
Porvair Bipolar Plate Project

- Has developed a manufacturing process for lower cost porous plate technology
- Transitioning from prepilot-scale (have made 10,000's of plates) to pilot-scale production (100,000's in first year)
  - Improving quality control and yield
  - Substantial private investment is building on the DOE-money seed to develop larger-scale production capacity



SEM image of molded carbon composite material with skin coating seal

porvair
fuel cell technology

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Manufacturing Issue: Membrane Electrode Assemblies

Challenges:

Low Cost: ~$10/kW

Catalyst: Minimize platinum usage, extremely fine, uniform distribution of catalyst media

Very High Volume: 77,000 m^2 per hour if every car sold in the U.S. today was a fuel cell vehicle (24 hours/day, 365 days per year)

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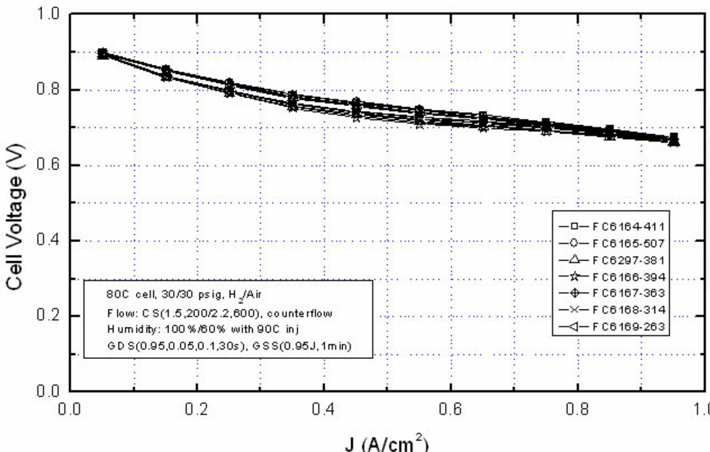
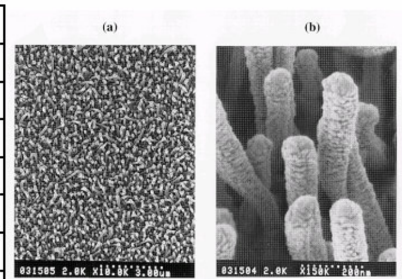
Multiple DOE Membrane Projects

3M – DeNora – UTC – Superior – Micropowders – Atofina – DuPont - Plug Power - Atofina

3M: Develop a set of high-performance, matched PEM fuel cell components and pilot manufacturing processes to facilitate high volume, high yield stack production.





Longest run: 450 lineal yards

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Energy Efficiency and Renewable Energy

Manufacturing Issues

Cost Analysis: Two major cost analysis projects have been supported

- Tiax
- Directed Technologies

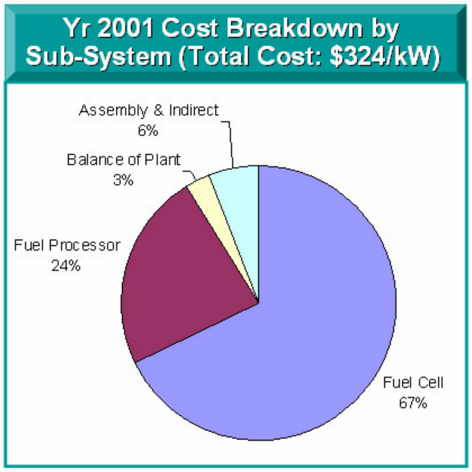
Major Findings from both concur that system cost is dominated by the fuel cell stack, which is dominated by the MEA, which is dominated by platinum cost

TIAX Powered by Innovation since 1886

DIRECTED TECHNOLOGIES INC.

U.S. Department of Energy
Energy Efficiency and Renewable Energy

TIAX Results



The fuel cell subsystem dominates the cost of the reformate system based on near-term technology but produced at high volume.

Basis: 50 kWe net, 500,000 units/yr.

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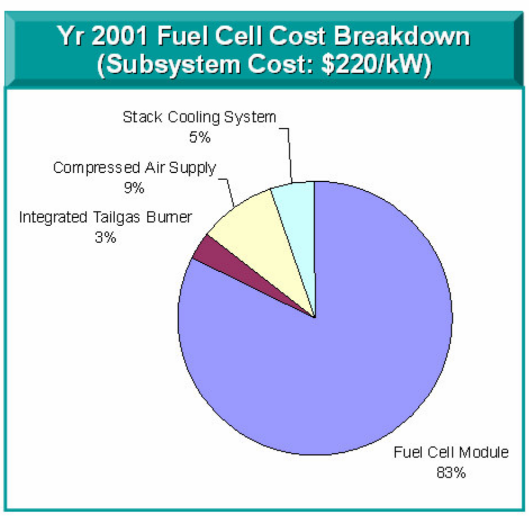
TIAX Results



The fuel cell stack dominates cost of the fuel cell subsystem, however, thermal management is critical to system size.

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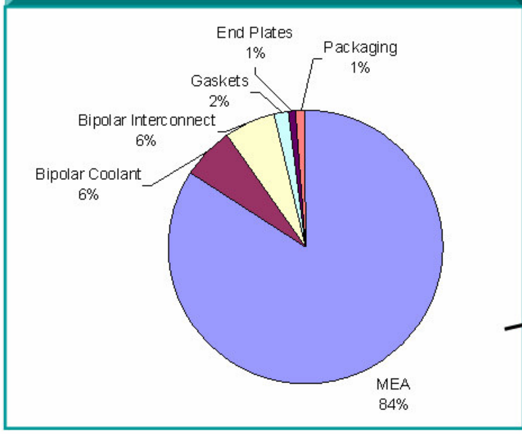
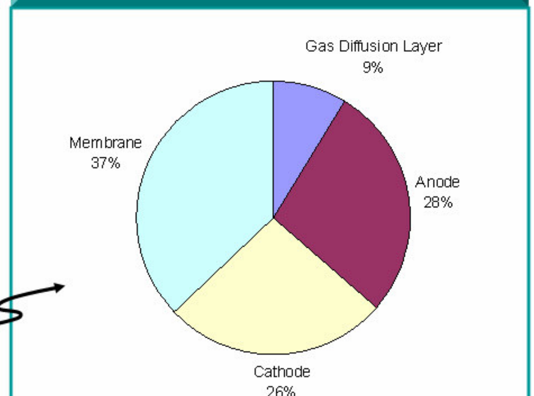
TIAX Results

Platinum and the electrolyte membrane are the major contributors to the stack cost.

Yr 2001 Fuel Cell Stack Cost Breakdown (Stack Cost: $181/kW)



Yr 2001 MEA Cost Breakdown (MEA Cost: $152/kW)



180 grams Pt (0.8 mg/cm^2) for 0.8V @ 250 mW/cm^2

While power density determines the actual amount of material in the system. Parasitic power losses further increase size and cost.

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Energy Efficiency and Renewable Energy

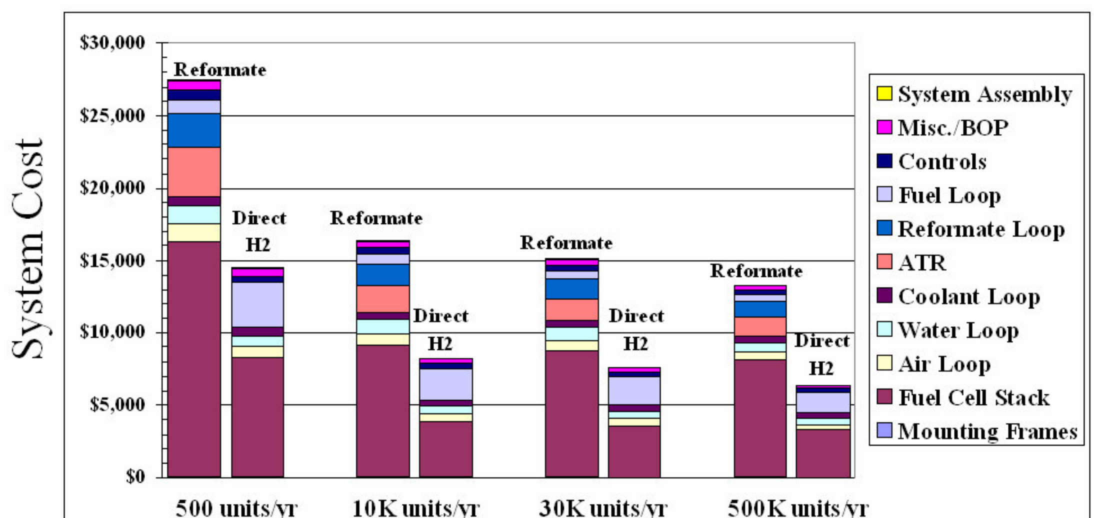
Directed Technologies Results

DIRECTED TECHNOLOGIES INC.

System Comparison

Reformate System vs. Direct H2 System

(both at 0.7volts/cell)



Directed Technologies Results

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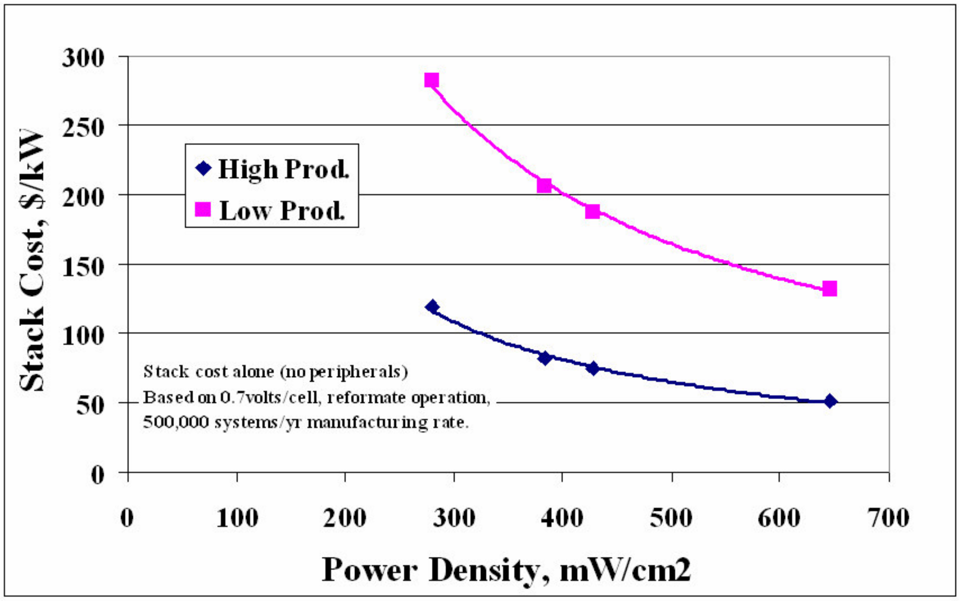
Sensitivity Analysis

DIRECTED TECHNOLOGIES INC



TIAX: Precious Metal Availability and Cost Analysis

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Incorporated direct feedback from all players along the Pt production chain into a coherent analysis clarifying, to the public, a materials-availability path to fuel cells

- Collected historical PGM supply/demand/pricing and resource data
- Developed fuel cell market commercialization scenarios
- Developed a PGM recycling scenario, including a high level PGM proton exchange membrane fuel cell (PEMFC) recycling cost model
- Developed an econometric model for the simulation of the impact of fuel cell introduction on PGM supply and price
- Solicited feedback from PGM industry and automotive original equipment manufacturers (OEMs)

Study Results Available Late December, 2003

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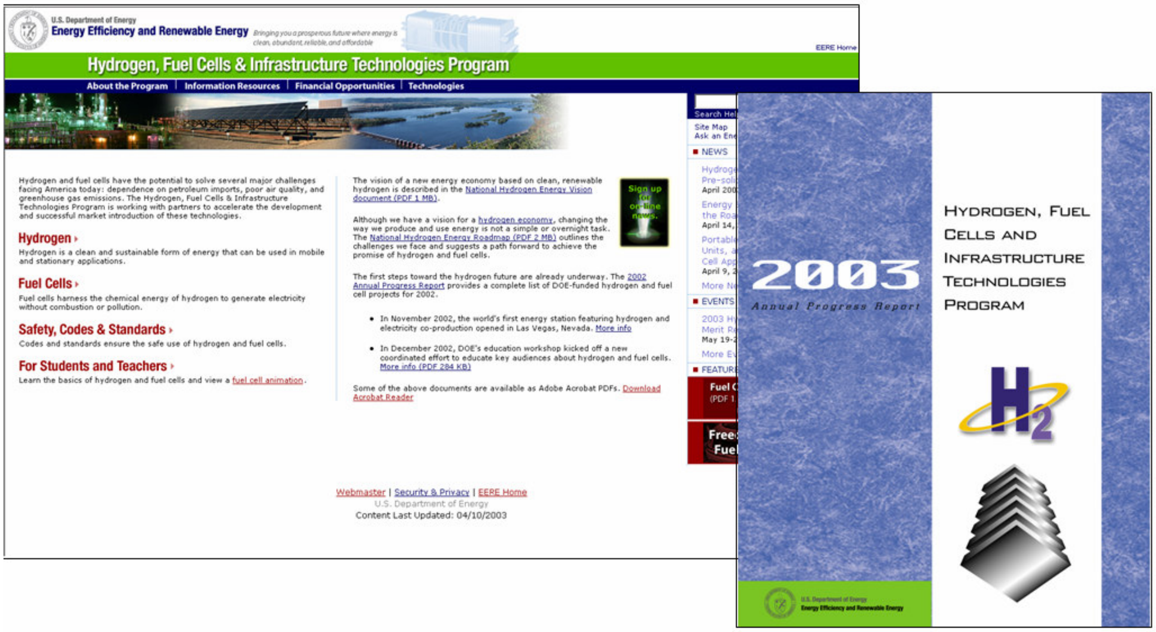
Information Resources



http://www.eere.energy.gov/hydrogenandfuelcells

Delphi


DELPHI
Challenges In High Volume SOFC Manufacturing
Dec 04, 2003
Page 1
Challenges In High Volume SOFC Manufacturing V2.ppt, SRS

DELPHI

Primary Stationary Applications

- Residential
  - Residential (2 to 5 kW) grid augmentation with Combined Heat and Power: Liquid or gaseous fuels

- Commercial
  - Commercial (25 kW) grid augmentation : Liquid , gaseous (natural gas or coal gas) fuels

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Primary Mobile Applications

- Passenger Car
  - Primary Application to satisfy increased electrical demand on vehicles
  - Integration with ICE, utilizing reformate to reduce ICE emissions
  - Other opportunity - range extension on electric vehicle (**Hybrid**)

- Heavy & Medium Duty Truck
  - Application of Engine-off electrical power on Long Haul Trucks
  - Applications on Short Haul and Smaller Trucks
  - Development of Essential Power Unit (**EPU**) for Long Haul Class 8 Truck
  - Satisfy increasing electrical demand
  - Worksite Electrical

- Other Mobile
  - Military Vehicles, Aircraft APUs, Ship Board Distributed Power, Other Portable Power

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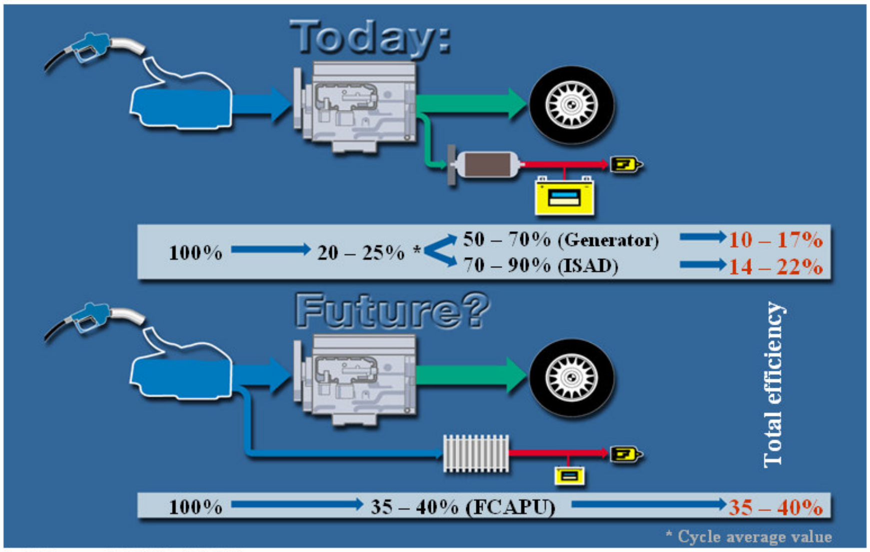
SOFC APU High Efficiency Power For Electrical Accessories



Why a SOFC APU?
- The APU is not competing with the IC Engine but complements it.
- Highly efficient generator providing power with the engine off
- The SOFC utilizes simple reforming technology

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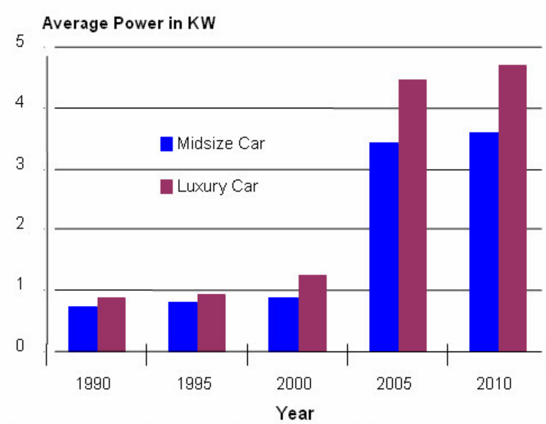
Transportation Market Automotive - Need for APU

- Increased electrical power needs are being driven by advanced IC Engines for enhanced performance, emission controls, and creature comforts

  – Electrical Power Steering
  – Direct Injection
  – Electrically Heated Catalyst
  – Electrical Water Pump
  – Electro-magnetic Valvetrain
  – Engine Cooling Fan
  – Electric AC Compressor
  – Heated Windshield, Seats



- These requirements are beyond the capabilities of the Lundell type generator and require supplemental electrical generation, such as from an SOFC APU.

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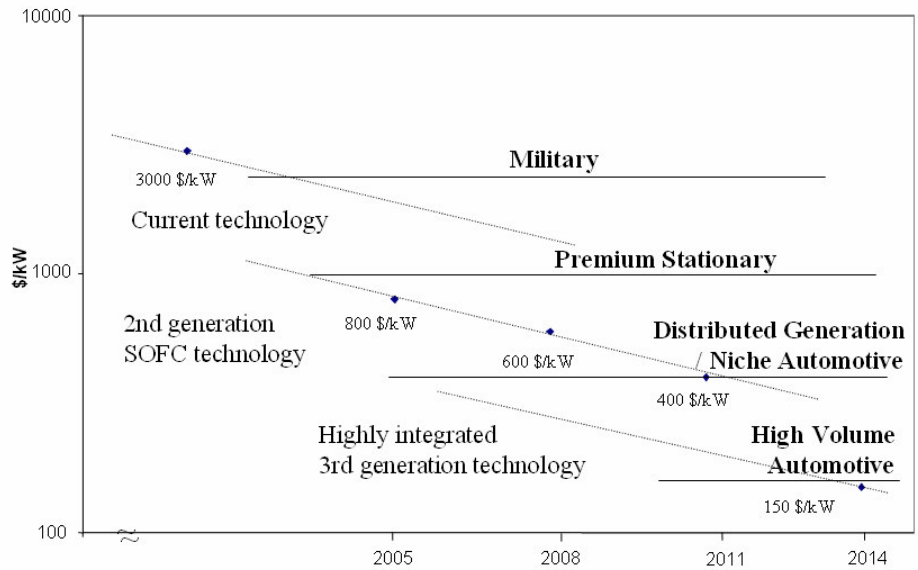
System Cost Targets By Application

System cost targets



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SOFC APU Target Design Features and Packaging

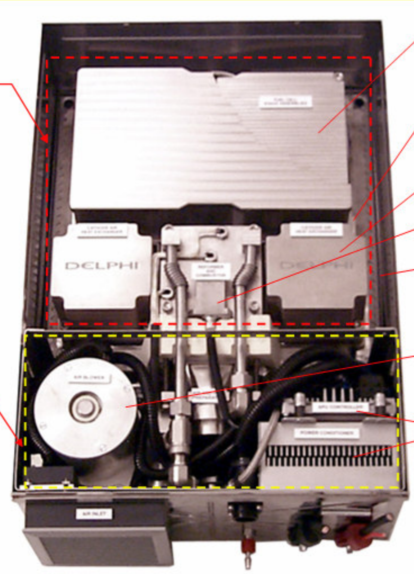
APU = 8 main components

Hot-Zone Module 6 components

- high-temperature subsystems (700-950 C)
- Surrounded by high-performance thermal insulation
- "Core" of the SOFC plant

Plant Support Module 2 components

- Low-temperature subsystems (40-125C)
- Inlet-air cooled electronic components
- Balance of plant
  - sensors, actuators, electronics, harness



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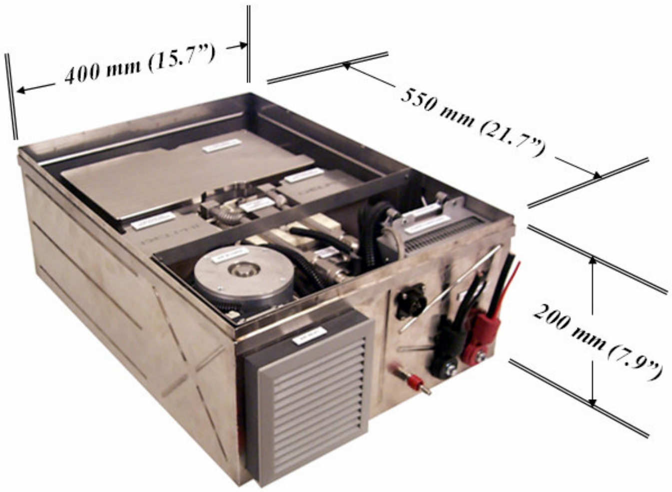
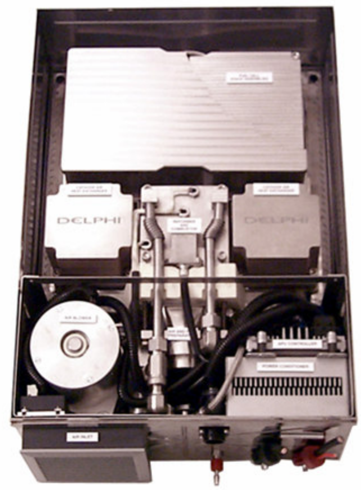
SOFC APU
Target Design Features and Packaging





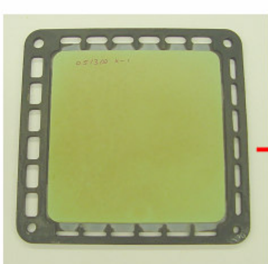
- Automotive compact design will drive costs down on SOFC systems for all applications.

DELPHI

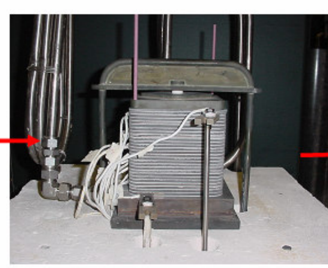
Planar SOFC Stack Components

Key components in a SOFC stack include:

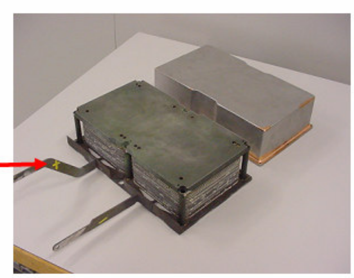
- Cell
  - Anode supported, electrolyte supported or other substrate supported
- Interconnects (or bipolar plates)
  - Metal based or ceramic based
- Seals
  - braze, ceramic glass or compressive seals
- Stack build includes assembly and sealing of of multiple repeating units.



Metal Cassette with cell (repeating unit)



30-cell stack



Integrated stack module-ISM
(Two 15-cell stacks+ current collector + load frame)

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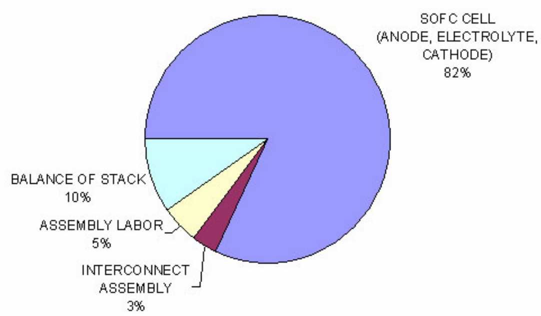
SOFC Stack Cost



- ~80% of the cost of a stack is estimated to be the cost of the cell (anode, cathode and electrolyte).
- Based on our experience in high volume manufacturing of automotive ceramic products, ~70% of the cost of the cell is estimated to be direct materials cost.

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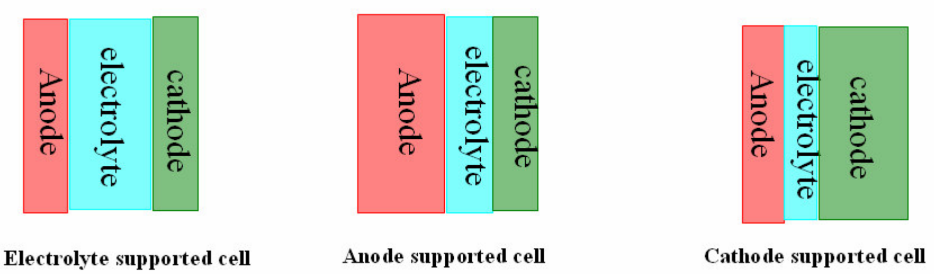
Cell Technology



Delphi is developing anode supported cell technology:

- High power density
  - Anode supported cells produce high power density thus reducing the number of cells needed in a SOFC stack for a given power output
- Lower temperature operation
  - Anode supported cells can produce adequate power at 700-800 ^{o}C
  - This allows for the use of metal interconnects (huge advantage for high volume manufacturing)
- Simple and cost effective materials and processes are used to fabricate anode supported cells

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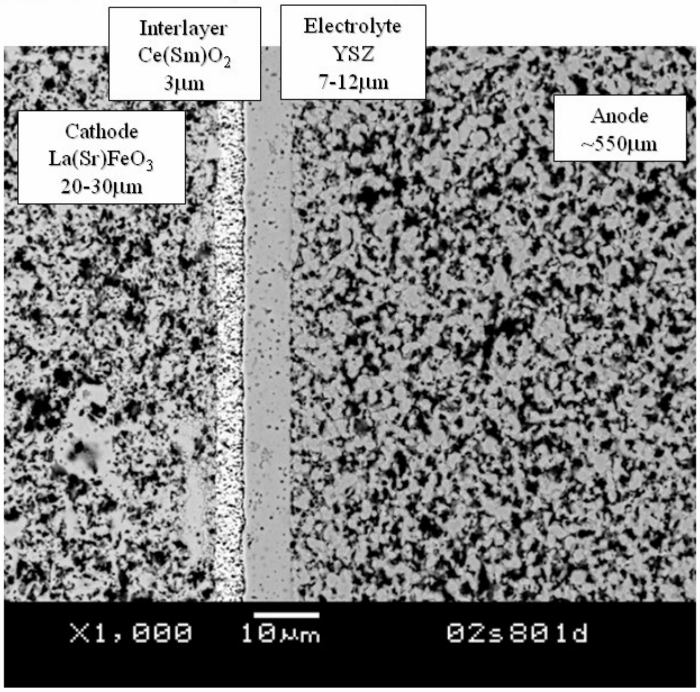
Anode supported Solid Oxide Fuel Cell



Anode-supported cell

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Cell Manufacturing Processes – Direct Raw Materials Cost

- High volume production will drive materials cost down to the targets needed to meet customer goals.
- Optimizing material key characteristics and their affect on performance may allow for lower cost raw materials
  - Purity requirements may be lowered once their affect is understood

Direct Material Cost Summary	Current $/cell	Long Range $/cell*
Bulk Anode	8.24	2.19
Active Anode	0.91	0.22
Electrolyte	0.69	0.25
Cathode	4.05	1.05
	$ 13.90	$ 3.71

* Long range raw material costs from "SECA - A U.S. Department of Energy Initiative to Promote the Development of Mass Customized Solid Oxide Fuel Cells for Low-Cost Power", W.A. Surdoval *et.al.*, SOFC 7

Cell Manufacturing Processes- Conventional Processes

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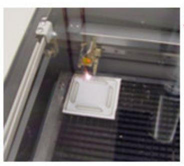
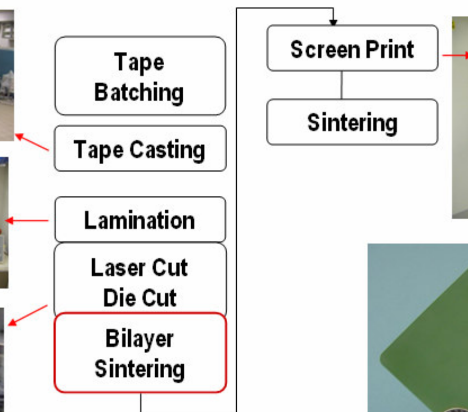
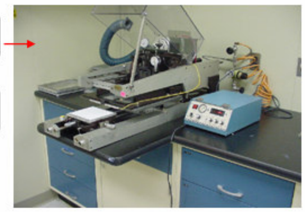
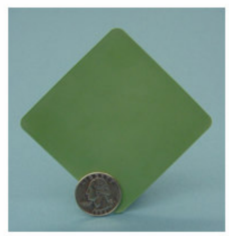
- Cell fabrication includes tape-casting, screen-printing and sintering processes
- These processes are currently used for high volume manufacturing of ceramic automotive components like oxygen sensors
- Key challenge for manufacturing cells is to reduce or eliminate the number of sintering or thermal steps to increase cell throughput for high volume manufacturing
- Reducing cost of starting raw materials is also key to meeting manufacturing goals









Cell Manufacturing Processes - Alternate Processes

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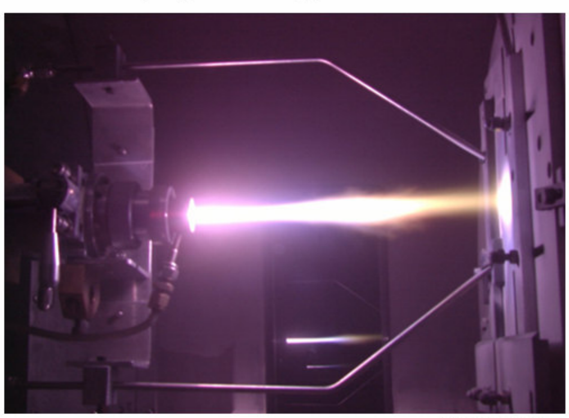
- Spray processes like vacuum plasma spray can potentially allow for increasing throughput and reducing cost for high volume manufacturing by eliminating the sintering temperature cycles
- Spray processes can also allow for new generation of cells like metal substrate supported cells that have performance and manufacturing advantages
- However, key technical challenges still remain in demonstrating cells of optimum performance based on spray technology



Courtesy of DLR

SOFC Stack Interconnects (bipolar plates) Manufacturing Processes

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- Lower temperature (750°C) operation of anode supported cells allows for use of metallic interconnects
- High volume manufacturing processes like stamping can be used to fabricate these parts
- Delphi is leveraging its automotive based expertise in precision stamping to fabricate metallic interconnects for SOFC
- Lowering the temperature of SOFC operation to ~600°C will further reduce cost and enhance durability by allowing for use of lower cost alloys

Sheet metal stamped parts
for SOFC interconnects (bipolar plate)

Dec 04, 2003 Page 16 *Challenges in High Volume SOFC Manufacturing V2.ppt, SRS*

SOFC Stack Sealing Processes

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- Laser welding and brazing are two high volume manufacturing processes that can be used in SOFC for seals
  - Commonly used in the automotive industry for injectors, head gaskets (laser welding), heat exchangers (brazing).
- Delphi is using a novel ceramic to metal braze and developing this process for higher volumes to seal repeating units in a stack
- Ceramic-glass seals and compressive seals are also used widely for SOFC sealing
- Key to sealing is solving the technical challenges (long term durability and thermal cycling) to meet durability requirements
  - Stationary requirements are 40,000 hours of operation and greater than 100 thermal cycles
  - Automotive requirements are 10,000 hours of operation and greater than 5000 thermal cycles

Stack sealing in progress

Dec 04, 2003 Page 17 *Challenges in High Volume SOFC Manufacturing V2.ppt, SRS*

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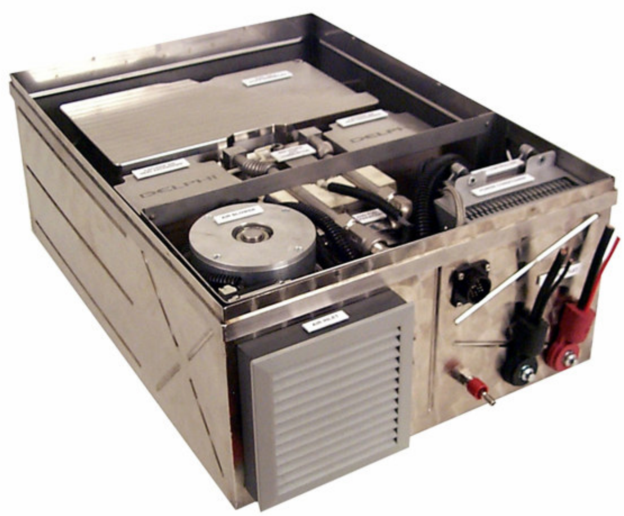
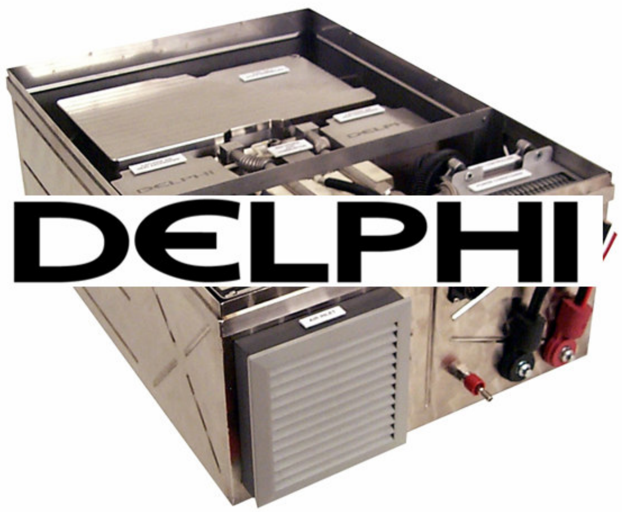
Conclusions

- The SOFC APU is an attractive, efficient, clean source of power for transportation, military and stationary applications.
- High volume manufacturing will bring this novel technology to the customer at a competitive cost (automotive, $150/kW).
- Challenges in manufacturing include:
  - Raw materials cost – 70% improvement needed
  - Cell fabrication process – 60% improvement needed
  - Quality control of cells – 50% improvement needed
  - Cell throughput – 70% improvement needed
  - Low cost alloys for metal components – 60% improvement needed
- Delphi intends to use both existing technical and manufacturing competencies and develop new technology/processes to target the growing market for SOFC power systems to provide the following customer benefits:
  - Electric power with engine on or off to permit operation of any electrical accessory including high-power consuming advancements (e.g., PVT)
  - Improved efficiency versus traditional alternators (2 to 4 times more efficient vs baselines)
  - Near zero emissions (significantly lower than SULEV)
  - Use of conventional fuels (natural gas, coal gas, gasoline, diesel)

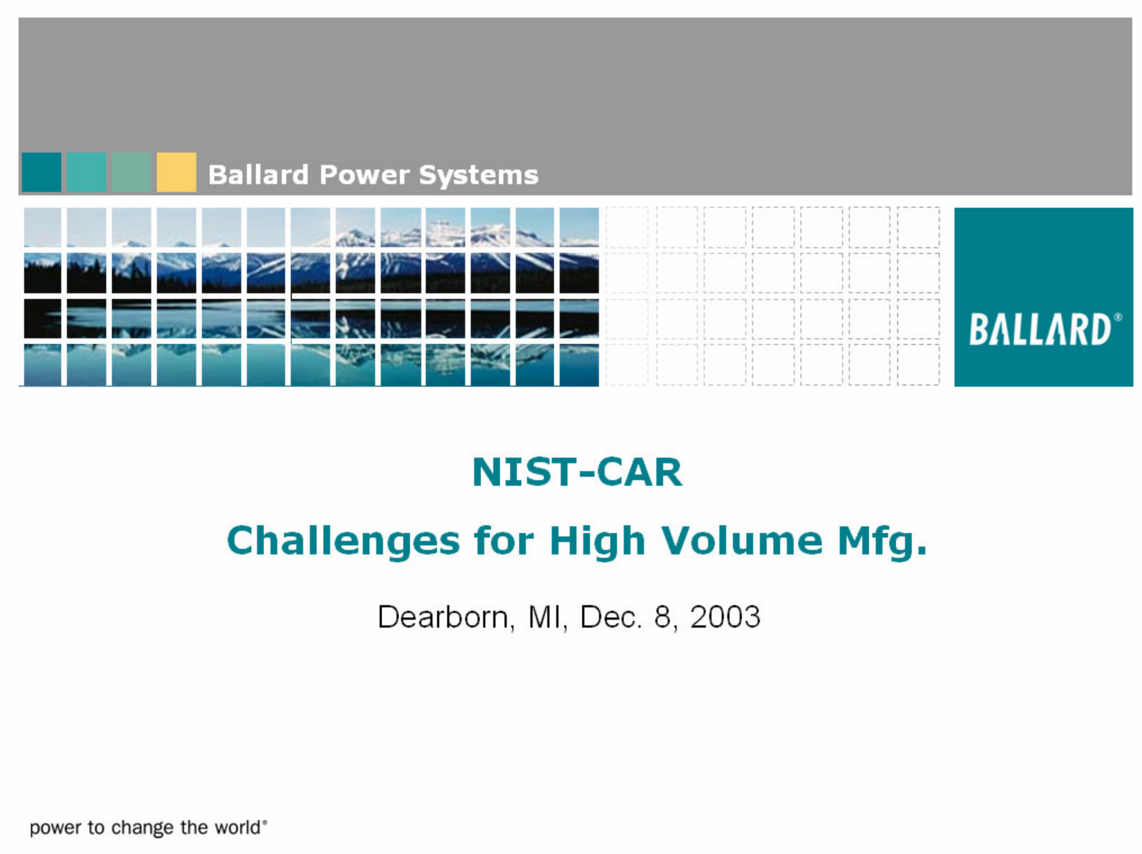
DELPHI



DELPHI



Ballard


Ballard Power Systems
BALLARD®
NIST-CAR
Challenges for High Volume Mfg.
Dearborn, MI, Dec. 8, 2003
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Overview

BALLARD®

- PEMFC: State-of-the Art & Key Technical Challenges
- Cost Reduction Strategies
- Unit Cell Component Technologies
- PEMFC Operational Functionality & Modeling
- Summary

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State of the Art in PEM Fuel Cells

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- Dynamic operation has been demonstrated
  - Many companies have both car and bus prototypes operating in field trials
- Field trials have demonstrated reliability and durability
- Multiple fuels demonstrated (CH_4, CH_3OH, gasoline reformate; H_2)
- Power density increases, both volumetric and gravimetric
  - >2200 W/L demonstrated
- Products in the hands of customers (field trials/early commercialization)
- Cost reduction has been demonstrated
  - The first commercial fuel cell product, AirGen™, based on the Nexa™ module

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Technical Challenges For PEM Fuel Cells

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- Maximize fuel cell performance *while* meeting customer durability and price targets
- Design and optimize based on an integrated power train (i.e. combined stack and system)
- Improve reliability and durability (to automotive levels), must be demonstrated in field trials with customers under real-world conditions
- Develop fundamental understanding of linkage between materials failure and operational requirements
- Improve simulation models and accelerated test methods (reduce reliance on slow, costly empirical design)
- Stimulate and leverage supplier base to produce lower cost materials with high volume process capability

Cost Reduction (Materials and Design)

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- Development of low cost materials that enhance existing fuel cell performance
- DFM/DFA
  - Select materials that enable the use of low cost, high volume, manufacturing processes
  - Increase consideration for manufacturing yield and material utilization
  - Eliminate components, parts and process steps
  - Standardize core components across products
  - Standardize non-core components across supplier-base
- Formation of supplier relationships & partnerships to ensure manufacture of fuel cells in volume, resulting in economies of scale to drive down the material costs

Cost Reduction Strategies

BALLARD®

All areas of the fuel cell stack and system are potential candidates for **optimization** and **cost reduction**.

Examples include:

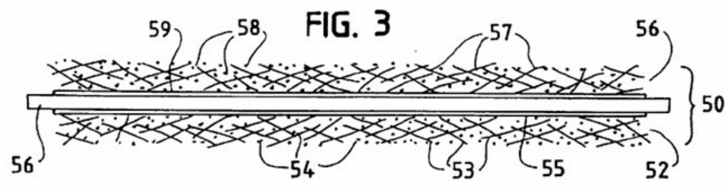
- Non-noble metal, low-Pt content catalysts
  - Reduce ORR over potential
  - Increase stability of electrocatalyst systems
- Combined GDL and flowfield function
  - Reduce parts count and increase reliability
- Ultra-thin, robust, low gas permeable membranes
  - Greater tolerance to changes in temperature and RH
- Unit cell structure optimized for water and thermal management

Gas Diffusion layer (GDL)

BALLARD®

- Originally developed in R&D, a novel, low-cost structure for the GDL has been transferred to Ballard Material Products scale-up to high volume manufacture.

FIG. 3



- This design is the subject matter of issued US Patent 6,060,190

GDL on a Roll – Ballard Material Products

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Cost Reduction - GDE Continuous Processing

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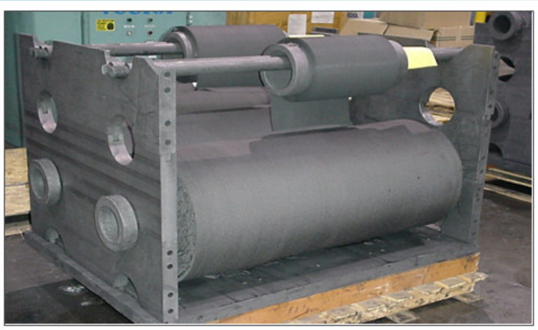
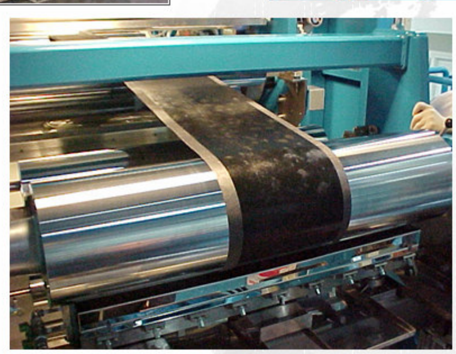


Finished GDL

Teflonation



Diffusion, Catalyst Coatings (GDE)

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Component Integration: Flowfield + GDL

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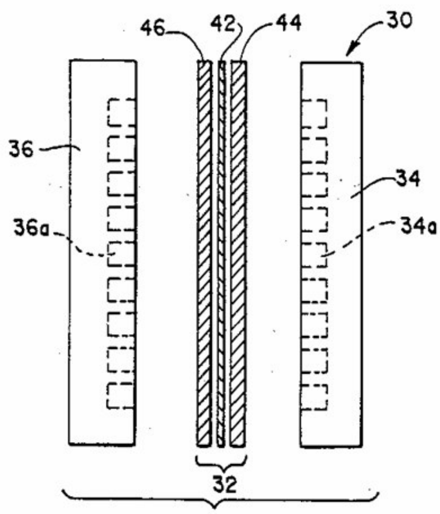
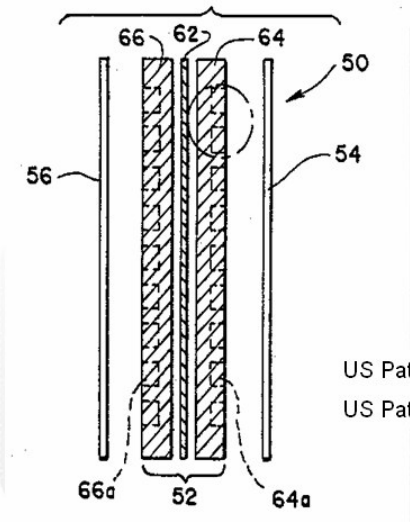
Prior Art



Next Generation



US Patent 5,252,410

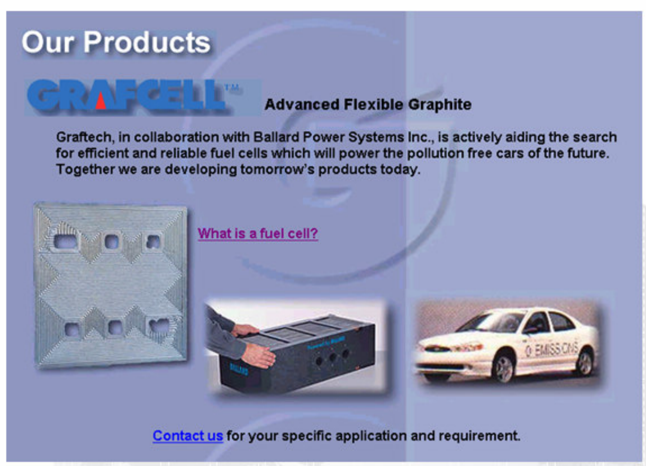
US Patent 5,976,726

Bipolar Plate Materials: AET Grafcell™

BALLARD®

Requirements:

- Processability
- Low Mass
- Mechanically Stable
- Thin
- Thermal and Electrical Conductivity



- Processed particulate graphite flakes which can be molded or calendared.
- Flexible, compressible, resilient, chemically inert, and stable under load and temperature.
- Excellent electrical and thermal conductivity.

Cathode Electrocatalyst Development

BALLARD®

- Development activity is focused on:
  - Improved kinetic performance
  - Low-Pt catalyst alloys; lower Pt loadings
  - Improved catalyst support structures to mitigate against cathode corrosion
  - Non-noble metal catalyst, with specificity for the oxygen reduction reaction
    - Increase catalyst efficiency
    - Minimize water solubility in high voltage oxidizing environments

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Operational Flexibility: Sub-Zero Conditions

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- The system must be able to withstand freeze/thaw cycles
- Main issues:
  - Water production at subzero conditions can result in ice blockages (GDL, FF, electrocatalyst structure)
  - Reduced performance at low temperature due to increased kinetic, ohmic and reactant transport losses
  - Reformer systems have long start-up times
- Advances required:
  - Reduction of water in fuel cell under start-up conditions
  - Fast heat input into the cell

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Known Issues with Unit Cell Related to Residual Water & Freeze Damage

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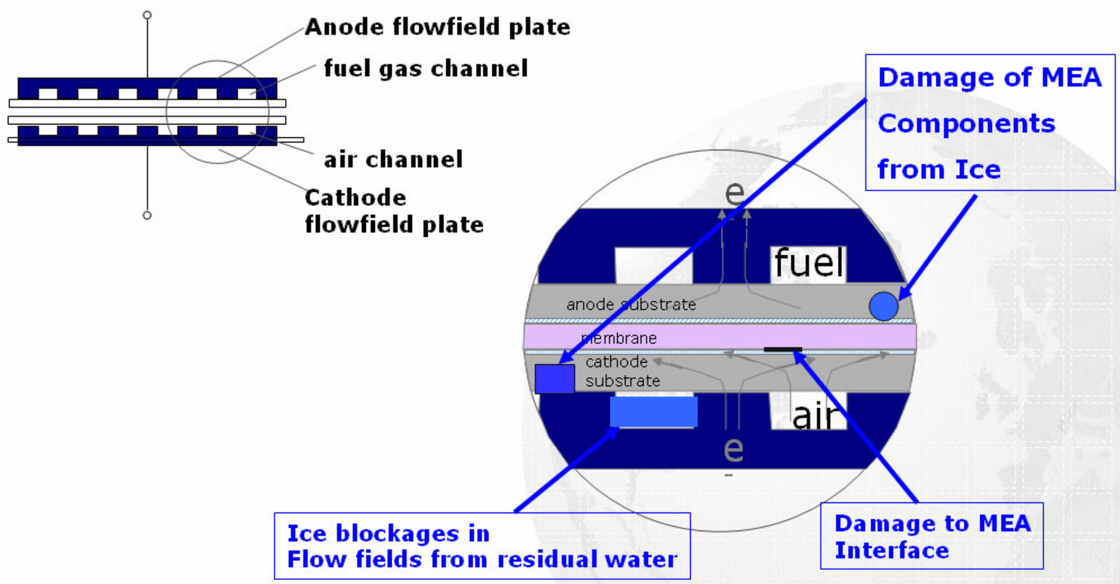

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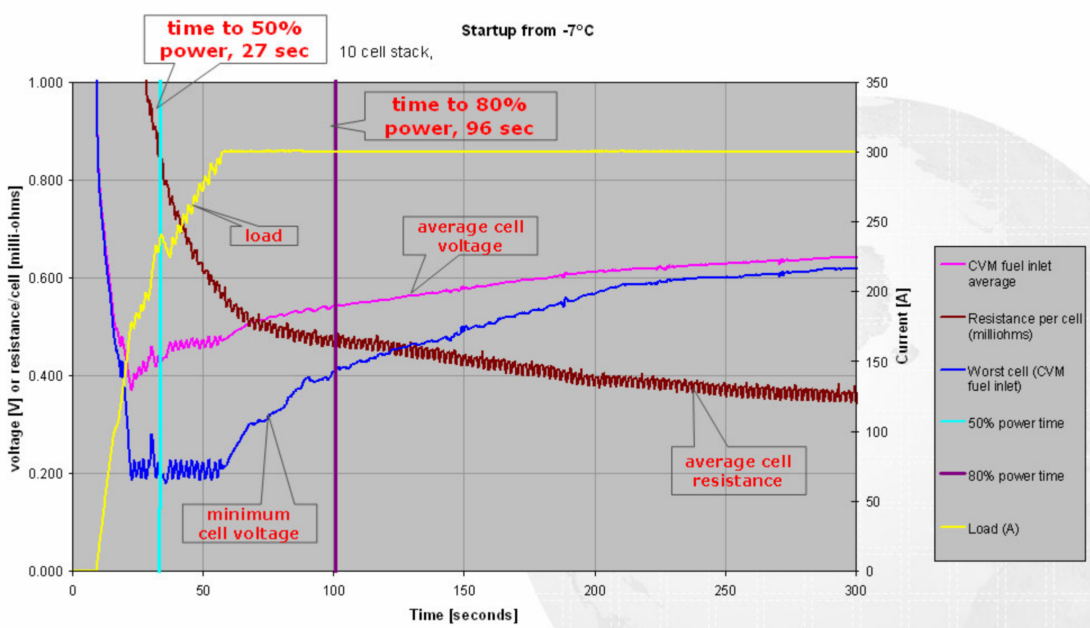
Start-up tests from -7°C: 50% power in 27 sec

BALLARD®



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Low Humidification: Effect on Lifetime

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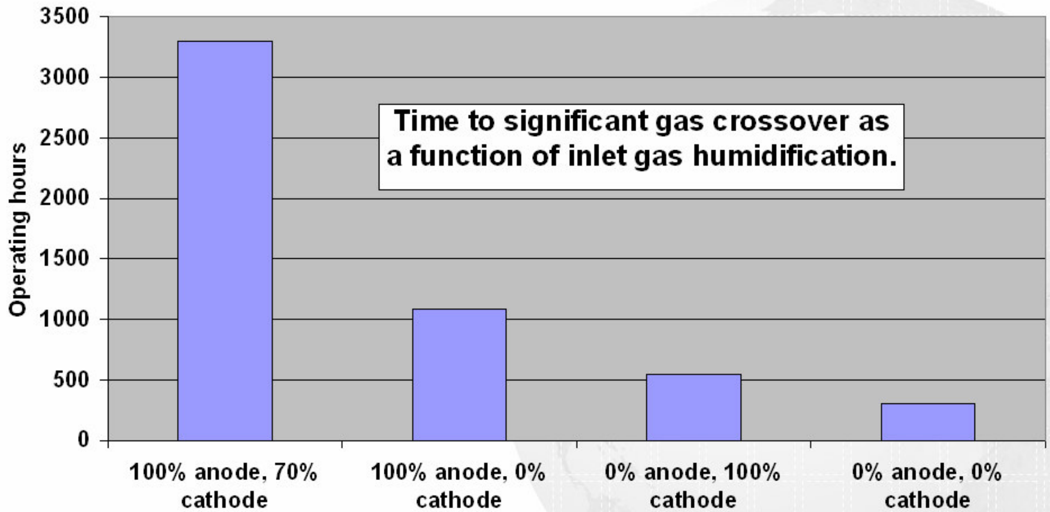
- Insufficient membrane water content results in early degradation and significant increases in gas crossover for a non-optimized cell/MEA design.



PEMFC Modeling and Measurement Tools

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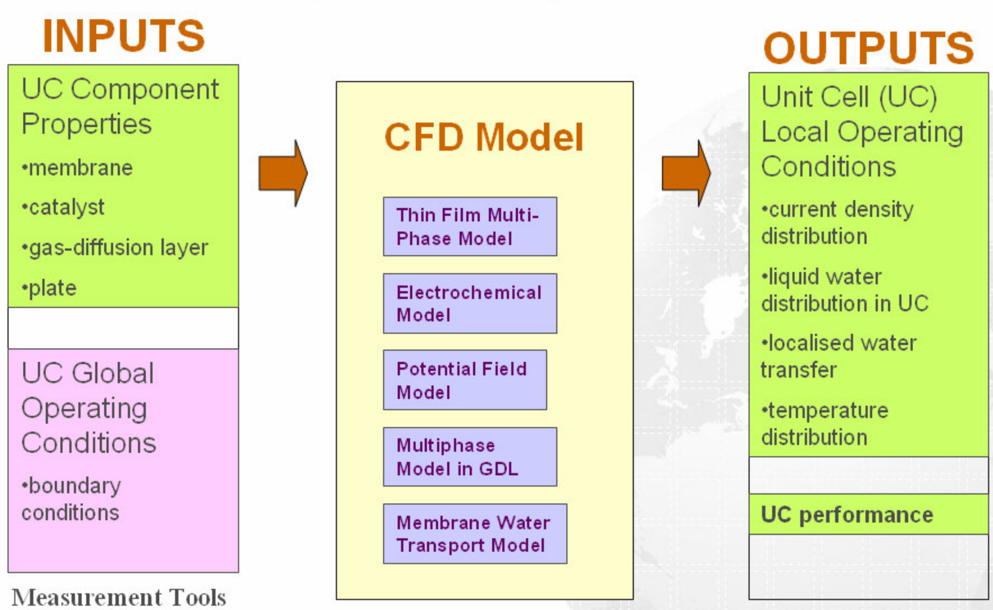
Measurement tools provide data input and validation for CFD model



Summary

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Key areas for Unit Cell advancement include:

- Cost reduction
  - new materials and efficient manufacturing processes
  - component simplification/integration
- Improved operational flexibility and durability
  - Robust, stable components, able to withstand a wide range of conditions
  - high fuel efficiency
  - improved ORR kinetics (better catalysts)
  - tolerance of sub-zero conditions, fast start-up from sub-zero conditions
  - no external humidification requirements
- Better analytical tools:
  - predictive models
  - accelerated test methods; aging tests
  - diagnostic and maintenance tools (drive component specification)

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E : Affinity Grouping Exercise

Instructions

NIST National Institute of Standards and Technology

Process

- Provide a challenge statement
- Participants will respond on Post-It™ notes
- Participants place notes on the walls (any order)
- Participants reorganize the notes into similar groups or categories
- When done, sit down or go out and take a break.
- Organizers will review and determine workgroups
- Participants return and decide which workgroups they wish to join.

2 CAR CENTER FOR AUTOMOTIVE RESEARCH

NIST National Institute of Standards and Technology

Advantages

- Participants determine what they want to talk about.
- Organizers get an understanding of how participants perceive issues
- Less time wasted during workgroup defining topic.

3 CAR CENTER FOR AUTOMOTIVE RESEARCH

NIST
National Institute of Standards and Technology

Challenge

- Purpose: To identify critical manufacturing issues associated with the high volume production of fuel cells and to explore the development of a *national strategy for fuel cell manufacturability*
- Instructions: Write down the 5 greatest technical barriers to full cell manufacturing.

4

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NIST
National Institute of Standards and Technology

In-Scope

- Fabrication processes (chemical or mechanical)
- Manufacturing control issues
- Assembly techniques, including automation issues
- Systems integration and interoperability
- Software issues
- Metrology (hardware)
- Measurement technology, procedures, and protocols
- Technical, non-regulatory standards

5

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Out-of-Scope

- H2 Generation
- H2 Distribution
- H2 Storage
- Education
- Regulatory codes and standards
- Any proprietary information

6

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National Institute of Standards and Technology

Grey Area

- Grey area is product innovation as it affects manufacturing (e.g., product architecture, materials development, product durability, etc.).
- Example Out-of-scope:
  - *PEM FC durability is an issue that may well be solved by a new material, that will in turn have manufacturing implications.*
- Example In-scope:
  - *materials that need to be developed to make manufacturing easier/ cheaper (e.g. materials that are easier to manufacture and assemble) and do not have a detrimental effect on product quality*

7

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NIST
National Institute of Standards and Technology

Challenge

- Purpose: To identify critical manufacturing issues associated with the high volume production of fuel cells and to explore the development of a *national strategy for fuel cell manufacturability*
- Instructions: Write down the 5 greatest technical barriers to full cell manufacturing.

8

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NIST
National Institute of Standards and Technology

POST BREAK INSTRUCTIONS

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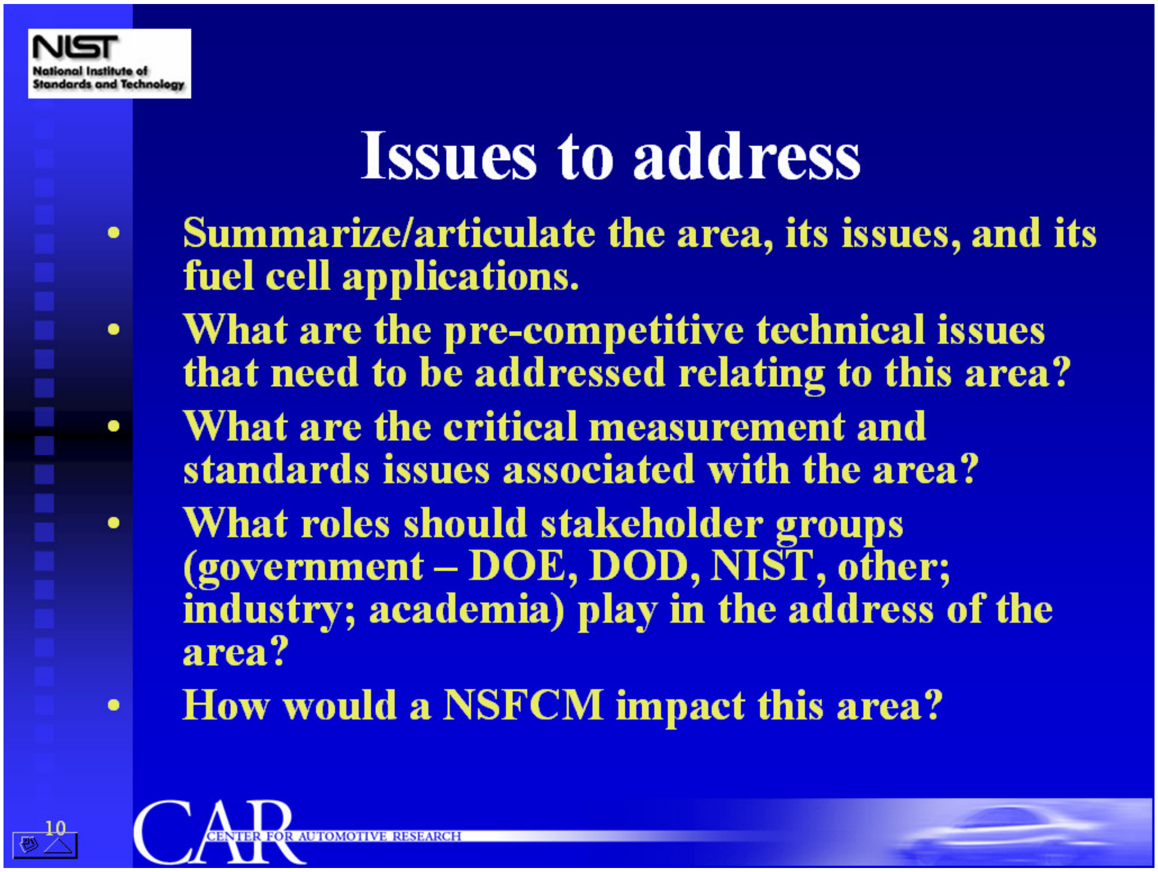
NIST
National Institute of Standards and Technology
Issues to address
• Summarize/articulate the area, its issues, and its fuel cell applications.
• What are the pre-competitive technical issues that need to be addressed relating to this area?
• What are the critical measurement and standards issues associated with the area?
• What roles should stakeholder groups (government – DOE, DOD, NIST, other; industry; academia) play in the address of the area?
• How would a NSFCM impact this area?
10
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Affinity Grouping Results

The following pages present the verbatim responses on the adhesive note slips. After every response it is noted whether the response applies to PEM, SOFC or both, and whether the participant was from industry (I), the government (G), or academia (A). The notes are presented in columns ordered from left to right as the participants had organized them. In general, the SOFC topics were ordered first, the PEM topics were ordered last, and topics that applied to both were in the middle.

F : Workgroup Notes

Facilitator Instructions

Purpose:

To identify critical manufacturing issues associated with the high volume production of fuel cells and to explore the development of a ***national strategy for fuel cell manufacturability***NSFCM

Challenge Statement:

What are the 5 greatest technical barriers to full cell manufacturing?

Within scope

Fabrication processes (chemical or mechanical)
Manufacturing control issues
Assembly techniques, including automation issues
Systems integration and interoperability
Software issues
Metrology (hardware)
Measurement technology, procedures, and protocols
Technical, non-regulatory standards

Out of scope

H2 Generation
H2 Distribution
H2 Storage
Education
Regulatory codes and standards

Grey area

Product related issues (durability, performance, etc.)
Materials
Product architecture

Specific Items that must be addressed during the workshop:

Discuss the challenge area
Determine how that challenge area would be addressed in the NSFCM
Propose industries' and government's responsibilities in the NSFCM as it relates to this challenge area?
What government action would be most useful to the industry:

- National testbed
- Funding for specific activities (what activities and how much over what time period?)
- Focus national labs on specific activities (what activities)

Challenge to the working groups (identified during the Affinity Grouping session):

1. Summarize/articulate the area, its issues, and its fuel cell applications.
2. What are the pre-competitive technical issues that need to be addressed relating to this area?
3. What are the critical measurement and standards issues associated with the area?
4. What roles should stakeholder groups (government – DOE, DOD, NIST, other; industry; academia) play in the address of the area?
5. How would a NSFCM impact this area?

Workgroup A: Metrology and Standards

Joel Berry, Kettering University (facilitator)
Jon Foreman, NexTech Materials
Muhammad Arif, NIST
Terry Udovic, NIST
Dale Hall, NIST
Paul Burton, Plug Power
Shinichi Hirano, Ford Motor Co.

Metrology issues applied to fuel cells

In line process control measures, reduce post inspection; build more quality in

Continuous in line inspection

Supplier certification the same

Continuous testing of MEA

In line crystallography

Registry Issues?

Dimensional tolerance

What is the micro-environment like?

Goal:

Improved in line sensing of parameters will ensure manufactured product will meet design specifications

Does technology need to change as volume increases?

Identification of process and performance parameters and the interaction between them

Develop testing procedures to measure and control parameters; which ones are critical to product performance?

Testing protocol standardization.

Identify acceptable limits of testing.

Identify acceptable precision and accuracy limits of the technique and equipment.

Align limits of technique with the design criteria.

Impact of levels of contamination and environmental quality on manufacturing processes and product quality

Establish guidelines for best practices for manufacturing processes quality

Is the industry ready to accept universal protocol development?

Are international standards a concern? What about multiple regional standards?

What are non-competitive technical issues to be addressed?

What should approach be to developing standards, what is strategy?

Industry representation is needed in standards development.

NIST's role is to gather and facilitate information from industry, and develop methods for testing.

What is the role of academia in standards development?

What is best method for dealing with internal/manufacturing/metrology standards?

SAE has dedicated committees

The role of external professional organizations is to proliferate the standards to industry helping to refine the process of acceptance criteria.

The role of industry is to define what needs to be measured, to what level of accuracy.

Critical parameters flow from qfd

Industry has to agree on importance of establishing product performance standards

Is there a need for an independent fuel cell testing entity?

NIST can set up test beds for industry to make measurements under controlled conditions; and laboratory accreditation programs

What are the benefits of metrology and standards?
Ensures quality in the supply chain, lowers costs, enhances international trade, improves quality of end product.

Summary: Defining performance criteria, creating standards for performance criteria, defining component attributes and manufacturing controls.

Relation to fuel cells: tests and relationships not fully understood at this time. The time is right to discuss metrology standards across fuel cell industry and across markets for developer/supplier relationships.

Defining the important product criteria, and how do we measure them?

Agreeing on what to measure, using a workshop at NIST: what are the top ten product and component performance parameters?

Define testing protocol and limitations of protocol (NIST with partners)

Development of standard reference materials (NIST role)

Distribute standard test procedures (industry groups or SDOs)

What are the manufacturing or component parameters that are important and how do we measure?

Industry should work with government to determine relationships between generic manufacturing/process factors and performance parameters. We need a method for finding out how to do this. Consortium? US Fuel Cell Council? Freedom Car? IUCRC?

We must maintain sensitivity to generic criteria versus proprietary.

How measure various manufacturing criteria/standards/processes; how to measure at full scale production levels, e.g., 80,000 plates per hour

Workgroup B: Fabrication and Assembly

Attendees:
Fred Proctor, NIST MEL (facilitator)
Joe Mitchell, Ballard Power
Amit Bagchi, NIST ATP
Stephen L. Wiedmann, Southwest Research Institute
Gerald Ceasar, NIST ATP
Kevin Smith, United Technologies Fuel Cell
Denise McKay, University of Michigan (scribe)
Ken Baker, Altarum
Ray Puffer, Rensselaer Polytechnic Institute
Robert Mulcahey, Nuvera Fuel Cells
Alkan Donmez, NIST MEL
Gary Anderson, NIST ATP

Summary/General Ideas

- Supply chain management
- Scalability
- Drive cost down by increasing manuf capability but customers not buying quantities that justify high production volumes
- Interfacing process mapping/process transition, maintain control over process and assembly
- How does product design handle volume constraints
- Assessing quality in-situ
- Developing automated systems
- Finding components more conducive to manufacturing
- Platinum loading (technical hurdle)
- Assembly constraints
- Thermal expansion mismatch of materials
- FC design as related to efficiency as compared to other energy production mechanisms
- Cell stack assembly
- Sealing for high volume
- Plate manuf for high volume
- Design to satisfy customer needs, produced cost effectively/consistently at low/high volume
- Sub micron precision manufacturing (optical alignment, sensor technologies needed, image acquisition), robust for manuf floor
- Assembly/alignment at practical speeds
- Cost reduction for auto volumes, should auto volumes be reference point
- Tolerance specifications, are they necessary and how do we decide, who dictates tolerances specs, are we burdening manuf equip suppliers
- Flexible manufacturing that is viable with broad material applications, how to handle product specific manuf processes

- In process inspection (geometry, functional inspection)
- Development of manuf equipment (national focus, who is currently providing equipment suitable for FC components?)
- Quantitative sensitivity analysis cause and effect relationship between component and system specs/tolerances, budgeting errors and adjust strategy for manuf
- Environmental control, do we know what conditions are necessary
- Simulation with out substantial empirical studies
- Process measurement, what is important to measure, how do you use measurements
- Reduce parts count

Characterization of Fabrication Issues/Options

- Robust cell/stack design to leverage existing production capabilities (would this solve existing problems)
- What do designs relate to in terms of manuf processes, what processes do various designs require
- How to transition through design phase (alpha, beta, …) and handle manuf requirements for different component needs. Have separate tolerances/expectations at different design phases
- Over-specifying component requirements
- Manuf equipment while new tech are being developed
- Redesign to satisfy manuf limitations/constraints
- Common practice now involves short run, hand made components in an R&D environment (are we prepared for higher volume, will design be continually changing, is technology mature enough)
- What are common “best practices”?
- what existing manuf technologies/capabilities are similar to FC manuf requirements? Flexible circuits, copier systems, …
- multi-market strategy, market adaptation
- are there different manuf criteria for different applications, dictated by different fuel cell technologies (PEM, SO, MC, …)?
- with no FC technological development are we currently able to compete against existing energy production technologies at large volumes? Can we manuf at the levels necessary to satisfy high volume demand if the demand existed? Is R&D necessary to compete?
- *Have a design that works in the intended consumer environment and that can be reproducible at low volume and can be scaled cost effectively to high volume (who is doing this now, private sector?)*
- Involve high production manuf at the early stages of product development
- Where are resources allocated, small or large scale production requirements

Cost Reduction Opportunities

- Scale

- Design improvements (design for manufacturability)
- Reduce catalyst requirements without decreasing performance
- Government initiated incentives

Manuf Road Map

1. Current State-of-the Art (prototype, hand-made components, current supply/demand economics)
2. technology hurdles accomplished (Durability, reliability, robustness, operating condition requirements addressed)
3. combine existing and new manuf technologies given a design

Government Involvement

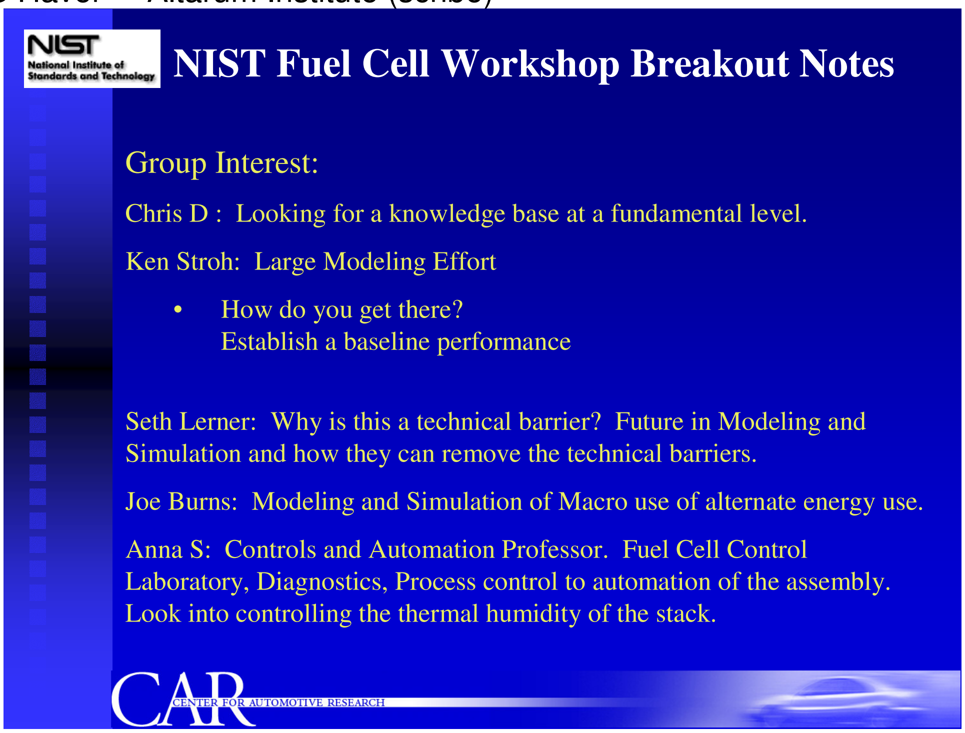
- Regulation
- Subsidies
- Consortium (Sematech model)

Summary, Important Concepts

- Consortium for transitioning between low volume and high volume production that satisfies industry needs, enable and engage academia cost effectively (currently not coordinated, redundant, …). Compile resources (process capabilities, surrogate processes, resource document to shorten research timeline to streamline manuf process, manuf techniques available and applicability, …) so all companies aren't investing resources into researching alternatives
- Need a design that works in the intended consumer environment and that can be reproducible at low volume and can be scaled cost effectively to high volume

Workgroup C: Simulation and Modeling

Anna Stefanopoulou	University of Michigan (facilitator)
Seth Lerner	Kettering University
Chris Di Lello	Ballard Power Systems
Joe Burns	Altarum Institute
Ken Stroh	Los Alamos National Laboratory
Michelle O'Haver	Altarum Institute (scribe)



NIST Fuel Cell Workshop Breakout Notes

Predicting through an accurate model that the fuel cell is working?

Testing for High Volume Production

Manufacturing Process: Specific milestones – Do you know what you should check in the specific milestones? Yes, it's controlled by ISO, but need to add some elements and take some off.

Manufacturing so different with each engine making a universal model so difficult.

The testing aspect with some specifications, how do you test it? You can't really

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NIST Fuel Cell Workshop Breakout Notes

How would a NSFCM impact this area?

- **Identify technical Barriers that need to be removed to move forward**
  - **Design verification**
  - **Process Improvements**
    - **- Fundamental change to design**
  - **Modeling minus proprietary information will push the movement forward.**
  - **Need accelerated testing.**
  - **Simulation Modeling**
  - **Core Manufacturing Standards? None known.**

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NIST Fuel Cell Workshop Breakout Notes

It is critical to manufacturing: design parameters, models, key product characteristics that can be controlled,

Bumps in the road: All systems are so different, Proprietary information, not enough generic information.

Simulations and modeling would be able to help in identifying the critical sensor requirements. This would help reduce cost (due to less sensors, since they are so expensive e.g., oxygen sensor).

Simulation and modeling can identify weak links in the manufacturing process. Defining a manufacturing process needs to be achieved.

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NIST Fuel Cell Workshop Breakout Notes

Process Changes, e.g., new sealant – you can't spend 8 month's of testing and move forward. There will be five new designs in that amount of time.

Strategy for standardization, Applying to Fuel Cell Manufacturing

1. Corrosion Model
2. Using common materials in the process
3. Coating process and deposition of catalyst and carbon
4. Plate Stamping Process (no, special gluing, special materials, not for public viewing.) Challenge bringing stamping down to microns.
5. Thermal Expansion Model
6. Distribute common technologies, to save development time from those that are starting from scratch.

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NIST Fuel Cell Workshop Breakout Notes

Strategy for standardization, Applying to Fuel Cell Manufacturing (Continued)

7. Propose a task force? Addressing things like identifying needs and knowledge, similar processes, e.g., compression technology.

   Thermal Technology, PEM? Can they be integrated into the fuel cell arena?
   Nationalistic… Honda, Toyota – they could take over the industry. Don't try to reinvent all technologies, just improve the ones that are out there. GM is on the right track. That is what Toyota, GM, and Honda are doing, assumed. They aren't worrying too much about manufacturing.

8. NIST's plays a much less sig. Role than METI. Interested in voluntary interest, and where the industry tells them to focus. They are involved with trying to figure out where the work/standardization is needed.

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NIST Fuel Cell Workshop Breakout Notes

Strategy for standardization, Applying to Fuel Cell Manufacturing (Continued)

-- If recommendations come from this workshop, would NIST have an RFP to academia.
NIST can be a source of funding for this operation. '04 FY, has $60 Million for ATP. Also through labs, have a base of resources that operate technology development. They have much smaller amounts of $$, but it's a source for research and academia project. They will not push technology, they lead in standards levels in an unbiased way.

-- National Strategy for fuel cells? We lost stereos, TV's, etc., are we protected by this important technology? Policy implications, by the Pres., to help implement the manufacturing standards. What NIST has in mind is is something that identifies areas that may not have appropriable benefits to a company, but something that will ….help a companies bottom-line. NISTZ can help w/ Architecture of provision of validation data. Stating requirements. Emissions. NIST will make sure a technical basis will be set to be legit.

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NIST National Institute of Standards and Technology

NIST Fuel Cell Workshop Breakout Notes

Strategy for standardization, Applying to Fuel Cell Manufacturing (Continued)

-- Need to connect all models, Can it be made at this point that can benefit more than one company. Does the technology exist yet?

-- "What's available today?"

-- NIST could thread common practices that exist w/in industry consortium.

-- Think about the stakeholders. Bring in other other agency funding. NIST, DOE, etc. Many may not fund right now, but addressing it to the right people may change that.

-- Are we too late?

-- NEED A NIST WEB-PORTAL TO HAVE DISCUSSIONS? SEE WHAT MODELS, STANDARDS & TECH. IS OUT THERE?

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NIST National Institute of Standards and Technology

NIST Fuel Cell Workshop Breakout Notes

Strategy for standardization, Applying to Fuel Cell Manufacturing (Continued)

-- TESTING

1. Testing Stations: Help specify constraints?
Successful sharing and not giving away too much.
2. What can we share about process manufacturing.
3. Simulate what we know and don't.

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NIST Fuel Cell Workshop Breakout Notes

Strategy for standardization Summary

Summarize/articulate the area, its issues, and its fuel cell applications.

- **Developing a model that integrates models of manufacturing processes.**
  - **Relates manufacturing parameters, variability to performance (robustness, durability, Mean Time to Failure.**
  - **Design intent verification.**
- **Issues**

1. **Proprietary (data, product design, and sequence of process)**
2. **Complexity and variability of processes**
3. **Multi-disciplinary expertise of domains**
4. **Validation**

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NIST Fuel Cell Workshop Breakout Notes

What are the pre-competitive (generic) technical issues that need to be addressed relating to this area?

- **Consolidation of existing of applicable simulation tools (e.g., Stamping, deposition and molding).**
- **Virtual Testing**
- **Order of magnitude enhancement.**
- **Fundamental linkage between material performance and process change.**

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NIST Fuel Cell Workshop Breakout Notes

What are the critical measurement and standards issues associated with the area?

- **Critical Measurements:**
  - **"lifetime" of an FCS?**
  - **Process Model Validation**
- **Standards Issues**
  - **Safety (e.g., Hydrogen leakage)**
  - **Test Protocol**

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NIST Fuel Cell Workshop Breakout Notes

What roles should stakeholder groups (government – DOE, DOD, NIST, other; industry; academia) play in the address of the area?

- NIST could thread common practices that exist within industry consortium.
- DOT? creating standards for transportation, Hydrogen, High Pressure.
- DOE – Take the lead on the modeling development of this mega" process in collaboration with industry, academia, and other government agencies.

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NIST Fuel Cell Workshop Breakout Notes

How would a NSFCM impact this area?

- **Near-term -- facilitate access to existing simulation tools and processes that can accelerate development in manufacturing of fuel cells.**
- **Long-Term – support need for sustained resources and effort necessary to develop and validate such a process.**
-

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Workgroup D: Materials and Sealants

Attendees:

Patrick Davis, Department of Energy
Ed Seebauer, University of Illinois—Urbana
David Lane, W.L. Gore and Associates
Steve Koch, Freudenburg NOK
John Halloran, University of Michigan (Facilitator)
Manish Mehta, NCMS (Scribe)
Wil Conner, BNCI
Mei Cai General Motors
Bill Schawnk, Ford
Prabhakar Singh. PNNL

GROUP D – MATERIALS & SEALANTS BREAKOUT

Low loading (e.g., vacuum deposition) is a technology issue TODAY and not yet considered a Manufacturing issue! (Consensus)

Catalyst that is robust to H2 purity variations - Materials development issue

- NIST can help define purity levels of catalyst
- FreedomCAR spec for Direct H2 systems is 98% purity with 1.99% inerts (P. Davis)

Too much emphasis on manufacturing & measurement tolerances (Bill Schank)
- Should we really pursue micron-level tolerances? Or avoid the need for …

Stamping of plate components (P. Singh) requires large-scale tolerances and uniformity standards
- Need Large-scale materials & process development for SOFC plate welding and joining of plates to seals and manifolds.

Bipolar plates technology
- Bulk Molding of composite Plates (W. Conner)
-1000s of different MEAs & plates designs investigated - Prominent designs needed to pursue standardization (D. Lane)!
    - Possibility of an industry-std. flow field?
- Composite-type, Plate Thickness, Flatness, parallelism, molded to net shape for flow fields
- Measurement of Series conductivity of plates is not consistently done – too much variability – need a round robin on variability studies – e.g., USFCC, ASTM, NIST, NCMS (S. Kock, Bill Schank)
- Cost-Performance targets are not well correlated

Uniformity (defect) of PEM membranes & Pt loading and dispersion, durability (Mei, P. Singh, Dave Lane- USFCC)

- ⇨ NIST role - Need standards/protocols for materials and components, using a test protocol
- ⇨ Dev. Standard tests on membranes per each attribute (e.g., tensile, cycling, conductivity, etc.)
- ⇨ On-line monitoring of large-scale, hi-volume processes – too far out! What attributes need to be measured?
- ⇨ Std. Measurement of Catalytic activity developed by various vendors of FC components (DuPont, Cabot Superior Micropowders)
- ⇨

NIST should emphasize the testing technique, not the actual standard/specification.
-Accelerated FC life testing does not work!

Conductivity (ionic, bulk, proton) tests needed for PEMs.
Sealing – No consensus – too many ways of achieving it!

Robustness of components/products for FCs – we are still way behind on the learning curve to really determine it! Too many system level interactions confound the investigations – this is being done individually by developers (because of IP issues).

Lack of "open" industry (OEM-supplier) sharing of knowledge that can help define non-competitive areas for R&D, measurement, standards, etc., which are mutually beneficial to all industry.

GDL Measurement (D. Lane) is not being done fast enough (USFCC) – need standardized and better organized testing!

Need a standard (published) test for Degradation of monomers in membranes

What level of sealing effectiveness is critical for FCs (Technology issue at present, but could become a mfg. issue in future)

- Long term (6-month vs 10 years) durability and performance of seals
- How to consistently produce seals in high-vol mfg processes (P. Davis)?
- Materials do not fail sooner, but the FCs do!

Seal materials' behavior under operating temperatures inside a long-term oxygen-hydrogen environment (Bill Schank)

Too early to talk about a National (NSFCM) strategy for FC performance, mfg., durability, etc. since the base FC materials are not yet well-defined (Mei, D. Lane,)

Japanese collaborations in FCs are proactively dominated/driven/led by the Govt. & OEMs Toyota and Honda

NIST should collaborate/coordinate/examine/benchmark strategies for bridging the gap, e.g., ISO standards, SAE, ASTM, etc., as well as other countries (Asians, Europeans)