

# Pathways to Commercial Success:

Technologies and Products Supported by  
the Hydrogen, Fuel Cells & Infrastructure  
Technologies Program

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# Summary

The Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program integrates activities in hydrogen production, delivery, and storage with transportation and stationary fuel cell activities, in addition to crosscutting efforts in technology validation; safety, codes, and standards; education; manufacturing research and development; and market transformation. The Program office consolidated efforts within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) in the 2002 time frame. The HFCIT Program and the predecessor programs that were consolidated have been conducting a wide range of hydrogen and fuel cell research and development projects, some of which have resulted in products and technologies now available in the commercial marketplace.

The purpose of the project described in this report was to identify and document the commercial and near-commercial (emerging) hydrogen and fuel cell technologies and products that benefited from EERE support. To do this, Pacific Northwest National Laboratory (PNNL) undertook two efforts simultaneously. The first effort was a patent search and analysis to identify hydrogen- and fuel-cell-related patents that are associated with HFCIT-funded projects (or projects conducted by DOE-EERE predecessor programs) and to ascertain the patents' current status, as well as any commercial products that may have used the technology documented in the patent.

This patent analysis identified 144 patents associated with research supported by HFCIT, out of approximately 360 potential HFCIT patents, dating back to 1977, that were found in the original patent search. The 144 HFCIT patents include: 74 fuel cell patents, 49 production/delivery patents, and 21 storage patents. More than 70 of these patents were issued after 2002. Three types of organizations received the patents: national laboratories (69 patents), private companies (56 patents), and universities (19 patents). The national laboratories had patent awards for fuel cell and production/delivery technologies that were almost equal to those awarded to private companies in these two areas. The national laboratories had 62% of the awards in the storage area. While the universities received fewer total patent awards, they had 74% of their patents in the production/delivery area. The national laboratories and private companies both received more than half of their patents in the fuel cell area.

The patent award status by use indicated that 3 patents are currently used in commercial products and 18 are part of research now taking place on emerging technologies. In addition, 51 awarded patents are still being used in research that is more than 3 years from a commercial product and the status of one patent is still unverified. Of the patents reviewed, 50% are no longer being used in research. This was particularly true in the fuel cell area, where 44 of the 73 patents (60%) are no longer being used in research. However, this is not true in the storage or production/delivery area, where most of the patents are still being used in research.

The second effort was a series of interviews with current and past HFCIT personnel, a review of Hydrogen Program annual reports, and an examination of hydrogen- and fuel-cell-related grants made under the Small Business Innovation Research and Small Business Technology Transfer Programs, and within the HFCIT portfolio.

This effort identified 22 commercial technologies including three using patents identified in the first effort. From 2000 – 2006, one to three commercial technologies entered the market per year. In 2007, five technologies entered the market, and in 2008, six technologies did so. This effort identified 47 emerging technologies. An almost equal number of emerging technologies occurred between the fuel cell and production/delivery areas, with the storage area having far fewer emerging technologies.

This report documents the details of this study including the specific patents as well as commercial and emerging technologies that resulted from the HFCIT Program.



# 1.0 Introduction

This report documents the results of an effort to identify and characterize commercial and near-commercial (emerging)<sup>1</sup> technologies and products that benefited from the support of the Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program and its predecessor programs within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). The effort was undertaken to meet the following primary objective:

To identify and characterize commercial and near-commercial (emerging) technologies that benefited from support of the HFCIT Program and its predecessor programs within DOE's EERE.

Commercialization of technologies that were cultivated in a government research and development (R&D) program is generally viewed as a measure of success. However, in addition to developing this indicator of the general success of the HFCIT's R&D program, by studying the commercial successes documented in this report, the reader may gain insight into pathways for more widespread introduction of hydrogen and fuel cell technologies. With the tracking of commercialization successes, HFCIT is likely to more effectively manage its R&D programs, repeat successful approaches to commercialization, and learn from unsuccessful pathways.

PNNL has been conducting similar technology tracking activity for the EERE Industrial Technologies Program (and its predecessors) for over two decades and agreed to develop a similar methodology and undertake the commercial technology tracking project for hydrogen and fuel cells.

The results presented in this report represent the findings from the first stage of the PNNL effort. The information presented on commercial and emerging technologies fulfills the primary objective – to assess the commercialization status of EERE-developed hydrogen and fuel cell technologies. Insights about pathways to successful introduction of hydrogen and fuel cell technologies are beginning to emerge from this analysis, but this topic has not yet been fully explored. The effort is expected to continue, with an updated report produced annually. Next year's report is expected to provide more insight on the mechanisms by which hydrogen and fuel cell technologies were successfully commercialized and why other technologies were not successfully commercialized, so that the HFCIT Program can benefit from “lessons learned.”

To provide some context, this chapter presents a brief history of HFCIT and its predecessor programs and an overview of the HFCIT Program research thrusts that are leading to commercial technologies and products. This chapter concludes with a summary of the contents of this report.

## 1.1 A Brief History of HFCIT

The HFCIT Program was formed under the Assistant Secretary for EERE in fiscal year 2002 (FY 2002) to integrate activities in hydrogen production, storage, and delivery with transportation and stationary fuel cell activities. The formation of the new office consolidated other efforts within EERE, such as projects underway in the Fuel Cells for Transportation R&D Program within the Office of Transportation Technologies (which was founded in the late 1980s) and in the Distributed Energy Program within the Office of Building Technologies.

The formation of the HFCIT Program was coincident with the formation in January 2002 of the FreedomCAR Partnership, a cooperative R&D partnership between DOE and the U.S. Council for Automotive Research, the precompetitive research organization of Ford, General Motors, and DaimlerChrysler.

To place additional emphasis on fuel infrastructure issues, this program was later expanded (September 2003) into the FreedomCAR and Fuel Partnership, with the addition of five major energy companies (BP America, Chevron, ConocoPhillips, ExxonMobil, and Shell).

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<sup>1</sup> “Commercial” technologies, as defined in this report, are those available for purchase and that have been sold to at least one party. “Emerging” technologies, as defined in this report, are technologies that are projected to be commercialized within the next 3 years, based on the opinion of the technology developer.

A year after the FreedomCAR Partnership was formed, the Hydrogen Fuel Initiative (HFI) was announced to accelerate the research, development, and demonstration of technologies for fuel cell vehicles and the hydrogen fuel infrastructure to support them. As a result, DOE formulated an even more comprehensive program that cut across its R&D programs – the DOE Hydrogen Program. The Program, launched in FY 2004, was a partnership between several DOE Program offices: EERE, Fossil Energy (FE), Nuclear Energy (NE), and Science. The Hydrogen Program’s mission was to “research, develop, and validate hydrogen production, storage, and fuel cell technologies and to overcome the non-technical barriers to the commercialization of these technologies—with the ultimate goals of reducing oil use and carbon emissions in the transportation sector and enabling clean, reliable energy for stationary and portable power generation.”

In 2006, the Administration announced the Advanced Energy Initiative (AEI), which accelerates R&D of technologies for both transportation and stationary power generation, including near-term transportation solutions such as plug-in hybrids and ethanol vehicles, as well as the hydrogen R&D efforts that were underway. The HFCIT Program’s R&D efforts were a key part of this expanded EERE transportation and stationary power portfolio, which worked to achieve AEI’s goals by developing a comprehensive suite of energy efficient and renewable energy technologies to improve the way homes, cars, and businesses are powered.

This report focuses on commercial successes arising from the HFCIT R&D efforts that started in FY 2002 *and* from prior EERE efforts related to hydrogen and fuel cells for transportation and stationary uses that were previously dispersed in various EERE buildings and transportation programs. Other commercial successes, not covered here, have undoubtedly emerged from the Hydrogen Program’s fossil, nuclear, and basic science R&D.

## 1.2 Organization of the HFCIT Program

The HFCIT Program is focused on key technical challenges associated with fuel cells and hydrogen production, delivery, and storage, as well as institutional barriers, such as hydrogen safety, codes and standards, and public awareness. The Program is currently conducting applied research, technology development, and learning demonstrations, as well as safety research, systems analysis, and public outreach and education activities. Because the research involved in solving critical technological barriers is often high risk, the Program encourages public-private partnerships, which include automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, standards development organizations, other federal agencies, state government agencies, universities, national laboratories, and other national and international stakeholder organizations.

The Program is currently conducting R&D, demonstration, analysis, and other efforts to support development of hydrogen energy systems for transportation (including fuel cell vehicles and hydrogen refueling infrastructure), stationary power (including back-up emergency power and residential electric power generation), and portable power applications (including consumer electronics such as cellular phones, hand-held computers, radios, and laptop computers). The HFCIT sub-Programs that are relevant to technology development represented in this report include the following:

- Hydrogen Production
- Hydrogen Delivery
- Hydrogen Storage
- Fuel Cells
- Manufacturing R&D.

The first four sub-Programs are the primary focus of this report because they are focused on technology R&D that would result in patents and other intellectual property that could be incorporated into commercial technologies and products. Manufacturing R&D is a relatively new sub-Program that is likely to lead to commercial technologies in the future.

The current goals and thrusts of these four sub-Programs are briefly summarized below.

**Hydrogen Production.** The goal of the Hydrogen Production sub-Program is to develop low-cost, highly efficient hydrogen production technologies from diverse domestic sources, including natural gas and renewable sources. The current objectives include lowering the cost of distributed production (at the pump) of hydrogen from natural gas, biomass, and electrolysis; developing high-temperature thermo-chemical cycles driven by concentrated solar energy; and



developing advanced renewable photo-electrochemical and biological hydrogen generation technologies. Hydrogen separation is a key technology that cross-cuts hydrogen production options, and various separation membranes are being developed as part of distributed and central hydrogen production systems. In addition, work in the sub-Program includes developing better catalysts needed in production systems and coordinating with the Office of Science on basic research, such as hydrogen production from algae and other biological systems. The sub-Program also coordinates with the Office of FE on coal gasification (with sequestration) and separation processes, and with the Office of NE on hydrogen production from thermochemical processes.

**Hydrogen Delivery.** The goal of the Hydrogen Delivery sub-Program is to develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power. Some of the current objectives include reducing the cost of compression, storage, and dispensing at refueling stations and stationary power facilities; reducing the cost of hydrogen transport from central and semi-central production facilities to the gate of refueling stations and other end users; and reducing the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units. Some of the technical challenges that must be addressed include resolving hydrogen embrittlement concerns and developing new and improved materials for pipeline delivery of hydrogen, developing novel liquid and solid carrier technologies, improving compression and bulk storage technologies, and improving hydrogen liquefaction approaches.

**Hydrogen Storage.** The goal of the Hydrogen Storage sub-Program is to develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications, with the primary objectives focused on developing and verifying on-board hydrogen storage systems for transportation applications. Various research activities are being pursued, such as those related to lightweight composite tanks with high-pressure ratings and conformability and high-capacity metal hydrides, including boron-based materials, adsorbent-based and nanostructured materials, chemical carriers, and other promising materials with potential for hydrogen storage. Coordination with the Office of Science is also significant, particularly in developing a fundamental understanding of hydrogen-material interactions.

**Fuel Cells.** The goal of the Fuel Cells sub-Program is to develop and demonstrate fuel cell power system technologies for transportation, stationary, and portable power applications. The sub-Program emphasizes polymer electrolyte membrane (PEM) fuel cells as replacements for internal combustion engines in light-duty vehicles as well as fuel cells for stationary power, portable power, and auxiliary power applications. Research focus areas include work on membranes, electrocatalysts and electrode design, membrane electrode assemblies, gas diffusion layers, bipolar plates, seals, and other aspects of fuel cell design including water management and balance-of-plant components. More recently, the sub-Program has included small-scale solid oxide fuel cell (SOFC) R&D to complement FE's Solid State Energy Conversion Alliance (SECA) Program<sup>2</sup> on megawatt-scale SOFC power systems. Work on fundamental catalysis is coordinated with the Office of Science.

More information on program goals, objectives, research thrusts, and activities can be found in the [HFCIT Multi-Year Program Plan](http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/). (<http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/>).

The objectives of, and R&D activities funded by, the HFCIT Program and its predecessor programs have changed over the years as the Program has become more focused on the goals described above and as advancements have been made in R&D. Because this report looks retrospectively at commercial successes over the history of hydrogen and fuel cell research within EERE, the patents and commercial/emerging technologies and products described in the remainder of this report may be broader than one would expect from examining the current Program.

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<sup>2</sup> FE's SECA Program is supporting the development of large-scale SOFCs that can be mass produced in modular form at \$400/kW. The objective of the SECA Program is to put reliable fuel cells into a more compact, modular, and affordable design to allow widespread penetration into high-volume stationary, transportation, and military markets.

## 1.3 Contents of this Report

The remaining chapters explain in more detail the methodology used and provide the results of the effort in tables and charts. The appendices provide detail related to the data-gathering techniques and descriptions of each of the commercial and emerging technologies and products that were identified in the study, as well as the list of patents resulting from the R&D efforts undertaken by the HFCIT Program and its predecessors.

Note that in this report, the delivery technologies have been grouped with production technologies because of the overlap between the two categories.

## 2.0 Approach

Two efforts were undertaken simultaneously by PNNL to start the HFCIT technology tracking project. The first effort was a patent search and analysis to identify hydrogen- and fuel-cell-related patents that are associated with HFCIT-funded projects (or projects conducted by DOE-EERE predecessor programs) and to ascertain the patents' current status, as well as any commercial products that may have used the technology documented in the patent. The second effort was a series of interviews and document reviews to identify and characterize commercial and emerging technologies that have benefited in a direct way as a result of direct funding from the HFCIT Program (or funding from EERE predecessor programs) or from grants under programs such as the Small Business Innovation Research and Small Business Technology Transfer. The approach taken for each effort is summarized in Sections 2.1 and 2.2 below.

### 2.1 Patent Search and Analysis

PNNL conducted several patent searches using the United States Patent Office (USPTO) database. The searches included key words related to the hydrogen program<sup>1</sup> and focused exclusively on patents for which DOE had a "Government Interest."<sup>2</sup> The resulting list contained 118 fuel cell patents (mostly related to PEMs) and 239 hydrogen production, storage and delivery patents dating back to 1977. The PNNL team then conducted an initial screening analysis to winnow the patent list to those likely to be associated with EERE research. (Other parts of DOE, including FE, Office of Nuclear Energy, and Office of Science, also conduct research on hydrogen and fuel cells, but those patents were not included in this study.)

To conduct this screening process, the PNNL team considered the following factors in deciding whether a patent should be included on the list of possible EERE-sponsored hydrogen and fuel cell patents:

- Most research on phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) was funded by DOE's FE, so patents for these types of fuel cells were not included in the EERE list (with the exceptions noted in the next bullet). However, almost all PEM fuel cell research was funded by EERE. Therefore, PNNL typically included PEM fuel cell patents in the list of possible EERE-sponsored patents (with the exceptions noted below).
- EERE started research on PAFCs *for buses* in 1987, and its PEM research program began in 1990. In addition, beginning in 1996, EERE's charter (based on the HFCIT Program Multi-Year Program Plan) includes direct methanol fuel cell (DMFC) work for portable power. Therefore, some patents related to PAFCs and patents for PEMs and DMFCs that were filed after those dates were assumed to be associated with EERE's hydrogen and fuel cell research. However, the PNNL team assumed it takes at least 2 to 3 years to conduct the research and have a patent awarded and took that time lag into account when developing the list of possible EERE-sponsored patents. For example, any patents awarded before 1990 for PAFCs and before 1992 for PEMs were assumed to be related to research outside EERE.

In addition, PNNL obtained the list of patents that were cited in the Hydrogen Program's Annual Progress Reports for 2002 – 2007<sup>3</sup> and included them in the patent list after checking against the two bulleted factors above (in almost all cases, the patent search had already found these patents). The list was sent to HFCIT staff to review, and some patents were removed or recategorized (e.g., from fuel cells to production). The resulting list contained patents for 77 fuel-cell-related and 103 hydrogen-related technologies or inventions (180 total).

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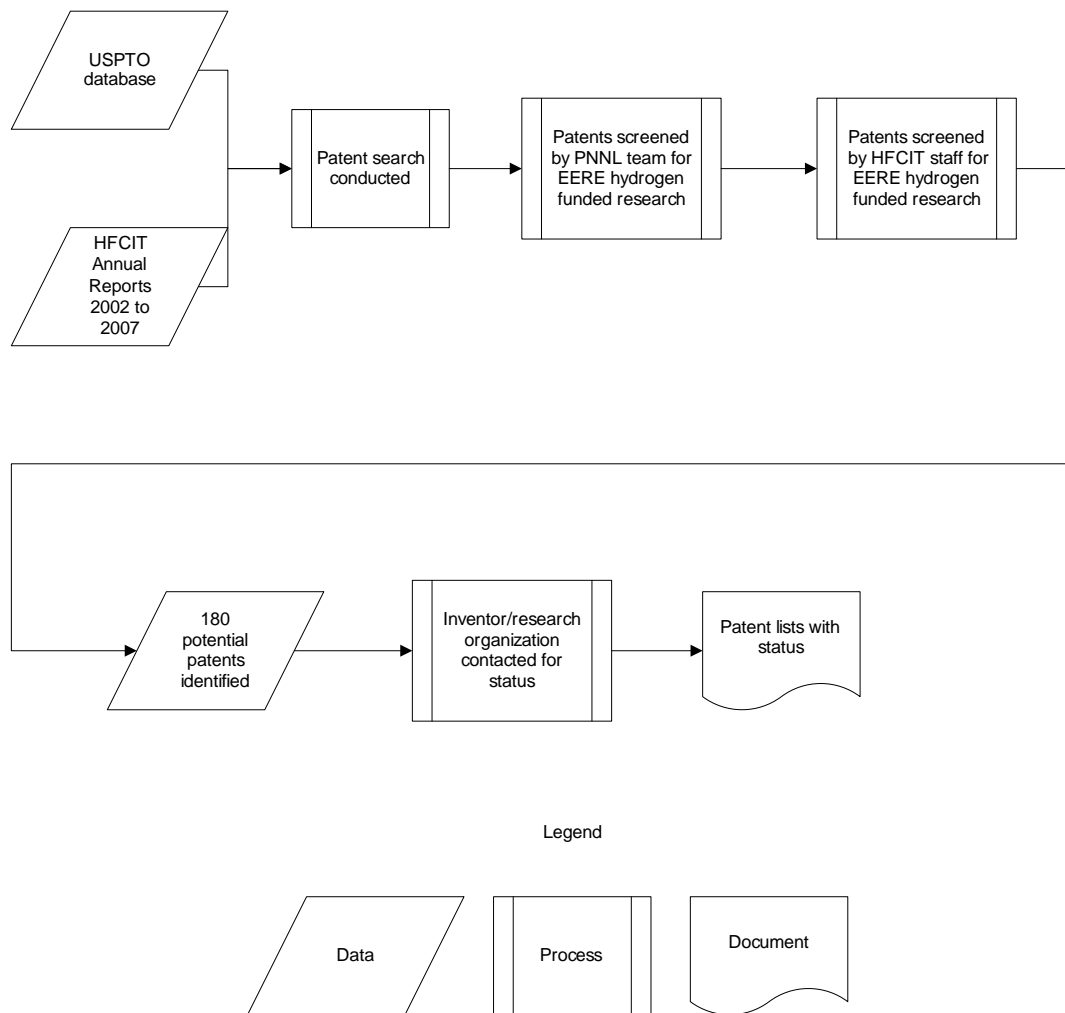
<sup>1</sup> One search used the following search terms: "hydrogen" AND "storage" OR "transport" OR "delivery" OR "dispensing" AND "government/energy." The other search used the following search terms: "fuel cell" AND "pem" OR "membrane" AND "government/energy."

<sup>2</sup> Note that the patent database has a separate field that designates whether there is a "Government Interest" in the patent. If DOE has an interest, that field says, for example, "The United States Government has rights in this invention pursuant to Contract No. [...] between the United States Department of Energy and [...] a national laboratory or other party]." It is possible that not all of the parties with EERE-related patents correctly indicated that their patents had a "Government Interest."

<sup>3</sup> These reports can be found at [http://www.hydrogen.energy.gov/annual\\_progress.html](http://www.hydrogen.energy.gov/annual_progress.html).

The next step was to get more information about the government’s role in developing the patent and to determine the current status. The PNNL team contacted patent holders by phone or email. For large organizations (e.g., national laboratories, universities, and multinational corporations), PNNL team members were often referred to a central office within the organization, such as a technology transfer, commercialization, or legal affairs office.

The PNNL team members asked the patent holders or central offices whether HFCIT or EERE (or its predecessors) funded the research resulting in the patent. Patents not related to HFCIT or EERE funding were removed from the list. If a patent had received such funding, the PNNL team attempted to ascertain the current status of the patent and placed it in one of the following categories: no longer being pursued for commercialization or used in research, still being used in research, used in a commercial product, or licensed to another company. If the patent is still being used in research, PNNL asked if it was part of an emerging technology project for which PNNL was gathering data. If the technology was licensed to another company, PNNL asked for the name of the company and tried to ascertain whether a commercial product had resulted from the patent. As PNNL gathered technology data, other patents associated with HFCIT/EERE funding were sometimes identified and added to the list. Figure 2.1 depicts the patent analysis process for the hydrogen and fuel cell technologies.



**Figure 2.1. Patent Analysis Process for Hydrogen and Fuel Cell Technologies**

The results of this patent search analysis are discussed in Chapter 3. Some of the intellectual property in the patents on the list was used in technologies or products that were commercialized or that are soon to be commercialized. The section below describes the effort, conducted in parallel with the patent analysis, to identify and describe commercialized and emerging technologies. Chapter 3 provides information on these technologies and the patents related to them.

## 2.2 Technology Tracking to Identify and Describe Commercial and Emerging Technologies

The technology tracking approach used to gather information on commercial and emerging hydrogen technologies is based on one that PNNL has been using for 20 years to gather information on technologies funded by the EERE Industrial Technology Program (ITP). As a first step, the PNNL team identified HFCIT-funded projects that may have led to commercial or emerging technologies. To accomplish this, a series of one-on-one meetings was held with HFCIT personnel and former HFCIT personnel in which the lists of all HFCIT-funded projects, obtained from the Hydrogen Program Annual Progress Reports for 2002 – 2007, were reviewed. In addition, PNNL also reviewed earlier annual reports from HFCIT predecessor programs. From these meetings, the PNNL team obtained a preliminary list of projects that the HFCIT personnel indicated may have led to commercial or emerging technologies. The government personnel also provided information about points of contact (POC) or principal investigators (PIs) at each relevant research organization and, where available, hard copies of reports or presentations pertinent to the technologies. The resulting list of projects from these meetings was separated into three lists according to these research areas: fuel cells, hydrogen production/delivery, and hydrogen storage. These areas are included in the technology tracking list in Appendix A.

The PNNL team contacted the POCs or PIs for the technologies to determine whether they were commercially available, emerging, still in the research stage but more than 3 years from commercialization, or no longer being pursued. For technologies identified as commercial or emerging, a template, shown in Appendix B, was sent to the POCs/PIs to gather data on the technology.

The Hydrogen Program Annual Progress Report also includes descriptions of hydrogen and fuel cell projects from the annually funded Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) grants. The SBIR grants are funded in two phases: Phase 1 grants focus on the feasibility of an idea and are funded at a low level (typically up to \$100K), and Phase 2 grants focus on principal R&D and are funded at a higher level (typically up to \$500K). To receive a SBIR Phase 2 grant, a small business would have to have successfully completed a Phase 1 grant and have been selected to continue their research. The STTR grants are similar to SBIR grants as far as having small business participation, but a nonprofit research institution, such as a university or national laboratory, must also be involved. The PNNL team focused on the SBIR Phase 2 and STTR grant projects and contacted the PIs for all of these grants to determine the status of the technologies being developed. Any identified as commercial or emerging were added to the technology tracking list.

Data gathered about the technologies were then entered into a HFCIT Program Technology Tracking Database, a Lotus Notes database. The database is divided into commercial and emerging technology sections and into three types of research within each section: fuel cells, production/delivery, and storage. In addition, hard copy files are kept that include the template (database) information and other supporting data such as annual progress reports, presentations, and information from the organization's website. The database was created and populated by PNNL and is stored at PNNL, and HFCIT personnel have access to it. Periodically, PNNL transmits an updated version of the database to DOE to replace the older version on the DOE system.

For each of the commercial and emerging hydrogen technologies in the database, the PNNL team prepared and edited a summary description and sent it to the industry/research organization POC for review and subsequent approval before sending it to HFCIT Program personnel to review. The results of the technology tracking effort are discussed in Chapter 3. Figure 2.2 depicts the technology tracking process.

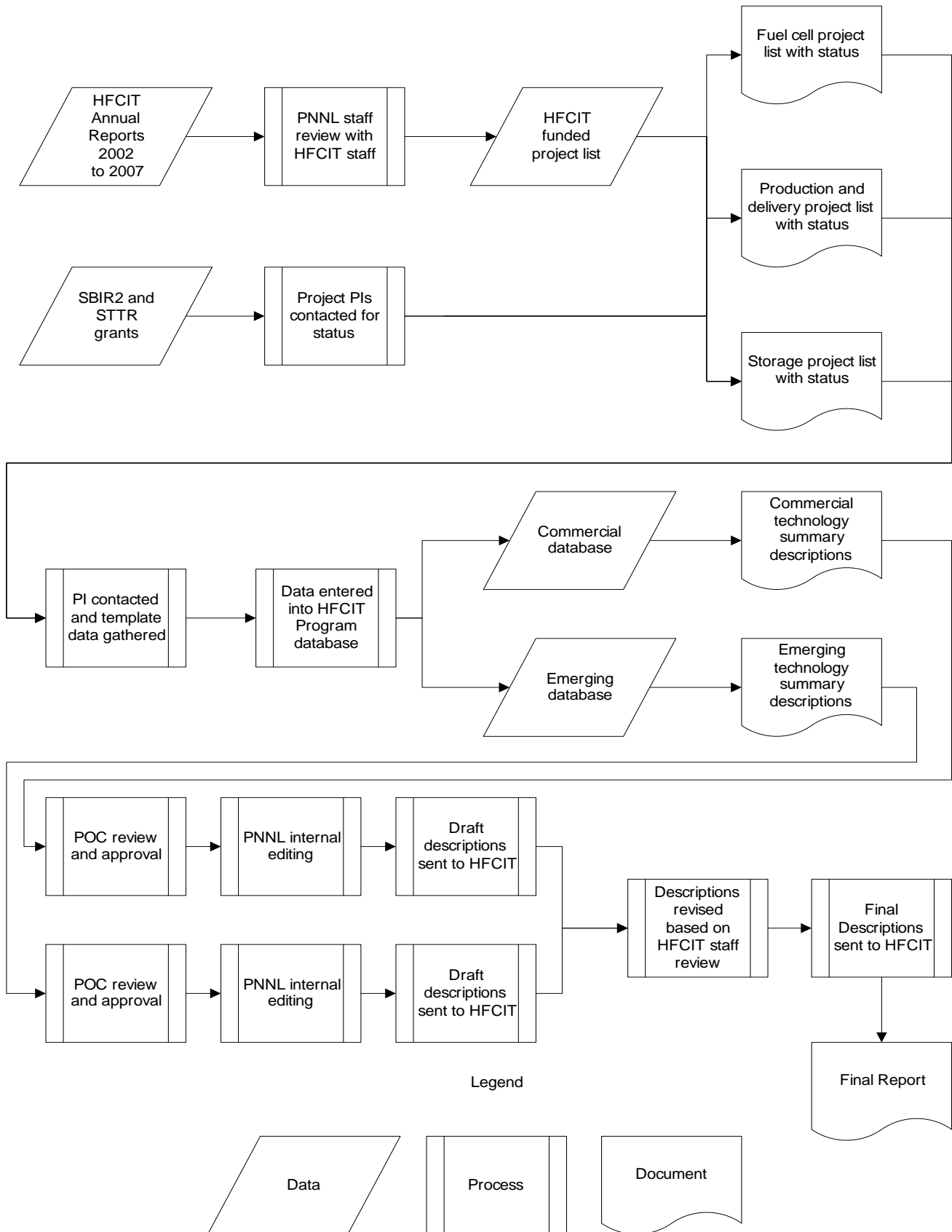


Figure 2.2. Technology Tracking Process for Hydrogen Technologies

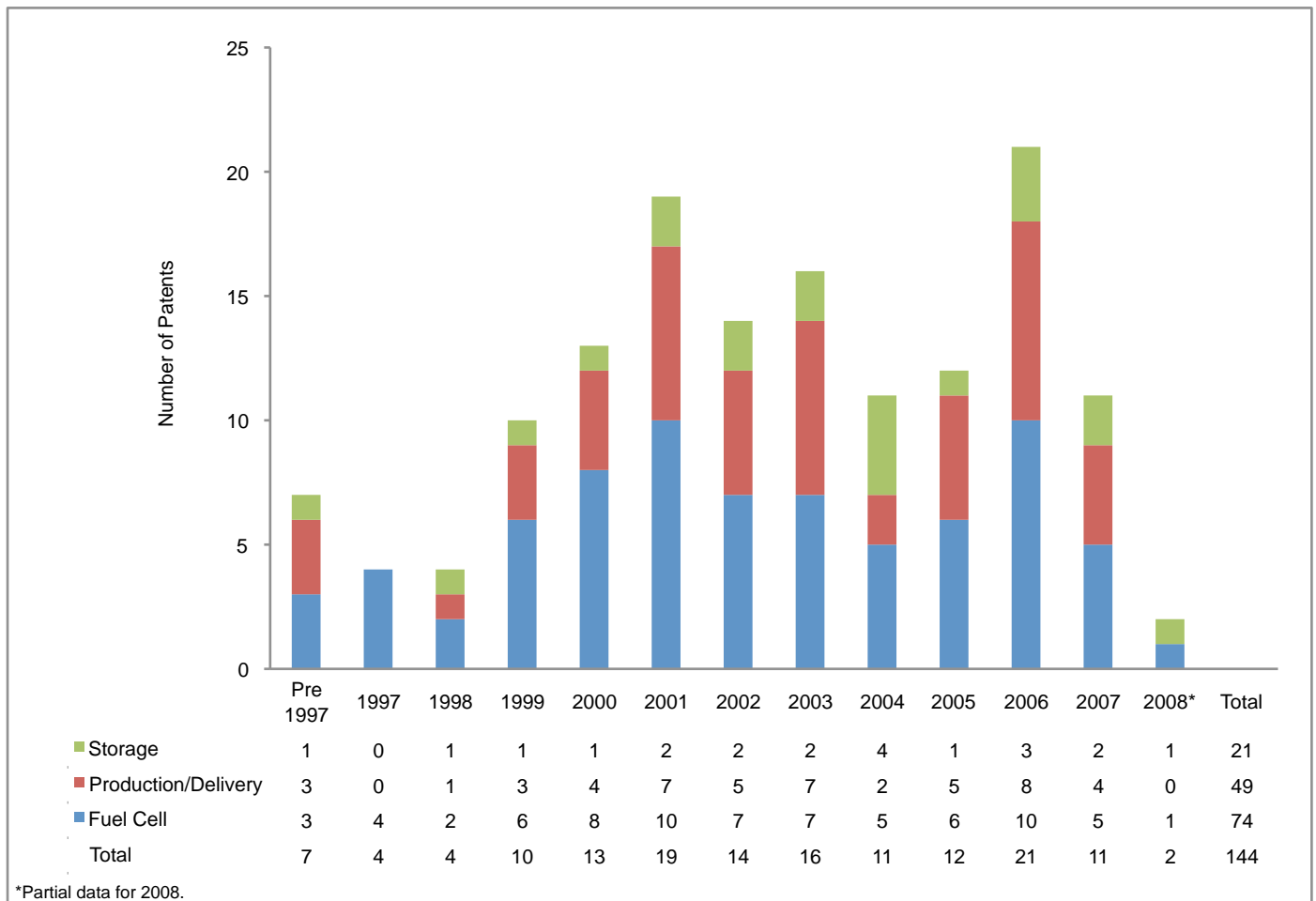
## 3.0 Results

The results of the efforts undertaken in the HFCIT Program technology tracking project are summarized in this chapter. Section 3.1 describes the patent search and analysis and Section 3.2 describes the results of the commercial and emerging technology identification and tracking effort.

### 3.1 Patent Search and Analysis

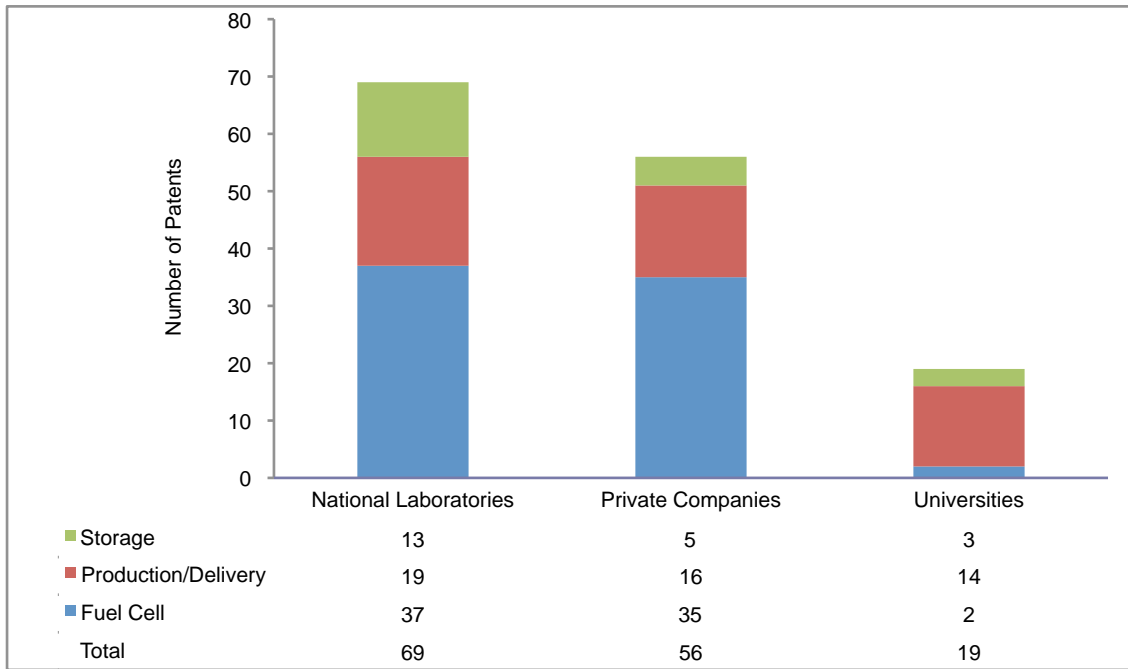
The results of the patent search are shown in tables in Appendix C; the 74 fuel cell patents are listed in Appendix C-1, the 49 production/delivery patents are listed in Appendix C-2, and the 21 storage patents are listed in Appendix C-3. The patent are listed in chronological order from the most recent to the oldest patent for each group. The tables list the patent number, award date, organization receiving the patent, patent title, patent description, and patent status.

Figure 3.1 shows the patents awarded in each year, starting with pre-1997 patent awards through 2007. As the figure shows, 2001 and 2006 had significantly more patents than the other years. This is due to both the fuel cell and production/delivery patents having their top two award years in 2001 and 2006. The storage patent awards are spread out over the entire period, with a peak of four awards in 2004.



**Figure 3.1. Number of Patents Awarded Over Time**

Another way to view the patent awards, shown in Figure 3.2, is by the type of organization that received the patent or the inventor's employer. Three types of organizations were identified: national laboratories (69 patents), private companies (56 patents), and universities (19 patents). The national laboratories had slightly more patent awards for fuel cell and production/delivery technologies than those awarded to private companies in these two areas. The national laboratories had 62% of the awards in the storage area. While the universities received fewer total patent awards, they had 74% of their patents in the production/delivery area. The national laboratories and private companies both received more than half of their patents in the fuel cell area.

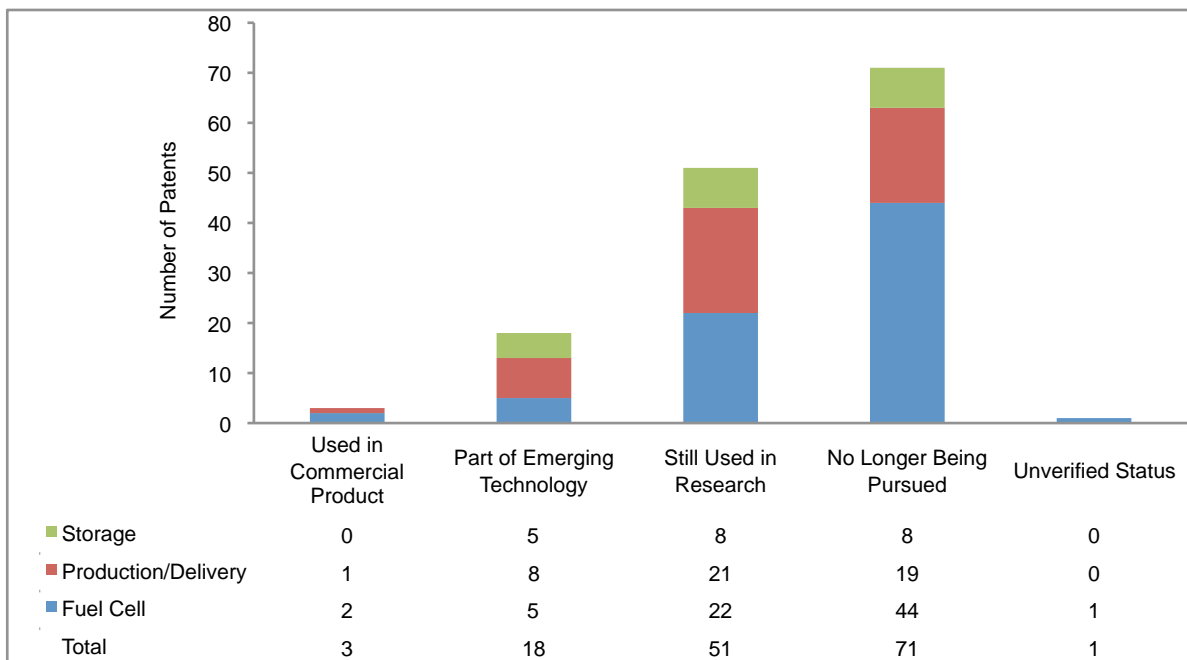


**Figure 3.2. Types of Organization Receiving Patent Awards**

Figure 3.3 shows the patent award status by use. As the figure shows, 3 patents are used in commercial products including:

- Control method for high-pressure hydrogen vehicle fueling station dispensers (Patent number 7,059,364)
- Composite bipolar plate for electrochemical cells (Patent number 6,248,467)
- Corrosion test cell for bipolar plates (Patent number 6,454,922).

And 18 are part of research now taking place on emerging technologies identified on the technology tracking list in Appendix A. In addition, 51 awarded patents are still being used in research that is more than 3 years from a commercial product. Of the patents reviewed, 50% are no longer being used in research. This was particularly true in the fuel cell area, where 44 of the 73 patents (60%) are no longer being used in research. However, this is not true in the storage or production/delivery area, where most of the patents are still being used in research.

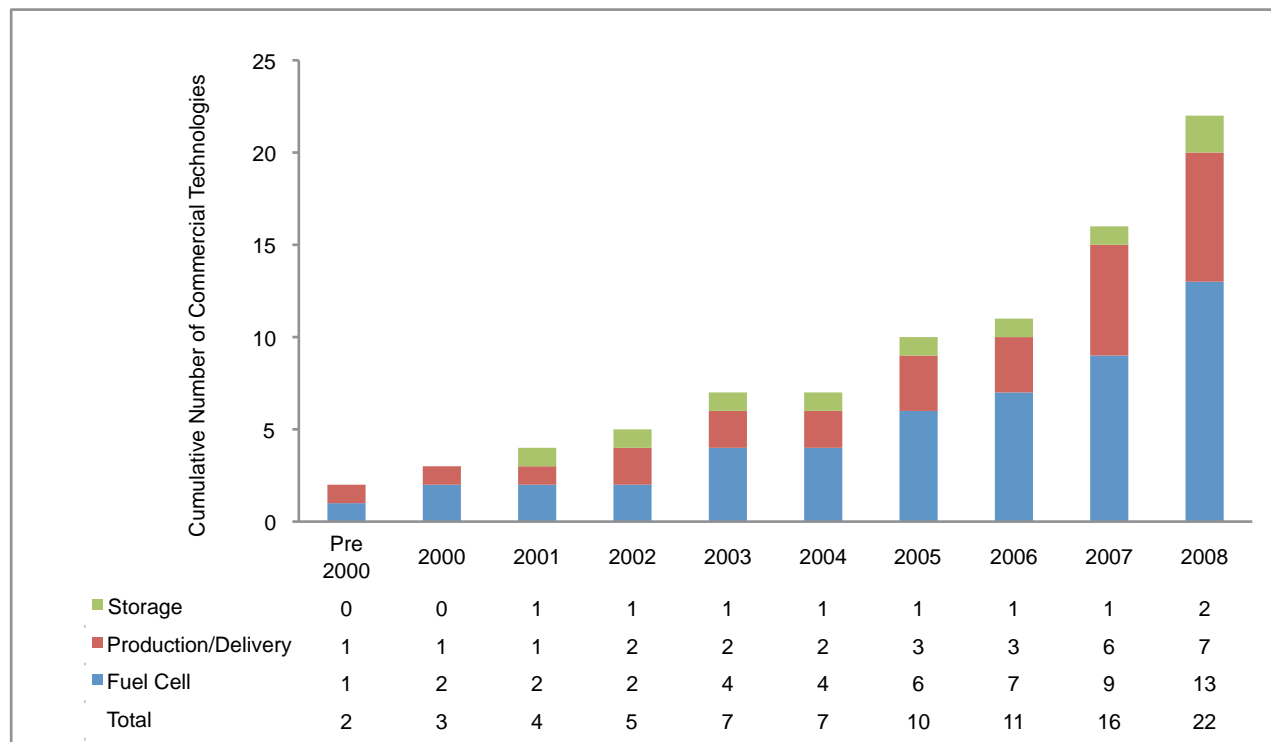


**Figure 3.3. Status of Awarded Patents**



## 3.2 Commercial and Emerging Technology Identification and Tracking Results

The HFCIT Program Technology Tracking Database contains 22 commercial technologies, all of which are described in Appendix D. These descriptions were reviewed and approved by the industry POC for each technology. Figure 3.4 shows the cumulative number of commercial technologies on the market. The years 2000 through 2006 showed a steady addition of technologies entering the market of one to three per year. In 2007 four technologies entered the market, and in 2008 three technologies have done so.



**Figure 3.4. Cumulative Number of Commercial Technologies on the Market**

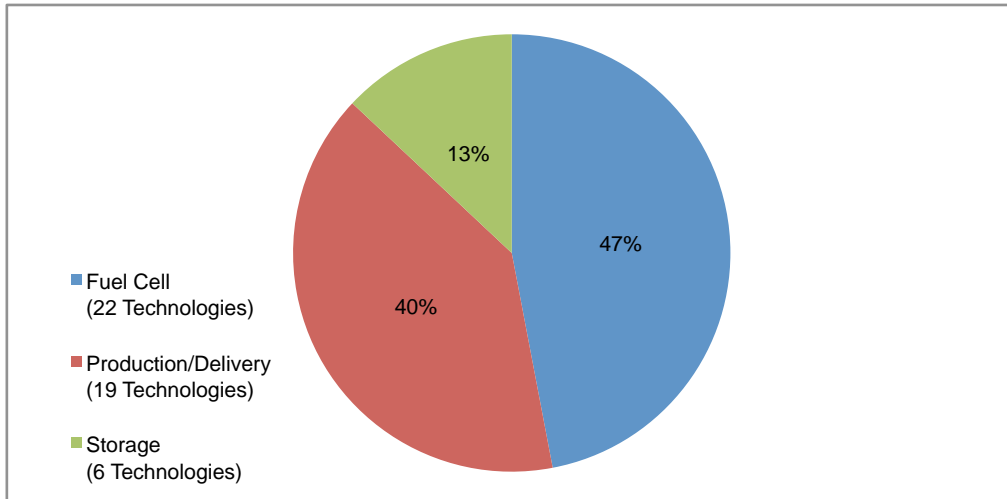
Table 3.1 briefly describes each of the 13 commercial fuel cell technologies and their benefits. The full descriptions of these technologies are provided in Appendix D-1. These technologies range from an analysis tool to manufacturing processes for fuel cells and their components to entire fuel cell systems that can be used in vehicles or stationary applications.

Table 3.2 briefly describes each of the 7 commercial production/delivery technologies and their benefits. The full descriptions of these technologies are provided in Appendix D-2. These technologies include improved catalysts, hydrogen generation systems for fueling vehicles, and technologies for providing high purity hydrogen.

Table 3.3 briefly describes the 2 commercial storage technologies and their benefits. The full descriptions of these technologies are provided in Appendix D-3. One of the technologies is a composite tank and the other is an improved screening method for hydrogen tanks/cylinders.

The HFCIT Program's Multi-Year Research, Development and Demonstration Plan, which was last updated in October 2007, was examined to see how the commercial technologies align with the HFCIT Program's objectives and goals. The plan lists challenges and approaches for the research areas funded by HFCIT. The fuel cell area listed 19 challenges. The 13 commercial technologies in Table 3.1 are aligned with 8 of these challenges, as Table 3.4 shows. Similarly, the 7 commercial production/delivery technologies in Table 3.2 were found to align with 2 of the 7 challenges in that area, as Table 3.5 shows. The 2 commercial storage technologies in Table 3.3 were found to align with 1 of the 7 storage approaches, as Table 3.6 shows.

The technology tracking database contains 47 emerging technologies for which descriptions are provided in Appendix E. These were reviewed and approved by the industry POC for each technology. Figure 3.5 shows the distribution of the emerging technologies in the three HFCIT research areas. As shown, there is an almost equal number of emerging technologies between the fuel cell and production/delivery areas with the storage area having far fewer emerging technologies.



**Figure 3.5. Distribution of Emerging HFCIT Technologies**

Table 3.7 briefly describes each of the 22 emerging fuel cell technologies and their benefits. The full descriptions of these technologies are provided in Appendix E-1. These technologies are quite diverse and include improved fuel cell components, such as membranes, plates, assemblies, cathodes and sensors, as well as entire systems for various uses.

Table 3.8 briefly describes each of the 19 emerging production/delivery technologies and their benefits. The full descriptions of these technologies are provided in Appendix E-2. These technologies include improved membranes, reformers, and compressors, as well as novel methods and fuels to produce hydrogen.

Table 3.9 briefly describes each of the 6 emerging storage technologies and their benefits. The full descriptions of these technologies are provided in Appendix E-3. These technologies include improved tanks or cylinders, as well as new approaches for storing hydrogen.

The 22 emerging fuel cell technologies in Table 3.7 are aligned with 14 of the 19 fuel cell challenges in the HFCIT Program plan, as Table 3.10 shows. Also, 3 challenges in the manufacturing research area of the plan for PEM fuel cells are aligned with 3 emerging fuel cell technologies. Similarly, the 19 emerging production/delivery technologies in Table 3.8 are aligned with 8 of the 13 production and delivery challenges in the plan, as Table 3.11 shows. The 6 emerging storage technologies in Table 3.9 are aligned with 3 of the 7 approaches in the storage area, as Table 3.12 shows.

**Table 3.1. Commercial Products Summary – Fuel Cells**

Technology	Organization	Description	Benefits	Commercial Status
Advanced MEAs for Enhanced Operating Conditions	3M Company	The advanced MEA uses a carbon-free nanostructured thin-film catalyst and an ion exchange membrane to achieve longer lifetimes using fewer precious metals.	The technology reduces costs because of lower precious metal loading and manufacturing costs, improved durability, and smaller fuel cell size. It can operate at higher temperatures and lower humidity.	Commercialized in 2007 and selling to select fuel cell developers.
Breakthrough Lifetime Improvements for PEM Fuel Cells	DuPont Fuel Cells	The Nafion® polymer technology, which can be used for both PEM fuel cells and water electrolyzers, reduces the reactive centers within the polymer to combat chemical degradation, leading to increased stability and longer life.	The technology reduces costs because of greater membrane durability and lifetime.	Commercialized in 2005.
Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.	The compound is a graphitized thermoset vinyl-ester, which is molded and used in producing bipolar plate (BPP) assemblies. (This technology was based on a technology licensed from Los Alamos National Laboratory.)	The compound allows thinner and less-expensive BPP assemblies to be produced; eliminates the need for expensive corrosion-resistant coatings; provides greater part flatness, creep resistance, and dimensional stability; and facilitates large-volume commercial production.	Commercialized in 2000, with 222,929 lb. sold in 2007.
Corrosion Test Cell for PEM Bipolar Plate Materials	Fuel Cell Technologies, Inc.	To screen materials that could be used in producing corrosion-resistant bipolar plates (BPPs), the test cell simulates, as closely as possible, the conditions at the anode and cathode of a PEM fuel cell. (This technology was based on a technology licensed from Los Alamos National Laboratory.)	The test cell reduces the costs of traditional fuel cell corrosion tests, shortens the fuel cell development time, and allows for an intermediate level of BPP material screening between potentiostatic measurements and long-term fuel cell tests.	Commercialized in 2008, with two units sold.
GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory	The GCtool allows designers to model, analyze, and manipulate different configurations of fuel cell propulsion systems without building a functional prototype in order to address issues such as thermal and water management, design-point and part-load operations, and fuel economies.	The model saves users time and money while exploring various fuel cell system configurations. It provides developers with a library of models for subcomponents and allows them to incorporate their own models.	Sold more than 67 licenses since 1999.
GenCore® Backup Fuel Cell Systems	Plug Power Inc.	The backup fuel cell system provides instant power for up to 11 hours during a grid outage and longer if additional hydrogen is supplied.	The system provides modular designs to enable multiple units to be installed at one location and provides a silent, nonpolluting power system with low maintenance and instant startup.	Deployed 20 units at five New Mexico National Guard facilities in 2008.
Improved Catalyst Coated Membrane (CCM) Manufacturing	Cabot Corporation	The spray deposition technology uses special electrocatalyst inks and a simple manufacturing process that allows for high-volume production with a lower platinum content compared with other techniques.	The system reduces manufacturing and raw material costs. It can be used with existing spray deposition systems and allows quick changeover to different materials.	Manufacturing technology is now available for licensing, and the associated electrocatalyst inks and catalyst powders were made commercially available in 2008.

**Table 3.1. Commercial Products Summary – Fuel Cells (Cont'd)**

Technology	Organization	Description	Benefits	Commercial Status
Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods (SBIR Project)	NuVant Systems Inc.	The MEA testing equipment is composed of two devices, an array potentiostat (Arraystat™) and a parallel array flow-field fuel cell, which allow rapid, accurate testing under realistic operating conditions.	The equipment allows for the preparation and testing of various MEAs in a single test stand with high throughput under realistic catalyst loadings and reactant flow rates. This eliminates random error introduced by multiple test stands and reduces the costs associated with testing MEAs.	The Arraystat was commercialized in 2006 and the parallel array fuel cell in 2007. To date six Arraystats and seven parallel array fuel cell test units have been sold.
Integrated Manufacturing for Advanced Membrane Electrode Assemblies	BASF Fuel Cell, Inc.	The advanced MEA fabrication process uses a new gas diffusion electrode that incorporates a “fine gradient” ELAT® electrode to develop assemblies that run longer with stable voltages.	The process decreases the amount of precious metal used and reduces fabrication costs. The resulting assemblies exhibit improved stability and allow operation at extreme temperature and humidity levels.	Currently marketing products such as catalysts, gaseous diffusion layer/gas diffusion electrodes, and MEAs for direct methanol fuel cells.
Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation	The one-step molding process creates the structure necessary to seal the stack and five layer MEAs. Two portable power system product lines are now using it: the Quantum™ line for commercial users and the Pulse™ line for military customers.	The process lowers costs because fewer components with lower tolerances are used. It reduces part count and manufacturing time and improves stack fabrication reliability.	Delivered 10 Pulse systems on a military contract in 2008.
PureMotion® 120 Fuel Cell Powerplant	UTC Power	The powerplant can be used as a power source for hydrogen-powered vehicles or as a stationary, 120-kW power source.	The power system reduces costs through mass manufacturing, produces only water as a byproduct, and uses hydrogen produced from various sources, including renewables.	First unit deployed in 2005 with six units now in use on buses.
Scale-Up of Carbon-Carbon Composite Bipolar Plates	Porvair Advanced Materials, Inc.	A carbon-carbon composite bipolar plate (BPP) formation technology was licensed and transferred from laboratory to full-scale production to produce low-cost BPPs using high-volume manufacturing with no machining. (This technology was based on a technology licensed from Oak Ridge National Laboratory.)	The resulting BPPs minimize contact resistance between cells, resist corrosion, are lightweight (1.2 grams per cc), and cost <\$4 per kW. The process allows for molding a wide variety of product designs.	Manufactured more than 50,000 BPPs from 2003 – 2008; manufactured more than 10,000 BPPs since 2007.
XX25™: Portable Reformed Methanol Fuel Cell	UltraCell Corporation	The XX25 fuel cell, using methanol as a fuel source, is a self-contained, 25-watt output power system that can be used by individual soldiers for portable power. Fuel cartridges can be hot swapped for continuous operation, and the fuel cell can be hybridized with external batteries for high power peaks or with a 5-gallon fuel tank for long run time.	The fuel cell features a rugged, lightweight (1.24 kg), reliable power system that uses a contained fuel with no toxic byproducts during use. It contains no moving parts that can fail.	Commercialized in 2007, with more than 200 units sold.

**Table 3.2. Commercial Products Summary – Production/Delivery**

Technology	Organization	Description	Benefits	Commercial Status
FuelGen® Hydrogen Fueling Systems	Proton Energy Systems, Inc.	The fueling station uses electrolysis to produce 99.999% pure hydrogen from water using electricity, which can come from wind or solar energy. The system can generate over 13 kg per day at pressures up to 400 psi.	The system produces high purity hydrogen without requiring additional cleanup, can be installed and operating within a day, requires only four hours of maintenance per year, and can use renewable energy sources.	Commercialized in 2007, with three units sold.
H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	GreenField Compression	The integrated, on-site hydrogen generation, purification, compression, storage, and dispensing system deploys quickly and produces 20 to 200 kg of hydrogen per day by reforming natural gas, propane, E-85, biodiesel, or other liquids. Alternatively, it can use electrolysis for hydrogen production. The dispenser can be purchased individually or as part of the system.	The system can produce hydrogen from various sources, achieves full-cycle energy savings compared with trucked-in hydrogen, and is delivered as a pre-assembled system, thereby minimizing costs and setup time.	Commercialized in 2007, with one fuel station in use at the University of Texas in Austin.
High-Efficiency, High-Pressure Electrolysis via Photovoltaic Arrays	Avalence, LLC	The system links a photovoltaic power supply to an ultra-high-pressure electrolysis unit that can generate 1 to 30 kg of fuel-grade hydrogen per day at pressures consistent with point-of-use storage and delivery (5,000 to 10,000 psi).	The system delivers pressurized hydrogen without additional compression and can potentially reduce hydrogen production and operating costs.	Commercialized in 2007, with 4 units sold and operating in the field and several more in production.
Hydrogen Distributed Production System	H <sub>2</sub> Gen Innovations, Inc.	The HGM-2000 uses a built-in pressure swing adsorption system that produces 565 kg of hydrogen per day at 200 to 300 psig at a fuel efficiency of up to 78% (based on the higher heating value).	The system cuts high-purity hydrogen costs by up to 50% compared with trucked-in hydrogen, is highly efficient, and uses a modular design that eliminates the need for large-scale hydrogen infrastructure. It allows remote monitoring without the need for staffing.	Became commercially available in 2008.
Hydrogen Generation from Electrolysis	Proton Energy Systems, Inc.	The HOGEN® electrolysis-based hydrogen generator incorporates a PEM and produces 99.999% pure hydrogen at 90 to 275 grams per hour at pressures up to 400 psi without requiring additional compression.	The system is very compact, can be installed in less than a day, is very reliable, and produces high-purity hydrogen.	Commercialized the HOGEN S series in 1999, selling 282 units in the U.S. and 121 internationally through 2007. Commercialized the HOGEN H series in 2004, selling 82 units in the U.S. and 37 internationally through 2007.
ME100 Methanol Reforming Hydrogen Generator (SBIR Project)	REB Research & Consulting	The generator is constructed with palladium-coated membranes within the reactor zone and can produce 99.99995% pure hydrogen independent of back-pressure changes or variable loads at a variable rate of up to 10 kg per day at pressures up to 40 psig.	The generator produces very high purity independent of back pressure changes caused by varying fuel cell demand. It produces hydrogen at costs far lower than bottled gas from a readily available feedstock (methanol). The system is compact, reliable, and ideal for remote and mobile applications.	More than 15 ME100 hydrogen generator systems sold since 2002.

**Table 3.2. Commercial Products Summary – Production/Delivery (Cont'd)**

Technology	Organization	Description	Benefits	Commercial Status
Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.	The water gas shift catalysts are based on ceria-supported precious metals that can be tailored to specific reactions/ conditions (i.e., steam reforming and/or the partial oxidation of various hydrocarbons) and can be used for small reactors and/or reactors with multiple startup-shutdown cycles.	The catalysts are available in multiple forms and allow applications to perform efficiently over a wide range of temperatures.	Commercialized in 2005 with >\$200,000 in sales to date.

**Table 3.3. Commercial Products Summary – Storage**

Technology	Organization	Description	Benefits	Commercial Status
Hydrogen Composite Tanks	Quantum Fuel Systems Technologies Worldwide, Inc.	For storage applications at 5,000 and 10,000 psig, the hydrogen tank uses a seamless, one-piece, ultra-high-molecular-weight polymer liner wrapped in layers of a carbon fiber/epoxy laminate and a proprietary external protective layer for impact resistance.	The 10,000-psig tank offers a high-capacity, lightweight, safe hydrogen storage system that exceeds regulatory safety requirements and may increase a hydrogen-powered vehicle's driving range by >55% compared with equivalent-sized 5,000-psig tanks.	Since 2001, sold more than 2,000 storage tank systems, primarily to major automobile manufacturers.
Non-Destructive Ultrasonic Scanning Technology	Digital Wave Corporation	The nondestructive testing method uses sound waves and stacks of polyvinylidene film piezoelectric transducers that can rapidly detect a wide range of flaws in various materials, including metals, polymers, ceramics, and composites.	The testing method rapidly and accurately detects flaws before they cause catastrophic failure and tests a wide range of cylinder geometries and material types.	Commercialized in 2008.

**Table 3.4. Fuel Cell Challenges and Related Commercial Technologies**

Challenges*	Technology Title	Organization
Develop membranes that meet all targets	Breakthrough Lifetime Improvements for PEM Fuel Cells	DuPont Fuel Cells
	Improved Catalyst Coated Membrane (CCM) Manufacturing	Cabot Corporation
Develop MEAs that meet all targets	Advanced MEAs for Enhanced Operating Conditions	3M Company
	Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems Inc.
	Integrated Manufacturing for Advanced Membrane Electrode Assemblies	BASF Fuel Cell, Inc.
Develop low-cost, durable bipolar plates that meet all targets	Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.
	Scale-Up of Carbon-Carbon Composite Bipolar Plates	Porvair Advanced Materials, Inc.
Develop cost-effective, efficient, reliable and durable fuel cells for stationary applications that meet all targets	GenCore® Backup Fuel Cell Systems	Plug Power Inc.
	PureMotion® 120 Fuel Cell Powerplant	UTC Power
Develop cost-effective, reliable, durable fuel cells for portable power applications (e.g., cell phones, computers, etc.) that meet all targets	XX25™: Portable Reformed Methanol Fuel Cell	UltraCell Corporation
Conduct system and tradeoff analysis	GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory
Test and evaluate fuel cell components and systems	Corrosion Test Cell for PEM Bipolar Plate Materials	Fuel Cell Technologies, Inc.
Develop innovative fuel cell designs that provide improved performance, durability and cost	Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation

\* Note: These challenges are described in the HFCIT Program Multi-Year Plan at [http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel\\_cells.pdf](http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf).

**Table 3.5. Production/Delivery Challenges and Related Commercial Technologies**

Challenges*	Technology Title	Organization
Cost reduction of distributed hydrogen production from natural gas and bio-derived liquids	H <sub>2</sub> ProGen: A Total Supply Solution for Hydrogen Vehicles	GreenField Compression
	Hydrogen Distributed Production System	H <sub>2</sub> Gen Innovations, Inc.
	ME100 Methanol Reforming Hydrogen Generator	REB Research & Consulting
	Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.
Hydrogen production from water via electrolysis	FuelGen® Hydrogen Fueling Systems	Proton Energy Systems, Inc.
	High-Efficiency, High-Pressure Electrolysis via Photovoltaic Arrays	Avalence, LLC
	Hydrogen Generation from Electrolysis	Proton Energy Systems, Inc.

\* Note: These challenges are described in the HFCIT Program Multi-Year Plan at <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf>.

**Table 3.6. Storage Approaches and Related Commercial Technologies**

Approaches*	Technology Title	Organization
Compressed, cryo-compressed and conformal hydrogen tanks	Hydrogen Composite Tanks	Quantum Fuel Systems Technologies Worldwide, Inc.
	Non-Destructive Ultrasonic Scanning Technology	Digital Wave Corporation

\* Note: The storage approaches are described in the HFCIT Program Multi-Year Plan at <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/storage.pdf>.



**Table 3.7. Emerging Products Summary – Fuel Cells**

Technology	Organization	Description	Benefits
Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.	The advanced, complex coolant fluid consists of a base mixture and additives of non-ionic corrosion inhibitors and ion-suppressing nanoparticles, which maintain low electrical conductivity.	The technology may eliminate de-ionizing filters, thereby reducing the overall cost and maintenance of the fuel cell while increasing the amount of time the cell can run continuously.
Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc.	The steam reforming module for producing hydrogen is designed to be cyclable (daily start/stop for 5 years) and runs at low pressure.	The system can produce a low-cost supply of hydrogen (compared with bottles) and can minimize thermal cycling induced stress and exposure, thus increasing the lifetime of the module.
Dimensionally-Stable High-Performance Membrane (SBIR Project)	Giner Electrochemical Systems, LLC	The robust PEM material uses a high-performance plastic support structure, which allows lower-equivalent-weight ionomers to be used without forfeiting mechanical durability.	Because of its mechanical properties, the new membrane prevents stress-induced failure and improves performance at low humidity and high temperature.
Direct Methanol Fuel Cell for Handheld Electronics Applications	MTI Micro Fuel Cells, Inc.	The Mobion® direct methanol fuel cell (DMFC) uses passive means for water and air management to simplify the conventional DMFC process, resulting in a smaller and simpler fuel cell for handheld applications.	The device uses methanol fuel instead of hydrogen, avoiding hydrogen-handling issues. Using micro fuel cells for handheld electronics may extend device operating times between charges and enhance device versatility.
Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors (SBIR Project)	InnoSense, LLC	The hydrogen sensor was developed using high-output, inkjet printing manufacturing techniques and detects hydrogen at concentrations from 1% to 75%.	The high-volume fabrication process produces safe, all-optical sensors and eliminates the individual calibration of sensors by making many identical sensors in one batch.
Fuel Cell Membrane Measurement System for Manufacturing (SBIR Project)	Scribner Associates, Inc.	The Rapid Membrane Measurement System uses a proprietary electrode design for robust long-term operation, custom measurement and control hardware and software, and state-of-the-art electrochemical measurement methods.	The system rapidly (a few minutes per test) and accurately measures the through-thickness ionic resistance of fuel cell membranes under controlled temperatures and humidity and may allow for more consistent results, higher productivity, and lower manufacturing costs because of waste reduction.
High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders	Applying an approach to formulate and test low-Pt cathodes has led to six Pt-alloy compositions that demonstrate up to a two-fold improvement in performance compared with pure Pt electrocatalysts.	Reducing Pt in cathodes reduces costs (Pt is very expensive), and in some cases, improves performance and durability. The new formulation and testing approach allow rapid synthesis and testing of electrocatalysts, thus reducing research costs.
High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.	The composite fuel cell membrane has enhanced ionic conductivity and mechanical properties, allowing the fuel cell to retain water and maintain proton conductivity and mechanical integrity at low humidities and elevated temperatures.	The membrane improves fuel cell durability, reduces system costs, and improves performance over extreme and fluctuating humidity and temperature conditions.
Improved Low-Cost, Durable Fuel Cell Membranes	Arkema Inc.	The fuel cell membrane technology uses semi-interpenetrated networks of Kynar® polyvinylidene fluoride and proprietary polyelectrolytes to decouple proton conductivity from all other requirements.	The membrane offers good mechanical properties, excellent resistance to hydrogen and oxygen, similar ex-situ conductivity to that of Nafion®, excellent durability in cycling tests, and a low cost potential.

**Table 3.7. Emerging Products Summary – Fuel Cells (Cont'd)**

<b>Technology</b>	<b>Organization</b>	<b>Description</b>	<b>Benefits</b>
Low-Cost Co-Production of Hydrogen and Electricity	Bloom Energy Corporation	A solid oxide fuel cell (SOFC) and an electrochemical hydrogen pump are being integrated to co-produce hydrogen and electricity. The H <sub>2</sub> pump processes the waste gas from the SOFC to form pure hydrogen that can be used in a PEM fuel cell or recycled to increase the efficiency of the SOFC.	The technology reduces the amount of natural gas used by extracting hydrogen from the SOFC's waste gas. Overall, energy efficiency is improved.
Low-Cost Hydrogen Sensor for Transportation Safety	Makel Engineering, Inc.	The micro electromechanical systems hydrogen sensor system incorporates a highly sensitive Schottky diode made of a palladium alloy on a silicon substrate for measurements in the low concentration range (50 ppm to a few percent). It can provide low-cost hydrogen leak monitoring in fuel cell vehicles, stationary fuel cells, or other areas where hydrogen leaks might occur.	The sensor is low-cost and compact, has low power consumption, can be mass-produced, and operates in suboptimal environmental conditions.
Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells (SBIR Project)	Nanotek Instruments, Inc.	A new system is being developed to produce low-cost/high-performance bipolar plates for fuel cells using sheet molding compound manufacturing techniques. Use of the new roll-to-roll system for producing multiple layer bipolar plates will allow large-scale manufacturing.	The new system optimizes the composition and forming process, improving the performance of the bipolar plates while reducing the manufacturing cost.
Low Platinum Loading Fuel Cell Electro-catalysts	Brookhaven National Laboratory	The patented anode electrocatalysts have low platinum (Pt) loading that resists CO poisoning.	The electrocatalysts are cost effective to fabricate because of the extensive use of noble metals (rather than Pt) and are more durable, thereby promising an improved fuel cell lifetime.
Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership	The seals, which will be used in fuel cell assemblies, use a custom elastomer and carrier material that provide an advanced interfacial design that exhibits superior chemical and mechanical properties compared with conventional silicons.	The seals increase durability, which will reduce fuel cell operation and maintenance costs, and eliminate catalyst poisoning concerns in the fuel cell. The system can be mass-produced and lead to shorter fuel cell assembly time.
Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.	The 1-kW modular, multi-fuel SOFC system is designed to produce electricity and heat for multiple mobile and on-site stationary applications.	The SOFC system is inherently flexible and sulfur tolerant and can operate on multiple renewable and conventional fuels, including biodiesel, vegetable oils, ethanol, diesel, kerosene, natural gas, and propane.
Nitrided Metallic Bipolar Plates for PEM Fuel Cells	Oak Ridge National Laboratory	The technique deposits a thin Cr-nitride coating on stainless steel bipolar plates to form an electrically conductive, defect-free, corrosion-resistant surface layer, even on complex surface geometries.	This technique allows for low-cost, high-volume production techniques that will reduce the net cost of fuel cells and improve their longevity and durability.
Off-Road Fuel Cell Applications	IdaTech, LLC	The methanol-powered PEM fuel cells are being tested in off-road vehicles to ensure they are able to survive shock, vibration, and airborne pollution.	Methanol-fueled off road vehicles use a clean, highly efficient, quiet fuel cell instead of a pollution-producing and noisy gasoline engine.

**Table 3.7. Emerging Products Summary – Fuel Cells (Cont'd)**

Technology	Organization	Description	Benefits
Platinum and Fluoropolymer Recovery from PEM Fuel Cells	Ion Power, Inc.	The process dissolves the used PEMs into a slurry, which is then processed to separate the Pt and Nafion® for re-use.	The process eliminates hydrofluoric acid emissions typical of other recycling methods in use today. It reduces PEM fuel cell replacement costs by recovering valuable materials from used cells.
Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC	The technology recovers >98% of the platinum from various MEAs, independent of MEA aging history, membrane construction, or electrocatalyst composition.	The technique eliminates the need for hydrofluoric acid remediation, and batching multiple fuel cell types eliminates manual separation labor in the recycling process.
Polymer Electrolyte Membrane (PEM) Fuel Cell Power Plant Development & Verification	UTC Power	A low-cost, high-durability stationary fuel cell uses a 5-kW system platform that is rack-mounted, weighs 100 kg, is self-contained (not including fuel), and consumes about 0.5 kg of hydrogen per 1.5 hours.	The system provides seamless, clean power during blackouts and is compact, reliable, and low maintenance.
Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd.	The bipolar plate uses expanded graphite in conjunction with an advanced high-temperature resin system that is designed for high-volume production.	The system results in improved gas impermeability, low contact resistance, high thermal/electrical conductivity, and improved mechanical strength. The plates continuously operate at temperatures up to 120°C.
Sensors for Automotive Fuel Cell Systems	NexTech Materials, Ltd.	The H <sub>2</sub> S sensor operates by a reversible change in resistance caused by adsorption and desorption of H <sub>2</sub> S in a film of H <sub>2</sub> S-sensitive material. It can detect H <sub>2</sub> S from 25 ppb to 10 ppm, with response times of less than one minute.	The sensor will detect H <sub>2</sub> S in the hydrogen stream, alerting operators so they can protect the cell stack from damage. This will increase membrane life, allow fuel cells to remain online longer, and extend the life of guard beds used to remove sulfur from hydrocarbon fuels before they are processed into hydrogen.

**Table 3.8. Emerging Products Summary – Production/Delivery**

Technology	Organization	Description	Benefits
High Performance Palladium-Based Membrane	Pall Corporation	The palladium-based membrane works as a selective barrier to let only H <sub>2</sub> pass through by using sophisticated high-temperature analysis and inorganic membrane development/manufacturing techniques.	The membrane can be economically integrated into the overall H <sub>2</sub> production process and is easily scalable to industrial applications.
Hydrogen Generation from Biomass-Derived Carbohydrates via Aqueous-Phase Reforming	Virent Energy Systems, Inc.	The BioForming™ process, using a proprietary catalyst that operates in the aqueous phase and has high hydrogen selectivity at low temperature, reforms water-soluble oxygenated-hydrocarbons in a single step and produces a hydrogen-rich gas that is easily purified.	The process allows hydrogen production from a range of carbon-neutral biomass sources and produces hydrogen at low temperatures without forming carbon monoxide.
Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.	A chemically stable carbon molecular sieve separates hydrogen from caustic streams that contain CO, CO <sub>2</sub> , H <sub>2</sub> S, and heavy hydrocarbons at stream temperatures above 250°C and pressures up to 1,500 psi.	The membrane offers a low-cost, mechanically durable option for hydrogen separation under harsh conditions and functions as a membrane reactor for water gas shift reactions.
Hydrogen Safety Sensor for Advanced Energy Applications	NexTech Materials, Ltd.	A chemi-resistive three-phase ceramic sensor exhibits a highly sensitive (500 ppm to 1%), selective (no interference from CO, CH <sub>4</sub> , or VOC), and rapid response to the presence of hydrogen in ambient air, even with varying humidities and background combustible gases.	Because of its low materials and fabrication cost, minimal power consumption, and wide detection range, the sensor lends itself to wide-scale implementation in any application requiring the safe use or handling of hydrogen gas. It is durable and reliable, with fast response and recovery times.
Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.	The hydrogen transport membrane features uniform small pores on the surface that enable a thin membrane layer to span the pores while larger pores in the bulk of the substrate provide strength to the membrane and do not restrict hydrogen flow.	The membranes help increase hydrogen yield, purity, and system energy efficiency and reduce capital costs. They are especially applicable to small, on-site hydrogen generators, such those located at fueling stations.
Integrated Hydrogen Production, Purification and Compression System	Linde Inc.	The technology produces high-purity hydrogen in a single step by using a membrane reformer that has elevated-temperature, H <sub>2</sub> -selective, palladium-alloy membrane modules immersed in a fluid bed reformer vessel. The reformer is combined with a novel hydride compressor to form an integrated reformer-compressor package. The waste heat from the reformer supplies part of the compression energy.	The system can generate hydrogen directly for vehicle fueling or other applications. It has lower capital costs compared with conventional processors and is energy efficient.
Integrated Short Contact Time Hydrogen Generator	GE Global Research Center	The technology integrates short contact time catalytic partial oxidation, steam reforming, and water gas shift catalysis into a single process (staged catalytic partial oxidation) in a compact reactor that can produce 60 kg of hydrogen per day.	The technology has relatively low operation temperatures that allow lower-cost stainless steel to be used, is relatively compact, is amenable to mass production, and provides efficiency gains and lower capital costs by staging and integrating three catalysts.
Low-Cost, High-Pressure Hydrogen Generator	Giner Electrochemical Systems, LLC	The technology simplifies an anode-side membrane support structure into a single-piece component having the required properties and tolerances.	The technology improves stack energy efficiency and power density while reducing part count and assembly costs.

**Table 3.8. Emerging Products Summary – Production/Delivery (Cont'd)**

Technology	Organization	Description	Benefits
Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	UC Berkeley	The technique involves genetically engineering the length of the chlorophyll “antenna” of a strain of algae to prevent over-absorption at the surface, allowing sunlight to penetrate deeper into the culture, thereby decreasing the heat dissipation and increasing the light utilization efficiency of hydrogen production from 3% to 15%.	The technology generates carbon-neutral hydrogen from algae and sunlight without requiring fossil fuels.
Membrane Structures for Hydrogen Separation (SBIR Project)	Genesis Fueltech, Inc.	The low-cost membrane to separate hydrogen from other gases in the reforming process will be used in a purifier module that can be scaled to larger sizes to increase capacity.	The low-cost purifier has improved mechanical support and sealing, as well as improved alloys for higher hydrogen flux.
Novel Catalytic Fuel Reforming	InnovaTek, Inc.	The hydrogen generator reforms multiple fuel types (natural gas, gasoline, and diesel) to produce pure hydrogen by integrating microreactor and microchannel heat exchanger technology with advanced sulfur-tolerant catalysts and membranes.	The generator system can produce 30 to 150 grams of hydrogen per hour that can be used to fuel a 1- to 5-kW polymer electrolyte membrane fuel cell or other auxiliary power unit.
Novel Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.	During hydrogen production via steam reforming, a drop-in replacement for the loose ceramic media eliminates the periodic replacement required in conventional ceramic packed beds.	The drop-in replacements lower costs, increase performance, and minimize maintenance costs and inconveniences.
Oil Free Hydrogen Compressor (SBIR Project)	Mohawk Innovative Technology, Inc.	The oil-free, high-speed centrifugal compressor uses advanced compliant surface foil gas bearings and seals, engineered coatings in conjunction with advanced high-speed drives, and centrifugal compressors.	The technology reduces capital, maintenance, and operating costs of compressors; improves compressor reliability and efficiency; and eliminates the potential for hydrogen contamination for sensitive hydrogen-consuming devices such as fuel cells.
Photoelectrochemical Hydrogen Production	University of Hawaii	Five material classes have been studied, with a focus on understanding and improving photoelectrochemical (PEC) behavior and identifying relevant aspects of structural, optoelectronic, and electrochemical properties of PEC target films.	Advanced PEC hydrogen production systems allow pollution-free, sustainable, and renewable hydrogen synthesis.
Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory	The approach reduces the impact of the inherent variability of renewable energy production by storing excess energy in the form of hydrogen. Varying renewable sources are being matched to the DC requirements of multiple alkaline and PEM electrolyzer stacks.	Coupling hydrogen production to renewable energy production allows for greater renewable energy infrastructure penetration and pollution-free production of energy.
Reversible Liquid Carriers	Air Products and Chemicals, Inc.	This technology deploys a fully reversible liquid carrier that can be readily hydrogenated, transported to a distribution center, and then catalytically dehydrogenated to provide hydrogen gas to an end use such as fuel cells.	The technology increases catalyst efficiency and allows thermodynamically favorable liquid carriers to be deployed.

**Table 3.8. Emerging Products Summary – Production/Delivery (Cont'd)**

Technology	Organization	Description	Benefits
Scalable Steam Methane Reformer System for Distributed Hydrogen	Catacel Corp.	The system provides a platform for service station hydrogen production and may be configured to produce 20 kg of hydrogen per day, is fully scalable to commercial sizes, and has a target of producing hydrogen for \$2.50/gge.	The system may lower capital costs, increase production performance, and allow operations to be scaled to customer specifications.
Solar-Thermal Production of Hydrogen Using Renewable Feedstock	Sundrop Fuels, Inc.	The system produces hydrogen by taking advantage of rapid chemical kinetics and favorable thermodynamics, and coupling an efficient solar collector and power reactor to the system.	The system reduces the demand and use of fossil fuels and demonstrates high conversion efficiency of feedstock to hydrogen and hydrogen-enriched fuels.
Turnkey Hydrogen Fueling Station	Air Products and Chemicals, Inc.	The hydrogen fueling station, based on a steam methane reformer with a capability of 50 nm <sup>3</sup> /hr, can blend natural gas and hydrogen, compress hydrogen and hydrogen/natural gas blends, store the gas, and dispense up to 1500 kg of gas per day.	The station provides on-site production and delivery, fast fill rates, and accurate blending of hydrogen and compressed natural gas.



**Table 3.9. Emerging Products Summary – Storage**

Technology	Organization	Description	Benefits
Compressed Hydrogen Integrated Storage System	Johns Hopkins University Applied Physics Laboratory	The integrated storage system, made of composite-reinforced polyethylene, provides 5,000 to 10,000 psi service pressure and has enhanced safety features, such as a reinforced dome region and a gas control module.	The system can be mass produced at the targeted manufacturing costs, provides sufficient fuel storage for extended driving ranges (over 300 miles) without sacrificing passenger or cargo space, and provides safety measures to withstand crashes.
High-Strength, Low-Cost Microballoons for Hydrogen Storage	Powdermet, Inc.	The microballoons are fabricated from light-weight carbon and have high-strength, defect-free coatings capable of a theoretical hydrogen storage capacity of >12 wt%, a burst strength >15,000 psig, and exceptional crush strength. The microballoons act as a scaffold for an impermeable barrier made of high-strength material.	The microballoons produce harmless waste products after hydrogen is released, may prove to be easily transportable, and flow like water to conform to any shape container.
Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory	The cryo-compressed hydrogen storage tank maintains high energy density without evaporative losses, requires fewer carbon fiber construction materials, and can store either compressed or liquid hydrogen.	The storage tank has a 500-mile range, can be dormant for extended periods without losing fuel from the tank, and has demonstrated an improved thermal endurance compared with low-pressure vessels.
Low-Cost Materials, High-Efficiency, High-Pressure Hydrogen Storage	Quantum Technologies, Inc.	The optimized storage tank is being developed to reduce cost using cost-competitive composite materials that meet safety and energy storage density expectations and can be used in both stationary and portable environments.	The low-cost tanks are being designed to withstand cycling fatigue and to be safe and reliable.
Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.	The fabrication technique can create high-pressure storage tanks in less than 20 minutes to allow a production rate approaching vehicle production.	The automated system will dramatically reduce production time, lower costs, improve fabrication reliability and volumes, and provide safer failure modes compared with filament winding tanks.
Safe and Effective Storage and Transmission of Hydrogen	Safe Hydrogen, LLC	The chemical hydride technology uses the existing fossil fuel infrastructure to deliver and store a pumpable and nonexplosive magnesium hydride mineral oil slurry as a future hydrogen fuel.	The slurry delivers hydrogen without requiring significant energy, displays superior storage density compared with cryogenically cooled liquid hydrogen, and can be reused by recycling the byproducts.

**Table 3.10. Fuel Cell Challenges and Related Emerging Technologies**

<b>Challenges*</b>	<b>Technology Title</b>	<b>Organization</b>
Develop membranes that meet all targets	Dimensionally-Stable High-Performance Membrane	Giner Electrochemical Systems, LLC
	High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.
	Improved Low-Cost, Durable Fuel Cell Membranes	Arkema Inc.
Develop electrodes that meet all targets	High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders
	Low Platinum Loading Fuel Cell Electrocatalysts	Brookhaven National Laboratory
Develop MEAs that meet all targets	Platinum and Fluoropolymer Recovery from PET Fuel Cells	Ion Power, Inc.
	Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC
Develop low-cost, durable bipolar plates that meet all targets	Nitrided Metallic Bipolar Plates for PEM Fuel Cells	Oak Ridge National Laboratory
	Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd.
Develop reliable, durable, low-cost seals	Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
Develop efficient, cost-effective thermal/water management systems	Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.
Develop effective, reliable physical and chemical sensors that meet all targets	Low-Cost Hydrogen Sensor for Transportation Safety	Makel Engineering, Inc.
	Sensors for Automotive Fuel Cell Systems	NexTech Materials, Ltd.
Develop cost-effective, efficient, reliable and durable fuel cells for stationary applications that meet all targets	Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc.
	Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.
	Polymer Electrolyte Membrane (PEM) Fuel Cell Power Plant Development & Verification	UTC Power
Develop cost-effective, reliable, durable fuel cells for portable power applications (e.g., cell phones, computers, etc.) that meet all targets	Direct Methanol Fuel Cell for Handheld Electronics Applications	MTI Micro Fuel Cells, Inc.
Develop system to allow PEM fuel cells to operate in off-road applications	Off-Road Fuel Cell Applications	IdaTech, LLC
Stationary fuel cell demonstrations	Low-Cost Co-Production of Hydrogen and Electricity	Bloom Energy Corporation
Develop manufacturing processes for high-volume production of high-quality, uniform bipolar plates (Manufacturing PEM Fuel Cells Challenge)	Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells	Nanotek Instruments, Inc.
Reduce cost of PEM materials through improved manufacturing operations (Manufacturing PEM Fuel Cells Challenge)	Fuel Cell Membrane Measurement System for Manufacturing	Scribner Associates, Inc.
Develop sensors to monitor performance of fuel cell and fuel cell leakage (Manufacturing PEM Fuel Cells Challenge)	Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors	InnoSense, LLC

\* Note: The challenges are described in the HFCIT Program Multi-Year Plan for fuel cells at [http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel\\_cells.pdf](http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf) and manufacturing at <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/manufacturing.pdf>.



**Table 3.11. Production and Delivery Challenges and Related Emerging Technologies**

<b>Challenges*</b>	<b>Technology Title</b>	<b>Organization</b>
Cost reduction of distributed hydrogen production from natural gas and bio-derived liquids	Hydrogen Generation from Biomass-Derived Carbohydrates via Aqueous-Phase Reforming	Virent Energy Systems, Inc.
	Integrated Hydrogen Production, Purification and Compression System	Linde Inc.
	Integrated Short Contact Time Hydrogen Generator	GE Global Research Center
	Novel Catalytic Fuel Reforming	InnovaTek, Inc.
	Novel Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.
	Scalable Steam Methane Reformer System for Distributed Hydrogen	Catacel Corp.
	Turnkey Hydrogen Fueling Station	Air Products and Chemicals, Inc.
Hydrogen production from water via electrolysis	Low-Cost, High-Pressure Hydrogen Generator	Giner Electrochemical Systems, LLC
	Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory
High-temperature, solar-driven thermochemical cycles for splitting water to produce hydrogen	Solar-Thermal Production of Hydrogen Using Renewable Feedstock	Sundrop Fuels, Inc.
Photoelectrochemical hydrogen production from water (direct water splitting)	Photoelectrochemical Hydrogen Production	University of Hawaii
Biological production of hydrogen	Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	UC Berkeley
Separation and purification systems	High Performance Palladium-Based Membrane	Pall Corporation
	Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.
	Hydrogen Safety Sensor for Advanced Energy Applications	NexTech Materials, Ltd.
	Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.
	Membrane Structures for Hydrogen Separation	Genesis Fueltech, Inc.
Develop carriers that can enable low cost hydrogen delivery	Reversible Liquid Carriers	Air Products and Chemicals, Inc.
Increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compression	Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.

\* Note: The challenges are described in the HFCIT Program Multi-Year Plan for production at <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf> and delivery at <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/delivery.pdf>.

**Table 3.12. Storage Approaches and Related Emerging Technologies**

Approaches*	Technology Title	Organization
Compressed, cryo-compressed and conformal hydrogen tanks	Compressed Hydrogen Integrated Storage System	Johns Hopkins University Applied Physics Laboratory
	Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory
	Low-Cost Materials, High-Efficiency, High-Pressure Hydrogen Storage	Quantum Technologies, Inc.
	Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.
Chemical hydrogen storage	Safe and Effective Storage and Transmission of Hydrogen	Safe Hydrogen, LLC
Additional new materials and conceptse	High-Strength, Low-Cost Microballoons for Hydrogen Storage	Powdermet, Inc.

\* Note: The approaches are described in the HFCIT Program Multi-Year Plan for storage at <http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/storage.pdf>.

# Appendix A: Technology Tracking List

Technology Tracking List.....A-2

## Fuel Cell Technologies

Technology Title	Company
50-kW (net) Integrated Fuel Cell Power Systems	UTC Fuel Cells
Advanced Buildings PEM Fuel Cell System	IdaTech LLC
Advanced High-Efficiency Quick-Start Fuel Processor for Transportation Applications	Nuvera Fuel Cells, Inc.
Advanced MEAs for Enhanced Operating Conditions	3M Co.
Breakthrough Lifetime Improvements for PEM Fuel Cells	DuPont Fuel Cells
Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.
Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.
Corrosion Test Cell for PEM Bipolar Plate Materials	Fuel Cell Technologies, Inc.
Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc.
Dimensionally-Stable High-Performance Membrane	Giner Electrochemical Systems, LLC
Direct Methanol Fuel Cell for Handheld Electronics Applications	MTI Micro Fuel Cells, Inc.
Direct Methanol Fuel Cell Power Supply for All-Day True Wireless Mobile Computing	PolyFuel, Inc.
Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors	InnoSense, LLC
Fuel Cell Membrane Measurement System for Manufacturing	Scribner Associates, Inc.
GCtool: Fuel Cell Systems Analysis Software Model	ANL
GenCore® Backup Fuel Cell Systems	Plug Power Inc.
High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders
High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.
Improved Catalyst Coated Membrane (CCM) Manufacturing	Cabot Corporation
Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems Inc.
Improved Low-Cost, Durable Fuel Cell Membranes	Arkema Inc.
Integrated Manufacturing for Advanced Membrane Electrode Assemblies	BASF Fuel Cell, Inc.
Low-Cost Co-Production of Hydrogen and Electricity	Bloom Energy Corp.
Low-Cost Hydrogen Sensor for Transportation Safety	Makel Engineering, Inc.
Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells	Nanotek Instruments, Inc.
Low Platinum Loading Fuel Cell Electrolyzers	BNL
Manufacturable Chemical Hydride Cartridges for Hydrogen Fuel Systems	Millennium Cell, Inc.
Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.
Nitrided Metallic Bipolar Plates for PEM Fuel Cells	ORNL
Non-Nafion Membrane Electrode Assemblies	LANL
Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corp.
Off-Road Fuel Cell Applications	IdaTech, LLC
PEM Fuel Cell Freeze Durability and Cold-Start Project	UTC Power
Platinum and Fluoropolymer Recovery From PEM Fuel Cells	Ion Power, Inc.
Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC
Polymer Electrolyte Membrane (PEM) Fuel Cell Power Plant Development and Verification	UTC Power
PureMotion® 120 Fuel Cell Powerplant	UTC Power
Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd
Scale-Up of Carbon-Carbon Composite Bipolar Plates	Porvair Advanced Materials, Inc.
Sensors for Automotive Fuel Cell Systems	NexTech Materials, Ltd.
Selective Catalytic Oxidation of Hydrogen Sulfide	ORNL
Transition Metal/Chalcogen Based Cathode Catalysts for PEM Fuel Cells	Ballard Power Systems
XXX25™: Portable Reformed Methanol Fuel Cell	UltraCell Corp.

Technologies highlighted in red are commercial, blue are emerging, and green are not being pursued.

## Production/Delivery Technologies

Technology Title	Company
Alkaline, High Pressure Electrolysis	Teledyne Energy Systems, Inc.
Autothermal Cyclic Reforming Based H <sub>2</sub> Generating/Dispensing System	GE Global Research
FuelGen® Hydrogen Fueling Systems	Proton Energy Systems, Inc.
H <sub>2</sub> ProGen: A Total Supply Solution for Hydrogen Vehicles	GreenField Compression
High-Efficiency, High-Pressure Electrolysis via Photovoltaic Arrays	Avalance, LLC
High Performance Palladium-Based Membrane	Pall Corporation
Hydrogen Distributed Production System	H <sub>2</sub> Gen Innovations, Inc.
Hydrogen Fueled ICE Scooter with On-Board Metal Hydride Storage	Energy Conversion Devices, Inc.
Hydrogen Generation from Biomass-Derived Carbohydrates via Aqueous-Phase Reforming	Virent Energy Systems, Inc.
Hydrogen Generation from Electrolysis	Proton Energy Systems, Inc.
Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.
Hydrogen Safety Sensor for Advanced Energy Applications	NexTech Materials, Ltd.
Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.
Integrated Hydrogen Production, Purification and Compression System	Linde Inc.
Integrated Short Contact Time Hydrogen Generator	GE Global Research Center
Low-Cost, High-Pressure Hydrogen Generator	Giner Electrochemical Systems, LLC
Low Cost Hydrogen Production Platform	Praxair, Inc.
Manufacturing Improvements for Water Electrolyzers	Giner Electrochemical Systems, LLC
Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	U. of California- Berkeley
ME100 Methanol Reforming Hydrogen Generator	REB Research & Consulting
Membrane Structures for Hydrogen Separation	Genesis Fueltech, Inc.
Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.
New York State Hi-Way Initiative	GE Global Research Center
Novel Catalytic Fuel Reforming	InnovaTek, Inc.
Novel, Low-Cost Solid Membrane Water Electrolyzer	Giner Electrochemical Systems, LLC
Novel Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.
Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.
Photoelectrochemical Hydrogen Production	U. of Hawaii
Production of Hydrogen by Superaadiabatic Decomposition of Hydrogen Sulfide	Gas Technology Institute
Renewable Electrolysis Integrated System Development and Testing	NREL
Reversible Liquid Carriers	Air Products and Chemicals, Inc.
Scalable Steam Methane Reformer System for Distributed Hydrogen	Catacel Corp.
Solar-Thermal Production of Hydrogen Using Renewable Feedstock	Sundrop Fuels, Inc.
Turnkey Hydrogen Fueling Station	Air Products and Chemicals, Inc.

Technologies highlighted in red are commercial, blue are emerging, and green are not being pursued.

## Storage Technologies

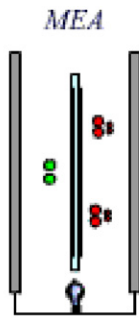
Technology Title	Company
Compressed Hydrogen Gas Integrated Storage System	Johns Hopkins U.
High-Strength, Low-Cost Microballoons for Hydrogen Storage	Powdermet, Inc.
Hydrogen Composite Tanks	Quantum Fuel Systems Technologies Worldwide, Inc.
Hydrogen Storage in Cryo-Compressed Vessels	LLNL
Hydrogen Storage in Insulated Pressure Vessels	LLNL
Low-Cost Materials, High-Efficiency, High-Pressure Hydrogen Storage	Quantum Technologies, Inc.
Non-Destructive Ultrasonic Scanning Technology	Digital Wave Corp.
Process for Regeneration of Sodium Borate to Sodium Borohydride for H <sub>2</sub> Storage	Millennium Cell, Inc.
Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.
Safe and Effective Storage and Transmission of Hydrogen	Safe Hydrogen, LLC

Technologies highlighted in red are commercial, blue are emerging, and green are not being pursued.

# Appendix B: Technology Tracking Data Collection Template

Technology Tracking Data Collection Template .....B-2

## Technology Tracking Data Collection Template

	<b>Primary Industry:</b> Fuel Cells
<p><b>Overview (Technology History):</b></p> <ul style="list-style-type: none"> <li>• Who is selling it.</li> <li>• What year it became commercially available</li> <li>• Number of units sold.</li> </ul> <p><b>Applications:</b> About 70 words. Where will it be used and what will be the impact of its use.</p> <p><b>Capabilities:</b> About 20 words describing what it does.</p> <ul style="list-style-type: none"> <li>• Produces...</li> <li>• Achieves...</li> <li>• Allows...</li> </ul>	<p><b>Graphic:</b></p> <div style="text-align: center;">  <p style="color: green; font-weight: bold;">Oxygen and Hydrogen</p> </div> <p>Graphic or photo showing process performed</p>
<p><b>Description:</b> Two or three paragraphs, about 80 words each. Tell the story of how it fills a need and describe it. First paragraph gives situation before this technology. Second paragraph gives situation after this technology and describes how it works.</p>	<p><b>Benefits:</b> Two or three headings, with about 8 to 16 words under each heading. Examples are:</p> <ul style="list-style-type: none"> <li>Production Cost Savings</li> <li>Reduced Fuel Costs</li> <li>Emissions Reductions</li> <li>Safety</li> <li>Productivity</li> </ul>

**Tracking Information:**

**Year Developed:**

**Year**

**Year First** (PNNL internal)

**Commercialized:**

**Year Stopped** (PNNL internal)

**Tracked:**

**Tracking:**

**Associated Parties:**

**DOE Manager(s)**

**Technology Partner(s)**

This is the DOE program manager contact:

..This is your contact information and the contact information of partners if any.



## Technology Tracking Data Collection Template

Name ..Name of Principal Investigator  
Address .. Company or Lab Name  
Phone ..Address  
Etc. Phone: .  
Fax:  
E-Mail:  
Website:

*Note: Please be sure to include the contact information of the person who someone could contact to obtain this product?*

### Status Information:

Year:	Status:	Comments:
2008	Commercial <i>Note: the definition of commercial is currently available for sale and at least one unit has been sold.</i>	This is a short (< 50 words) summary of development progress in the prior calendar year, your current status, future commercialization plans.

### Description:

#### Also Known As:

This is an alternative name for the technology if one exists.

#### Technical Description:

This is the technical description of the process/technology (short, about 80 words)

### References:

#### Source List:

This could be a website with further information or reference information

### Remarks:

#### History:

This is a short summary of when testing began and changes that may have occurred over time. 70 words.

## Technology Tracking Data Collection Template

**General Comments:**

Optional

**Markets and Economics:**

**Comments:**

Projected savings if any

**Selling Price:**

*Note: Please distinguish between units sold per year in the US versus foreign countries.*

# Appendix C: Patent Status Lists

C.1 Fuel Cell Patents Status.....	C-3
C.2 Production/Delivery Patents Status.....	C-12
C.3 Storage Patents Status.....	C-19



**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
7,323,159	01/29/08	ANL	Method for fast start of a fuel processor	An improved fuel processor for fuel cells is provided whereby the startup time of the processor is less than 60 seconds and can be as low as 30 seconds, if not less.	Not licensed and not being used in research at ANL.
7,264,778	09/04/07	SNL	Carbon monoxide sensor and method of use	Carbon monoxide sensors suitable for use in hydrogen feed streams and methods of use. The sensors are palladium metal/insulator/semiconductor sensors. The methods and sensors are particularly suitable for use in proton exchange membrane fuel cells.	Not licensed and not being used in research at SNL.
7,255,798	08/14/07	Ion Power, Inc.	Recycling of used perfluorosulfonic acid membranes	A method for recovering and recycling catalyst-coated fuel cell membranes includes dissolving the used membranes in water and solvent, heating the dissolved membranes under pressure, and separating the components.	Used in Ion Power's emerging technology.
7,247,403	07/24/07	ORNL	Surface modified stainless steels for PEM fuel cell bipolar plates	A nitridation treated stainless steel article (such as a bipolar plate for a proton exchange membrane fuel cell) having lower interfacial contact electrical resistance and better corrosion resistance than an untreated stainless steel article.	Part of an emerging fuel cell technology project.
7,211,346	05/01/07	ORNL	Corrosion-resistant metallic bipolar plate	An electrically conductive component such as a bipolar plate for a PEM fuel cell. The component has a substantially external, continuous layer of chromium nitride.	Part of an emerging fuel cell technology project.
7,195,835	03/27/07	ANL	Proton conducting membrane for fuel cells	An ion conducting membrane comprising dendrimeric polymers covalently linked into a network structure.	No licensee and no further development of this technology at ANL.
7,138,199	11/21/06	Dynalene, Inc.	Fuel cell and fuel cell coolant compositions	Directed to coolant compositions, particularly coolant compositions useful in fuel cells, and to fuel cells containing such coolant compositions.	Part of an emerging fuel cell technology project.
7,135,537	11/14/06	E.I. du Pont de Nemours and Company	Sulfonimide-containing poly(arylene ether)s and poly(arylene ether sulfone)s, methods for producing the same, and their uses	Directed to sulfonimide-containing polymers, for use in conductive membranes and fuel cells.	Not in a commercial product or licensed but being used in internally funded research.
7,101,635	09/05/06	LANL	Methanol-tolerant cathode catalyst composite for direct methanol fuel cells	A direct methanol fuel cell having a methanol fuel supply, oxidant supply, and its membrane electrode assembly.	Not licensed and not being used at LANL for research.

**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
7,052,793	05/30/06	Foster-Miller, Inc.	Composite solid polymer electrolyte membranes	The invention relates to composite solid polymer electrolyte membranes (SPEMs), which include a porous polymer substrate interpenetrated with an ion-conducting material. These SPEMs are useful in electrochemical applications, including fuel cells and electroanalysis.	Being used in continuing research at the company.
7,022,810	04/04/06	SNL	Proton exchange membrane materials for the advancement of direct methanol fuel-cell technology	A new class of hybrid organic-inorganic materials, and methods of synthesis, which can be used as a proton exchange membrane in a direct methanol fuel cell.	Not licensed and not being used in research at SNL.
7,018,604	03/28/06	Iowa State University	Compounds for novel proton conducting membranes and methods of making same	A new set of compounds for use in polymer electrolyte membranes which are able to operate in a wide variety of temperature ranges, including in the intermediate temperature range of about 100°C to 700°C.	Being used in research at Iowa State U. but no licensees.
7,014,931	03/21/06	LANL	Methanol-tolerant cathode catalyst composite for direct methanol fuel cells	A direct methanol fuel cell having a methanol fuel supply, oxidant supply, and its membrane electrode assembly.	Not licensed and not being used at LANL for research.
6,995,114	02/07/06	Symyx Technologies, Inc.	Platinum-ruthenium-palladium fuel cell electrocatalyst	A catalyst for use in electrochemical reactor devices, the catalyst containing platinum, ruthenium, and palladium.	Not licensed and no research being done with this patent.
6,986,963	01/17/06	ORNL	Metallization of bacterial cellulose for electrical and electronic device manufacture	Metallized bacterial cellulose used in constructing fuel cells and other electronic devices.	No commercialization and no further development being pursued using this patent.
6,986,961	01/17/06	LANL	Fuel cell stack with passive air supply	A fuel cell stack comprised of a plurality of polymer electrolyte fuel cells.	Not licensed and not being used at LANL for research.
6,977,122	12/20/05	ANL	Proton conducting membrane for fuel cells	An ion conducting membrane comprising dendrimeric polymers covalently linked into a network structure.	No licensee and no further development of this technology at ANL.
6,962,760	11/08/05	LANL	Methods of conditioning direct methanol fuel cells	Methods for conditioning the membrane electrode assembly of a direct methanol fuel cell.	Not licensed and not being used at LANL for research.
6,956,083	10/18/05	LBNL	Single ion conductor cross-linked polymeric networks	Single ion conductors comprising polymer electrolytes prepared by grafting a salt compound onto a comb-branch polymer or dendrimer are disclosed having superior properties.	Being used in research at LBNL but no licensees.
6,921,605	07/26/05	Symyx Technologies, Inc.	Platinum-ruthenium-nickel fuel cell electrocatalyst	A catalyst suitable for use in a fuel cell, especially as an anode catalyst, that contains platinum, ruthenium, and nickel.	Not licensed and no research being done with this patent.

**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,864,004	03/08/05	LANL	Direct methanol fuel cell stack	A stack of direct methanol fuel cells exhibiting a circular footprint.	Not licensed and not being used at LANL for research.
6,847,188	01/25/05	General Motors Corporation	Fuel cell stack monitoring and system control	A control method for monitoring a fuel cell stack in a fuel cell system in which the actual voltage and actual current from the fuel cell stack are monitored.	Being used in continuing research at the company.
6,818,341	11/16/04	LANL	Fuel cell anode configuration for CO tolerance	A polymer electrolyte fuel cell (PEFC) is designed to operate on a reformate fuel stream containing oxygen and diluted hydrogen fuel with CO impurities.	Being used in research at LANL but no licensees.
6,808,838	10/26/04	LANL	Direct methanol fuel cell and system	A fuel cell having an anode and a cathode and a polymer electrolyte membrane located between anode and cathode gas diffusion backings uses a methanol vapor fuel supply.	Not licensed and not being used at LANL for research.
6,723,678	04/20/04	Symyx Technologies, Inc.	Platinum-ruthenium-nickel alloy for use as a fuel cell catalyst	An improved noble metal alloy composition for a fuel cell catalyst, the alloy containing platinum, ruthenium, and nickel. The alloy shows methanol oxidation activity.	Not licensed and no research being done with this patent.
6,696,382	02/24/04	LANL	Catalyst inks and method of application for direct methanol fuel cells	Inks are formulated for forming anode and cathode catalyst layers and applied to anode and cathode sides of a membrane for a direct methanol fuel cell.	Not licensed and not being used at LANL for research.
6,682,837	01/27/04	Symyx Technologies, Inc.	Method for producing electricity using a platinum-ruthenium-palladium catalyst in a fuel cell	A method for producing electricity using a fuel cell that utilizes a ternary alloy composition as a fuel cell catalyst, the ternary alloy composition containing platinum, ruthenium, and palladium.	Not licensed and no research being done with this patent.
6,670,301	12/30/03	BNL	Carbon monoxide tolerant electrocatalyst with low platinum loading and a process for its preparation	An electrocatalyst is provided for use in a fuel cell that has low platinum loading and a high tolerance to carbon monoxide poisoning.	Part of an emerging fuel cell technology project.
6,653,005	11/25/03	U. Central Florida	Portable hydrogen generator-fuel cell apparatus	A compact hydrogen generator is coupled to or integrated with a fuel cell for portable power applications.	Being used in research at University of Central Florida but no licensees.
6,635,369	10/21/03	LANL	Method for improving fuel cell performance	A method is provided for operating a fuel cell at high voltage for sustained periods of time.	Being used in research at LANL but no licensees.
6,596,422	07/22/03	LANL	Air breathing direct methanol fuel cell	A method for activating a membrane electrode assembly for a direct methanol fuel cell is disclosed. The method comprises operating the fuel cell with humidified hydrogen as the fuel followed by running the fuel cell with methanol as the fuel.	Not licensed and not being used at LANL for research.

**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,576,359	06/10/03	General Motors Corporation	Controlled air injection for a fuel cell system	A method and apparatus for injecting oxygen into a fuel cell reformate stream to reduce the level of carbon monoxide while preserving the level of hydrogen in a fuel cell system.	Being used in continuing research at the company.
6,528,198	03/04/03	Plug Power, Inc.	Fuel cell membrane hydration and fluid metering	A hydration system includes fuel cell fluid flow plate(s) and injection port(s).	No longer being used.
6,517,965	02/11/03	Symyx Technologies, Inc.	Platinum-ruthenium-nickel alloy for use as a fuel cell catalyst	An improved noble metal alloy composition for a fuel cell catalyst, the alloy containing platinum, ruthenium, and nickel. The alloy shows methanol oxidation activity.	Not licensed and no research being done with this patent.
6,498,121	12/24/02	Symyx Technologies, Inc.	Platinum-ruthenium-palladium alloys for use as a fuel cell catalyst	A noble metal alloy composition for a fuel cell catalyst, a ternary alloy composition containing platinum, ruthenium and palladium. The alloy shows increased activity compared with well-known catalysts.	Not licensed and no research being done with this patent.
6,497,970	12/24/02	General Motors Corporation	Controlled air injection for a fuel cell system	A method and apparatus for injecting oxygen into a fuel cell reformate stream to reduce the level of carbon monoxide while preserving the level of hydrogen in a fuel cell system.	Being used in continuing research at the company.
6,492,052	12/10/02	LANL	Air breathing direct methanol fuel cell	An air breathing direct methanol fuel cell is provided with a membrane electrode assembly, a conductive anode assembly that is permeable to air and directly open to atmospheric air, and a conductive cathode assembly that is permeable to methanol and directly contacting a liquid methanol source.	Not licensed and not being used at LANL for research.
6,458,479	10/01/02	LANL	Air breathing direct methanol fuel cell	An air breathing direct methanol fuel cell is provided with a membrane electrode assembly, a conductive anode assembly that is permeable to air and directly open to atmospheric air, and a conductive cathode assembly that is permeable to methanol and directly contacting a liquid methanol source.	Not licensed and not being used at LANL for research.
6,454,922	09/24/02	LANL	Corrosion test cell for bipolar plates	A corrosion test cell for evaluating corrosion resistance in fuel cell bipolar plates.	Exclusive license to Fuel Cell Technologies, Inc. - Commercial
6,451,465	09/17/02	General Motors Corporation	Method for operating a combustor in a fuel cell system	A method of operating a combustor to heat a fuel processor in a fuel cell system, in which the fuel processor includes a reactor which generates a hydrogen containing stream.	No longer being pursued, abandoned.
6,413,661	07/02/02	General Motors Corporation	Method for operating a combustor in a fuel cell system	A method of operating a combustor to heat a fuel processor to a desired temperature in a fuel cell system, wherein the fuel processor generates hydrogen from a hydrocarbon for reaction within a fuel cell to generate electricity.	No longer being pursued, abandoned.



**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,296,964	10/02/01	LANL	Enhanced methanol utilization in direct methanol fuel cell	The fuel utilization of a direct methanol fuel cell is enhanced for improved cell efficiency.	Not licensed and not being used at LANL for research.
6,265,222	07/24/01	Advanced Technology Materials, Inc.	Micro-machined thin film hydrogen gas sensor and method of making and using the sensor	A hydrogen sensor including a thin film sensor element formed, e.g., by metalorganic chemical vapor deposition or physical vapor deposition, on a microhotplate structure.	Patent sold to Honeywell but no further R&D being done with the patent at this time.
6,265,092	07/24/01	General Motors/LANL	Method of controlling injection of oxygen into hydrogen-rich fuel cell feed stream	A method of operating a H <sub>2</sub> - O <sub>2</sub> fuel cell fueled by hydrogen-rich fuel stream containing CO. The CO content is reduced to acceptable levels by injecting oxygen into the fuel gas stream.	Being used in continuing research at the company.
6,248,469	06/19/01	Foster-Miller, Inc.	Composite solid polymer electrolyte membranes	The invention relates to composite solid polymer electrolyte membranes (SPEMs), which include a porous polymer substrate interpenetrated with an ion-conducting material. These SPEMs are useful in electrochemical applications, including fuel cells and electroanalysis.	Being used in continuing research at the company.
6,248,467	06/19/01	LANL	Composite bipolar plate for electrochemical cells	A bipolar separator plate for fuel cells consists of a molded mixture of a vinyl ester resin and graphite powder.	Exclusive license to BMCI - Commercial
6,232,005	05/15/01	General Motors Corporation	Fuel cell system combustor	A fuel cell system including a fuel reformer heated by a catalytic combustor fired by anode and cathode effluents.	No longer being pursued, abandoned.
6,207,310	03/27/01	LANL	Fuel cell with metal screen flow-field	A polymer electrolyte membrane fuel cell is provided with electrodes supplied with a reactant on each side of a catalyzed membrane assembly.	Not licensed and not being used at LANL for research.
6,192,596	02/27/01	PNNL	Active microchannel fluid processing unit and method of making	An active microchannel fluid processing unit.	Exclusive license to Velocys, Inc., and in pilot testing now.
6,183,894	02/06/01	BNL	Electrocatalyst for alcohol oxidation in fuel cells	Binary and ternary electrocatalysts are provided for oxidizing alcohol in a fuel cell.	Not licensed or commercialized. Research is on-going.
6,180,275	01/30/01	Energy Partners, LLC	Fuel cell collector plate and method of fabrication	An improved molding composition is provided for compression molding or injection molding a current collector plate for a polymer electrolyte membrane fuel cell.	No longer being used in research.

**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,159,626	12/12/00	General Motors Corporation	Fuel cell system logic for differentiating between rapid and normal shutdown commands	A method of controlling the operation of a fuel cell system wherein each shutdown command for the system is subjected to decision logic which determines whether the command should be a normal shutdown command or rapid shutdown command.	Being used in continuing research at the company.
6,159,533	12/12/00	Southwest Research Institute	Method of depositing a catalyst on a fuel cell electrode	Fuel cell electrodes comprising a minimal load of catalyst having maximum catalytic activity and a method of forming such fuel cell electrodes.	No licensee and no research being done this technology..
6,117,577	09/12/00	LANL	Ambient pressure fuel cell system	An ambient pressure fuel cell system is provided with a fuel cell stack formed from a plurality of fuel cells having membrane/electrode assemblies.	Non-exclusive license to IdaTech - Not being used.
6,077,620	06/20/00	General Motors Corporation	Fuel cell system with combustor-heated reformer	A fuel cell system including a fuel reformer heated by a catalytic combustor fired by anode effluent and/or fuel from a liquid fuel supply providing fuel for the fuel cell.	No longer being pursued, abandoned.
6,074,692	06/13/00	General Motors Corporation	Method of making MEA for PEM/SPE fuel cell	A method of making a membrane-electrode-assembly (MEA) for a PEM/SPE fuel cell by applying a slurry of electrode-forming material directly onto a membrane-electrolyte film.	Being used in continuing research at the company.
6,066,408	05/23/00	Plug Power, LLC	Fuel cell cooler-humidifier plate	A cooler-humidifier plate for use in a proton exchange membrane fuel cell stack assembly. The cooler-humidifier plate combines functions of cooling and humidification within the fuel cell stack assembly, thereby providing a more compact structure, simpler manifolding, and reduced reject heat from the fuel cell.	No longer being used.
6,063,516	05/16/00	General Motors Corporation/ Ion Power	Method of monitoring CO concentrations in hydrogen feed to a PEM fuel cell	The CO concentration in the H <sub>2</sub> feed stream to a PEM fuel cell stack is monitored by measuring current and/or voltage behavior patterns from a PEM-probe communicating with the reformat feed stream.	Being used in continuing research at the company.
6,017,648	01/25/00	Plug Power, LLC	Insertable fluid flow passage bridgepiece and method	A fluid flow passage bridgepiece for insertion into an open-face fluid flow channel of a fluid flow plate.	No longer being used.
6,007,933	12/28/99	Plug Power, LLC	Fuel cell assembly unit for promoting fluid service and electrical conductivity	Fluid service and/or electrical conductivity for a fuel cell assembly.	Still being used in research.
6,001,499	12/14/99	General Motors Corporation/ Ion Power	Fuel cell CO sensor	The CO concentration in the H <sub>2</sub> feed stream to a PEM fuel cell stack is monitored by measuring current and/or voltage behavior patterns from a PEM-probe communicating with the reformat feed stream.	Being used in continuing research at the company.

**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
5,998,054	12/07/99	Plug Power, LLC	Fuel cell membrane hydration and fluid metering	A hydration system including fuel cell fluid flow plate(s) and injection port(s). Each plate has flow channel(s) with respective inlet(s) for receiving portion(s) of a reactant fluid for a fuel cell. Each injection port injects a portion of liquid water directly into its respective flow channel to mix its portion of liquid water with a portion of the stream.	No longer being used.
5,952,119	09/14/99	LANL	Fuel cell membrane humidification	A method for supplying liquid water to the polymer electrolyte membrane of a fuel cell using distribution channels over the gas diffusion backing. This simple membrane humidification system uniformly distributes water to the membrane surface thus improving the performance of the fuel cell.	Non-exclusive license to IdaTech - Not being used.
5,945,229	08/31/99	General Motors Corporation	Pattern recognition monitoring of PEM fuel cell	The CO-concentration in the H <sub>2</sub> feed stream to a PEM fuel cell stack is monitored by measuring current and voltage behavior patterns from an auxiliary cell attached to the end of the stack.	Being used in continuing research at the company.
5,932,185	08/03/99	LLNL	Method for making thin carbon foam electrodes	A method for fabricating thin, flat carbon electrodes by infiltrating highly porous carbon papers, membranes, felts, metal fibers/powders, or fabrics with an appropriate carbon foam precursor material.	No licenses and no research being done with this patent.
5,798,187	08/25/98	LANL	Fuel cell with metal screen flow-field	A polymer electrolyte membrane fuel cell is provided with electrodes supplied with a reactant on each side of a catalyzed membrane assembly.	Not licensed and not being used at LANL for research.
5,707,755	01/13/98	General Motors Corporation/ Ion Power	PEM/SPE fuel cell	A PEM/SPE fuel cell including a membrane-electrode assembly (MEA) having a plurality of oriented filament embedded the face thereof for supporting the MEA and conducting current therefrom to contiguous electrode plates.	Being used in continuing research at the company.
5,654,109	08/05/97	The Dow Chemical Company	Composite fuel cell membranes	A bilayer or trilayer composite ion exchange membrane suitable for use in a fuel cell.	Unverified
5,641,586	06/24/97	LANL	Fuel cell with interdigitated porous flow-field	A polymer electrolyte membrane fuel cell is formed with an improved system for distributing gaseous reactants to the membrane surface.	Not licensed and not being used at LANL for research.
5,636,437	06/10/97	LLNL	Fabricating solid carbon porous electrodes from powders	Fabrication of conductive solid porous carbon electrodes for use in batteries, double layer capacitors, fuel cells, capacitive deionization, and waste treatment.	No licenses and no research being done with this patent.

**Fuel Cell Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
5,601,938	02/11/97	LLNL	Carbon aerogel electrodes for direct energy conversion	A direct energy conversion device, such as a fuel cell, using carbon aerogel electrodes, wherein the carbon aerogel is loaded with a noble catalyst, such as platinum or rhodium and soaked with phosphoric acid.	No licenses and no research being done with this patent.
5,248,566	09/28/93	ANL	Fuel cell system for transportation applications	A propulsion system for a vehicle having pairs of front and rear wheels and a fuel tank.	Not licensed but being used in research at ANL.
4,657,829	04/14/87	United Technologies Corporation	Fuel cell power supply with oxidant and fuel gas switching	Relating to a fuel cell vehicular power plant, fuel for the fuel stack is supplied by a hydrocarbon (methanol) catalytic cracking reactor and CO shift reactor.	Patent has expired and not used by UTC in commercial products.
4,650,727	03/17/87	LANL	Fuel processor for fuel cell power system	A catalytic organic fuel processing apparatus, which can be used in a fuel cell power system, contains within a housing a catalyst chamber, a variable speed fan, and a combustion chamber.	Not licensed and not being used for research at LANL.



**Production/Delivery Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
7,276,306	10/02/07	LLNL	System for the co-production of electricity and hydrogen	System for the co-generation of hydrogen gas and electricity, wherein the proportion of hydrogen to electricity can be adjusted from 0% to 100%.	No license issued and no research being done with this patent.
7,233,034	06/19/07	NREL	Hydrogen permeable protective coating for a catalytic surface	A protective coating for a surface comprising a layer permeable to hydrogen, said coating being deposited on a catalyst layer wherein the catalytic activity of the catalyst layer is preserved.	Exclusive license to Nuclear Filter Technology. Still working with NREL via CRADA on further development.
7,176,005	02/13/07	University of California - Berkeley	Modulation of sulfate permease for photosynthetic hydrogen production	Sustained hydrogen production is obtained by the culturing of a genetically-modified algae, where the ability of the chloroplasts to intake sulfate is reduced or eliminated compared with wild-type algae.	Part of an emerging hydrogen production technology project.
7,157,167	01/02/07	U. Central Florida Research Foundation	Thermocatalytic process for CO <sub>2</sub> -free production of hydrogen and carbon from hydrocarbons	A novel process and apparatus for sustainable CO <sub>2</sub> -free production of hydrogen and carbon by thermocatalytic decomposition (dissociation, pyrolysis, cracking) of hydrocarbon fuels over carbon-based catalysts in the absence of air and/or water.	Exclusive license to Contained Energy, Inc. Continued development with the goal of a commercial product in 3-5 years.
7,122,873	10/17/06	U. of Hawaii	Hybrid solid state/electrochemical photoelectrode for hydrogen production	A semiconductor device for producing a gas from a material comprising the gas using light as the sole power source.	Part of an emerging hydrogen production technology project.
7,067,453	06/27/06	InnovaTek, Inc.	Hydrocarbon fuel reforming catalyst and use thereof	The subject invention is a catalyst consisting of an oxide or mixed oxide support and bimetallic catalytically active compounds.	Part of an emerging hydrogen production technology project.
7,066,973	06/27/06	Nuvera Fuel Cells	Integrated reformer and shift reactor	A hydrocarbon fuel reformer for producing diatomic hydrogen gas.	Being used in the New Millennium Project.
7,059,364	06/13/06	Gas Technology Institute	Control method for high-pressure hydrogen vehicle fueling station dispensers	A method for quick filling a vehicle hydrogen storage vessel with hydrogen, the key component of which is an algorithm used to control the fill process, which interacts with the hydrogen dispensing apparatus to determine the vehicle hydrogen storage vessel capacity.	Being used in commercial product, H2 ProGen, by GreenField Compression.
7,033,570	04/25/06	NREL/U. of Colorado	Solar-thermal fluid-wall reaction processing	A method for carrying out high temperature thermal dissociation reactions requiring rapid-heating and short residence times using solar energy.	Part of an emerging hydrogen production technology project.
7,011,694	03/14/06	University of Kentucky	CO <sub>2</sub> -selective membranes containing amino groups	A CO <sub>2</sub> selective membrane constructed in the hollow-fiber configuration using air as the sweep gas for use in water gas shift reactors to aid in the production of high purity H <sub>2</sub> .	Still being used in on-going research efforts.



**Production/Delivery Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,989,252	01/24/06	NREL/UC Berkeley	Hydrogen production using hydrogenase-containing oxygenic photosynthetic organisms	A reversible physiological process provides for the temporal separation of oxygen evolution and hydrogen production in a microorganism.	Part of an emerging hydrogen production technology project.
6,985,082	01/10/06	NexTech Materials, Ltd.	Carbon monoxide sensor and method of use	A sensor and method of use for detection of low levels of carbon monoxide in gas mixtures.	Not being pursued at this time. Put on the shelf.
6,967,063	11/22/05	ANL	Autothermal hydrodesulfurizing reforming method and catalyst	A method for reforming a sulfur-containing carbonaceous fuel in which the sulfur-containing carbonaceous fuel is mixed with H <sub>2</sub> O and an oxidant, forming a fuel/H <sub>2</sub> O/oxidant mixture.	Licensed to a small company that wishes to remain anonymous and being used in research.
6,887,728	05/03/05	U. of Hawaii	Hybrid solid state/ electrochemical photoelectrode for hydrogen production	A semiconductor device for production of a gas from a material comprising the gas using light as the sole power source.	Part of an emerging hydrogen production technology project.
6,878,362	04/12/05	General Electric Co.	Fuel processor apparatus and method based on autothermal cyclic reforming	In a fuel processor based on autothermal cyclic reforming process, a method of generating hydrogen gas includes receiving a mixture of fuel and steam in the reformer reactor operating in a reforming step to produce hydrogen-rich reformate gas.	Research not continuing in this area and nothing being done with patent.
6,875,247	04/05/05	PNNL	Conditions for fluid separations in microchannels, capillary-driven fluid separations, and laminated devices capable of separating fluids	Methods of separating fluids using capillary forces and/or improved conditions. The improved methods may include control of the ratio of gas and liquid Reynolds numbers relative to the Suratman number. Also disclosed are wick-containing, laminated devices that are capable of separating fluids.	Exclusive license to Velocys, Inc. The patent is not planned for development for hydrogen production but for distillation purposes.
6,872,378	03/29/05	NREL/U. of Colorado	Solar thermal aerosol flow reaction process	An environmentally beneficial process using concentrated sunlight to heat radiation absorbing particles to carry out highly endothermic gas phase chemical reactions ultimately resulting in the production of hydrogen or hydrogen synthesis gases.	Part of an emerging hydrogen production technology project.
6,723,566	04/20/04	NREL	Pd/Ni-WO3 anodic double layer gasochromic device	An anodic double layer gasochromic sensor structure for optical detection of hydrogen in improved response time and with improved optical absorption real time constants.	Exclusive license to Nuclear Filter Technology. Still working with NREL via CRADA on further development.
6,716,275	04/06/04	SNL	Gas impermeable glaze for sealing a porous ceramic surface	A process for fabricating a gas impermeable seal on a porous ceramic surface using a thin, glass-based, pinhole free glaze.	Not licensed to anyone but still being used in research.
6,670,058	12/20/03	U. Central Florida	Thermocatalytic process for CO <sub>2</sub> -free production of hydrogen and carbon from hydrocarbons	A novel process for sustainable CO <sub>2</sub> -free production of hydrogen and carbon by thermocatalytic decomposition (or dissociation, pyrolysis, cracking) of hydrocarbon fuels over carbon-based catalysts in the absence of air and/or water.	Exclusive license to Contained Energy, Inc. Continued development with the goal of a commercial product in 3-5 years.

**Production/Delivery Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,666,909	12/23/03	PNNL	Microsystem capillary separations	Laminated, multiphase separators and contactors having wicking structures and gas flow channels. Some preferred embodiments are combined with microchannel heat exchange. Integrated systems containing these components are also part of the invention.	Exclusive license to Velocys, Inc. Being developed for distillation uses.
6,641,625	11/04/03	Nuvera Fuel Cells, Inc.	Integrated hydrocarbon reforming system and controls	A hydrocarbon reformer system including a first reactor configured to generate hydrogen-rich reformate.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.
6,623,720	09/23/03	University of Michigan	Transition metal carbides, nitrides and borides, and their oxygen containing analogs useful as water gas shift catalysts	Mono- and bimetallic transition metal carbides, nitrides and borides, and their oxygen containing analogs (e.g. oxycarbides) for use as water gas shift catalysts.	No license yet but looking for a commercial partner for future research.
6,572,829	06/03/03	U. Central Florida	Closed cycle photocatalytic process for decomposition of hydrogen sulfide to its constituent elements	System for separating hydrogen and sulfur from hydrogen sulfide (H <sub>2</sub> S) gas produced from oil and gas waste streams.	Not licensed and no research being done at University of Central Florida.
6,551,561	04/22/03	U. Central Florida	Apparatus for decoupled thermo-photocatalytic pollution control	A new method for design and scale-up of photocatalytic and thermocatalytic processes.	Not licensed and no research being done at University of Central Florida.
6,531,035	03/11/03	U. Central Florida	Apparatus and method for low flux photocatalytic pollution control	A new method for design and scale-up of photocatalytic and thermocatalytic processes.	Not licensed and no research being done at University of Central Florida.
6,492,290	12/10/02	Air Products & Chemicals, Inc.	Mixed conducting membranes for syngas production	A new class of multicomponent metallic oxides that are particularly suited in fabricating components used in processes for producing syngas.	Being used in research at Air Products.
6,478,077	11/12/02	SNL	Self supporting heat transfer element	An improved internal heat exchange element arranged so as to traverse the inside diameter of a container vessel such that it makes good mechanical contact with the interior wall of that vessel.	Not licensed and no research being done at SNL.
6,468,480	10/22/02	Nuvera Fuel Cells, Inc.	Apparatus for converting hydrocarbon fuel into hydrogen gas and carbon dioxide	Hydrocarbon fuel reformer suitable for producing synthesis hydrogen gas from reactions with hydrocarbons fuels, oxygen, and steam.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.



**Production/Delivery Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,448,068	09/10/02	NREL	System for rapid biohydrogen phenotypic screening of microorganisms using a chemochromic sensor	A system for identifying a hydrogen gas producing organism.	In license negotiations with two companies.
6,395,252	05/28/02	ORNL	Method for the continuous production of hydrogen	A method for the continuous production of hydrogen.	Not licensed and no research being done at ORNL.
6,321,775	11/27/01	Johns Hopkins University	Compressed gas manifold	A compressed gas storage cell interconnecting manifold including a thermally activated pressure relief device, a manual safety shut-off valve, and a port for connecting the compressed gas storage cells to a motor vehicle power source and to a refueling adapter.	Part of an emerging hydrogen storage technology project.
6,303,098	10/16/01	ANL	Steam reforming catalyst	A method of forming a hydrogen rich gas from a source of hydrocarbon fuel.	No longer being used in research.
6,277,589	08/21/01	NREL	Method and apparatus for rapid biohydrogen phenotypic screening of microorganisms using a chemochromic sensor	An assay system for identifying a hydrogen-gas-producing organism, including a sensor film having a first layer comprising a transition metal oxide or oxysalt and a second layer comprising hydrogen-dissociative catalyst metal.	In license negotiations with two companies.
6,254,839	07/03/01	Arthur D. Little, Inc.	Apparatus for converting hydrocarbon fuel into hydrogen gas and carbon dioxide	A hydrocarbon fuel reformer suitable for producing synthesis hydrogen gas from reactions with hydrocarbons fuels, oxygen, and steam.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.
6,244,367	06/12/01	ANL	Methanol partial oxidation reformer	A partial oxidation reformer comprising a longitudinally extending chamber having a methanol, water, and an air inlet and an outlet.	No longer being used in research.
6,238,815	05/29/01	GM Corp.	Thermally integrated staged methanol reformer and method	A thermally integrated two-stage methanol reformer including a heat exchanger and first and second reactors collocated in a common housing in which a gaseous heat transfer medium circulates to carry heat from the heat exchanger into the reactors.	No longer being pursued, abandoned.
6,207,122	03/27/01	Arthur D. Little, Inc.	Method for converting hydrocarbon fuel into hydrogen gas and carbon dioxide	A hydrocarbon fuel reforming method suitable for producing synthesis hydrogen gas from reactions with hydrocarbons fuels, oxygen, and steam.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.
6,126,908	10/03/00	Arthur D. Little, Inc.	Method and apparatus for converting hydrocarbon fuel into hydrogen gas and carbon dioxide	An apparatus and a method for converting hydrocarbon fuel or an alcohol into hydrogen gas and carbon dioxide.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.

**Production/Delivery Patents Status**

<b>Patent Number</b>	<b>Award Date</b>	<b>Organization</b>	<b>Title</b>	<b>Description</b>	<b>Status</b>
6,123,913	09/26/00	Arthur D. Little, Inc.	Method for converting hydrocarbon fuel into hydrogen gas and carbon dioxide	A method for synthesizing hydrogen gas from hydrocarbon fuel. A first mixture of steam and a first fuel are directed into a first tube to subject the first mixture to a first steam reforming reaction in the presence of a first catalyst.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.
6,083,425	07/04/00	Arthur D. Little, Inc.	Method for converting hydrocarbon fuel into hydrogen gas and carbon dioxide	A method for converting hydrocarbon fuel into hydrogen gas and carbon dioxide within a reformer.	Being used by Nuvera in research in a demo prototype for truck apus. Five years from commercialization.
6,051,125	04/18/00	LLNL	Natural gas-assisted steam electrolyzer	An efficient method of producing hydrogen by high temperature steam electrolysis that will lower the electricity consumption to an estimated 65 percent lower than has been achievable with previous steam electrolyzer systems.	One commercial license was issued but is terminated.
5,942,346	08/24/99	ANL	Methanol partial oxidation reformer	A partial oxidation reformer comprising a longitudinally extending chamber having a methanol, water, and an air inlet and an outlet.	No longer being used in research.
5,939,025	08/17/99	ANL	Methanol partial oxidation reformer	A partial oxidation reformer comprising a longitudinally extending chamber having a methanol, water and an air inlet and an outlet.	No longer being used in research.
5,895,518	04/20/99	SNL	Synthesis of alloys with controlled phase structure	A method for preparing controlled phase alloys useful for engineering and hydrogen storage applications.	Not licensed and no research being done at SNL.
5,821,111	10/13/98	Bioengineering Resources, Inc.	Bioconversion of waste biomass to useful products	A process for converting waste biomass to useful products by gasifying the biomass to produce synthesis gas and converting the synthesis gas substrate to one or more useful products.	No longer being pursued for hydrogen production
4,473,622	09/25/84	United Technologies Corporation	Rapid starting methanol reactor system	A methanol-to-hydrogen cracking reactor for use with a fuel cell vehicular power plant.	Patent has expired and is not being used at UTC.
4,358,429	11/09/82	ANL	Oxygen stabilized zirconium vanadium intermetallic compound	A new oxygen stabilized intermetallic compound that can repeatedly sorbing hydrogen from a mixture of gases.	No licensee and no further development of this technology at ANL.
4,142,300	03/06/79	ANL	Lanthanum nickel aluminum alloy	A ternary intermetallic compound capable of reversible sorption of hydrogen having the chemical formula $LaNi_{3-x}Al_x$ , where x is in the range of about 0.01 to 1.5 and the method of storing hydrogen using the intermetallic compound.	No licensee and no further development of this technology at ANL.



**Storage Patents Status**

Patent Number	Award Date	Organization	Title	Description	Status
7,402,234	07/22/08	INL	Polymeric hydrogen diffusion barrier, high-pressure storage tank so equipped, method of fabricating a storage tank and method of preventing hydrogen diffusion	An electrochemically active hydrogen diffusion barrier which comprises an anode layer, a cathode layer, and an intermediate electrolyte layer, which is conductive to protons and substantially impermeable to hydrogen.	No licenses issued and no internal research being done with this patent.
7,306,780	12/11/07	SNL	Method of generating hydrogen gas from sodium borohydride	Contacts water with micro-disperse particles of sodium borohydride in the presence of a metal catalyst, thus generating hydrogen gas.	Licensed to Nanodetex but license was terminated.
7,191,602	03/20/07	LLNL	Storage of H <sub>2</sub> by absorption and/or mixture within a fluid medium	Provides a container comprising a fixed volume remaining constant to within about 5% due to changes in pressure and temperature with a fluid mixture comprised of a high density of hydrogen molecules. Container will increase the density of the fluid mixture so the mixture can be withdrawn from the container and used as fuel.	Part of an emerging hydrogen storage technology project.
7,101,530	09/05/06	Air Products and Chemicals, Inc.	Hydrogen storage by reversible hydrogenation of pi-conjugated substrates	Provide a means of capturing and storing hydrogen by its chemical reaction, in the presence of a catalyst, conducted at moderate temperatures, with a medium having an extended pi-conjugated molecular structure to produce the corresponding significantly hydrogenated form of the pi-conjugated system.	Part of ongoing research project.
7,094,387	08/22/06	SRL	Complex hydrides for hydrogen storage	Melt a mixture of sodium aluminum hydride mixed with titanium under a combination of heat and pressure to provide a fused hydrogen storage material.	Being used in research at SRL but no licensees.
7,052,671	05/30/06	Safe Hydrogen, LLC	Storage, generation, and use of hydrogen	Operation of a hydrogen generator with a composition of a carrier liquid, a dispersant, and chemical hydride. A regenerator recovers elemental metal from byproducts of the hydrogen generation process.	Part of an emerging hydrogen storage technology project.
6,918,382	07/19/05	Energy Conversion Devices, Inc.	Hydrogen powered scooter	A scooter powered by a hydrogen fueled internal combustion engine utilizes an on-board metal-hydride hydrogen storage unit and the storage unit may be heated with an exhaust stream from the engine to help liberate the embedded hydrogen.	No licenses issued and no internal research being done with this patent.
6,793,909	09/21/04	SNL	Direct synthesis of catalyzed hydride compounds	Method of producing complex hydride compounds comprising mechanically milling powders of a simple alkali metal hydride material with a metal and a titanium catalyst compound followed by high pressure hydrogenation.	Being used in research at SNL but no licensees.

**Storage Patents Status**

Patent Number	Award Date	Organization	Title	Description	Status
6,787,007	09/07/04	INL	Polymeric hydrogen diffusion barrier, high-pressure storage tank so equipped, method of fabricating a storage tank and method of preventing hydrogen diffusion	Electrochemically active hydrogen diffusion barrier made of an anode layer and a cathode layer, each including a polymer material conductive to protons and substantially impermeable to hydrogen. There will also be a voltage source operably coupled to the anode layer and the cathode layer and a catalytic material proximate an interface between at least one of the anode layer and the electrolyte layer and the cathode layer and the electrolyte layer.	Not licensed and no research being done at INL with this patent.
6,746,496	06/08/04	SNL	Compact solid source of hydrogen gas	A compact solid source of hydrogen gas, where the gas is generated by contacting water with micro-disperse particles of sodium borohydride in the presence of a catalyst, such as cobalt or ruthenium.	Licensed to Nanodetex but license was terminated.
6,708,502	03/23/04	LLNL	Lightweight cryogenic-compatible pressure vessels for vehicular fuel storage	A lightweight, cryogenic-compatible pressure vessel for flexibly storing cryogenic liquid fuels or compressed gas fuels at cryogenic or ambient temperatures.	Part of an emerging hydrogen storage technology project.
6,616,891	09/09/03	Energy Conversion Devices, Inc.	High capacity transition metal based hydrogen storage materials for the reversible storage of hydrogen	A reversible transition metal-based (including titanium, vanadium, chromium, and manganese) hydrogen storage material is capable of storing up to 4 wt.% hydrogen and reversible delivering up to 2.8 wt.% hydrogen at temperatures up to 150°C.	Being used in research at Energy Conversion Devices.
6,593,017	09/09/03	Energy Conversion Devices, Inc.	High capacity calcium lithium based hydrogen storage material and method of making the same	Nonreversible metal hydrides can be used to store and release hydrogen. A nano-crystalline, calcium lithium based hydride is capable of storing up to 5% hydrogen by weight and can be easily ground to a fine powder to facilitate hydrogen transportation and storage.	No licenses issued and no internal research being done with this patent.
6,471,935	10/29/02	U. of Hawaii	Hydrogen storage materials and method of making by dry homogenation	A method of making such reversible hydrogen storage materials by dry doping is also provided and comprises the steps of dry homogenizing metal hydrides by mechanical mixing, such as be crushing or ball milling a powder, of a metal aluminum hydride with a transition metal catalyst.	Part of a research project for hydrogen storage technology.
6,418,962	07/16/02	John Hopkins University	Low cost compressed gas fuel storage system	A compressed gas vehicle fuel storage system comprised of a plurality of compressed gas pressure cells supported by shock-absorbing bumpers positioned within a low cost, shape-conforming container.	Part of an emerging hydrogen storage technology project.
6,262,328	07/17/01	SRL	Container and method for absorbing and reducing hydrogen concentration	A method for absorbing hydrogen from an enclosed environment.	Being used in research at SRL but no licensees.

**Storage Patents Status**

Patent Number	Award Date	Organization	Title	Description	Status
6,257,360	07/10/01	Johns Hopkins University	Compressed gas fuel storage system	A compressed gas vehicle fuel storage system comprised of a plurality of compressed gas pressure cells supported by shock-absorbing foam positioned within a shape-conforming container.	Part of an emerging hydrogen storage technology project.
6,017,600	01/25/00	LLNL	Method for forming a bladder for fluid storage vessels	Lightweight, low permeability liner for graphite epoxy composite compressed gas storage vessels. The liner is composed of polymers that may or may not be coated with a thin layer of a low permeability material, such as silver, gold, or aluminum, deposited on a thin polymeric layer or substrate, which is formed into a closed bladder using torispherical or near torispherical end caps.	No licenses issued and no internal research being done with this patent.
5,965,482	10/12/99	SRL	Composition for absorbing hydrogen from gas mixtures	A hydrogen storage composition that defines a physical sol-gel matrix having an average pore size of less than 3.5 angstroms, which effectively excludes gaseous metal hydride poisons while permitting hydrogen gas to enter.	Being used in research at SRL but no licensees.
5,798,156	08/25/98	LLNL	Lightweight bladder lined pressure vessels	A lightweight, low permeability liner for graphite epoxy composite compressed gas storage vessels. The liner may be used in most types of gas storage system and is particularly applicable for hydrogen, gas mixtures, and oxygen used for vehicles, fuel cells or regenerative fuel cell applications, high altitude solar powered aircraft, hybrid energy storage/propulsion systems, lunar/Mars space applications, and other applications requiring high cycle life.	No licenses issued and no internal research being done with this patent.
5,411,928	05/02/95	SRL	Composition for absorbing hydrogen	The composition comprises a porous glass matrix, made by a sol-gel process, having a hydrogen-absorbing material dispersed throughout the matrix. The glass matrix has pores large enough to allow gases having hydrogen to pass through the matrix, yet small enough to hold the particles dispersed within the matrix so that the hydrogen-absorbing particles are not released during repeated hydrogen absorption/desorption cycles.	Being used in research at SRL but no licensees.

# Appendix D: Commercial Technology Descriptions

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<b>D.1 Fuel Cell Technologies</b> .....	<b>D-3</b>
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# Advanced MEAs for Enhanced Operating Conditions

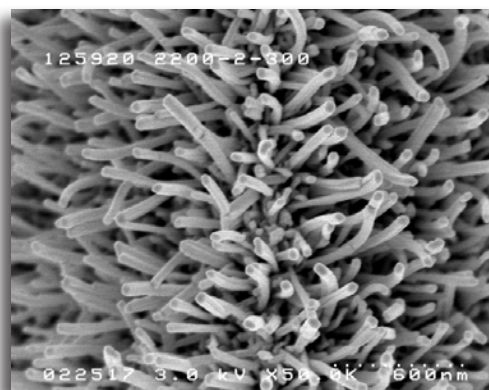
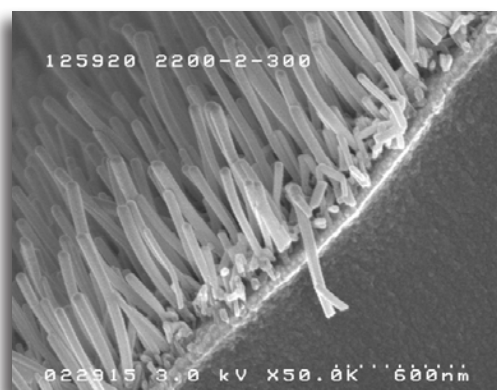
Commercial Technology

## Innovative Catalyst Electrodes and Membranes Result in Increased Durability and Superior Performance

3M Company, with grant assistance from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, has developed a new membrane electrode assembly (MEA) that demonstrates enhanced performance and significantly improved durability for fuel cell applications. The MEAs use the carbon-free 3M nanostructured thin film (NSTF) catalyst electrodes and 3M ion exchange membrane to achieve longer lifetimes with less precious metal than current state-of-the-art constructions. 3M uses high-volume-capable pilot line equipment to manufacture the catalyst coated membranes as roll-goods for improved quality and lower costs.

For polymer electrolyte membrane fuel cells to be commercially viable for automotive and distributed stationary applications, several issues must be addressed, including performance, durability, and cost. 3M addressed these issues by developing MEAs that meet demanding system operating conditions of higher temperature and low humidification, use less precious metal than current state-of-the-art constructions, have the required stability and durability, and are made by processes amenable to high-volume manufacturing.

The 3M NSTF catalyst support and deposition system eliminates the durability issues associated with carbon corrosion and platinum (Pt) dissolution of conventional dispersed Pt supported on carbon blacks. The NSTF ternary alloy catalysts exhibit a ten-fold gain in catalyst specific activity. Combined with the new 3M low equivalent weight membranes, the new MEAs demonstrate over a ten-fold gain in lifetime under numerous accelerated and load-cycling tests. Improved performance and stability of the MEAs results in higher current and power density with reduced catalyst loading. 3M is currently selling these advanced MEAs to select fuel cell developers.



*Scanning Electron Micrographs of the New NSTF Catalysts*

## Technology History

- ◆ Developed by 3M Company over a 10-year period.
- ◆ Became commercially available in 2007.

## Applications

Can be used in demanding hydrogen-fueled fuel cell systems where dynamic, hot, highly oxidative or off-nominal operating conditions require high resistance to catalyst corrosion and membrane degradation.

## Capabilities

- ◆ Uses established high-volume compatible roll-good processes for fabricating components.
- ◆ Demonstrates over a ten-fold gain in lifetime under many accelerated and load-cycling tests.
- ◆ Results in higher current and power density with reduced catalyst loading.

## Benefits

### Cost Savings

Uses less precious metal, lower-cost manufacturing, and smaller fuel cell stack size due to improved performance at the lower catalyst loading levels.

### Durability

Increases the operating life of fuel cells and offers more tolerance of off-nominal operating conditions and events.

### Efficiency

Meets demanding system operating conditions of higher temperature and low humidification.

**Contact Information:****Mark K. Debe***Email:* [mkdebe1@mmm.com](mailto:mkdebe1@mmm.com)*Phone:* (651) 736-9563**3M Company**

3M Center, Building 0201-01-N-19

St. Paul, MN 55144-1000

**Website:** [www.3m.com](http://www.3m.com)

# Breakthrough Lifetime Improvements for PEM Fuel Cells

Commercial Technology

## New Membranes and Resins Increase Lifetime of Fuel Cell Assemblies, Reducing Replacement Costs

Durability of polymer electrolyte membranes (PEMs) has been a major technical barrier for stationary and transportation applications of PEM fuel cells. The PEM used in fuel cells is made from polymers. Long-term operation of fuel cells causes chemical degradation of this polymer membrane material due to the formation of peroxides that attack the membrane's structure. This chemical degradation weakens the polymer in the membrane and reduces its ability to handle mechanical stress. Typically, mechanical stress is induced because of the cyclic operation of fuel cells, and this stress, coupled with the chemically-induced structural degradation, causes early failure of the membrane.

To solve this problem, DuPont Fuel Cells, with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, studied the degradation behavior of perfluorinated polymers. Their research resulted in the development of technologies to reduce the reactive centers within the polymer. The reactive centers are reduced by using proprietary, advanced stabilization technology. This stabilization technology combats the chemical degradation problem and increases the lifetime of fuel cell polymer membrane electrode assemblies, thereby reducing early failure replacement costs.

The stabilization technology approach resulted in a chemically stable Nafion® polymer technology that is eight times more stable than before. The modified materials have survived 4,900 hours in a demanding fuel cell accelerated test, which included load and relative humidity cycles. These new materials can be used for both PEM fuel cells and water electrolyzers. The commercially available DuPont Nafion resin, dispersions, membranes, and membrane electrode assemblies all incorporate this improved, chemically stabilized polymer.



*DuPont Nafion Resins, Dispersions, Membranes, and Membrane Electrode Assemblies*

## Technology History

- ◆ Initially researched by DuPont Fuel Cells in 2003.
- ◆ Marketed the first chemically stable Nafion products (resins, dispersions, membranes, and membrane electrode assemblies) by DuPont Fuel Cells in 2005.

## Applications

Can be used in both fuel cells and water electrolyzers using PEMs.

## Capabilities

- ◆ Demonstrates 50% reduction in swell compared with an earlier DuPont Nafion NRE211 membrane.
- ◆ Achieves significantly improved lifetime in fuel cell applications.

## Benefits

### Cost Savings

Reduces replacement costs because of increased membrane durability.

### Durability

Significantly improves lifetime in accelerated lifetime test simulating automotive drive-cycle approaching, 5,000 hours.

**Contact Information:****Dennis J. Kountz***Email:* [Dennis.J.Kountz@usa.dupont.com](mailto:Dennis.J.Kountz@usa.dupont.com)*Phone:* (302) 999-3354**DuPont Fuel Cells**

Chestnut Run Plaza 701

Wilmington, DE 19880-0701

**Website:** [www.dupont.com](http://www.dupont.com)

# Conductive Compound for Molding Fuel Cell Bipolar Plates

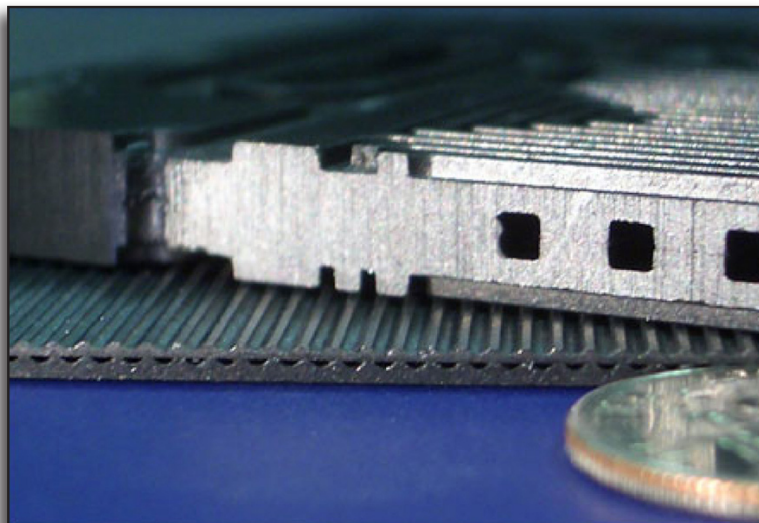
Commercial Technology

## New Compound Produces Thinner Fuel Cell Stacks and Enhanced Conductivity to Substantially Reduce Costs

Polymer electrolyte membrane (PEM) bipolar plates traditionally have been made from conductive thermoplastics or coated stainless steel. Flow and cooling channels are initially machined to make prototype PEM plates. Both technologies are high in cost compared with graphite-filled conductive thermoset molding compounds.

Graphite-filled conductive thermoset molding compounds can also be machined from molded slabs to produce initial prototype plate parts. Once flow and cooling channel designs are finalized, tools are built for the direct compression molding of finished plates. Anode and cathode plate designs are then bonded together along the cooling channel side of each plate to form a bipolar plate assembly, which can then be used to build a PEM fuel cell stack.

Bulk Molding Compounds, Inc. (BMCI), developed and commercialized a graphitized thermoset vinyl-ester compound for molding bipolar plates with assistance from technology licensed from Los Alamos National Laboratory (LANL). This LANL patented technology was developed using funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. Initial formulations developed in 1998 and 1999 yielded some commercialization by BMCI in 2000. From January 1, 2002, through December 31, 2007, 817,399 lbs. of the BMCI compound were sold.



*Evolution of Plate Thickness in Bonded Bipolar Assemblies*

## Technology History

- ◆ Developed and being marketed by BMCI using patented LANL technology.
- ◆ Became commercially available in 2000 with sales of 222,929 lbs. in 2007.

## Applications

Can be used where bipolar plate assemblies are needed for PEM cells in stationary, automotive, and portable power.

## Capabilities

- ◆ Provides enhanced through- and in-plane conductivity with good chemical and corrosion resistance to survive the fuel cell environment.
- ◆ Uses a conductive vinyl-ester adhesive to minimize contact resistance and enhance conductivity in making bipolar plate assemblies.

## Benefits

### Cost Savings

Allows the thickness of bipolar plate assemblies to be reduced from 7 mm to less than 2 mm, which reduces material costs and provides chemical resistance in a PEM fuel cell environment, avoiding the need for expensive corrosion resistant coatings.

### Product Quality

Offers exceptional part flatness, creep resistance, and overall dimensional stability by using proven thermoset technology.

### Productivity

Allows for large-volume commercial production because flow and cooling channels are directly molded into the part.

**Contact Information:****Al Lemoi***Email:* [aglemoi@gmail.com](mailto:aglemoi@gmail.com)*Phone:* (401) 647-3022**Bulk Molding Compounds, Inc.**

1600 Powis Court

Chicago, IL 60185

**Website:** [www.bulkmolding.com](http://www.bulkmolding.com)

# Corrosion Test Cell for PEM Bipolar Plate Materials

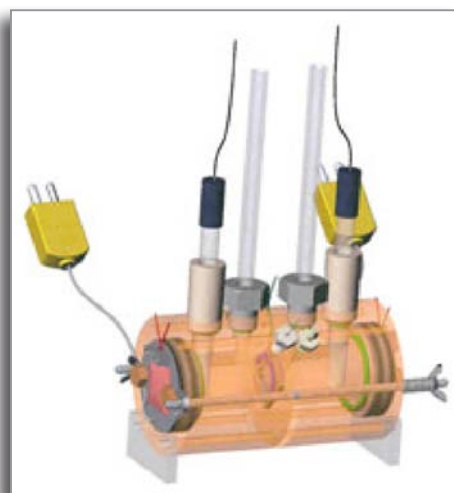
Commercial Technology

## New Test Cell Simulates Conditions in PEM Fuel Cells Allowing for Efficient and Less Costly Materials Testing

Fuel cells are composed of multiple bipolar plates (BPP). Fuel cell developers are currently working with different materials to determine the best combination of durability, efficiency, and performance under unfavorable operating conditions. One of the factors determining durability is the reaction of the BPPs to the fuel cell environment. The operation of a fuel cell can result in an environment that corrodes the BPPs. Therefore, one of the major challenges in developing these BPPs is corrosion protection at a reasonable price.

To aid in screening different fuel cell materials, a corrosion test cell was developed by Los Alamos National Laboratory (LANL) in 1999 with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. The purpose of the test cell was to represent as closely as possible the conditions at the anode and cathode of an operating polymer electrolyte membrane (PEM) fuel cell. An exclusive license to this technology was granted to Fuel Cell Technologies, Inc., and a commercial product was developed and sold in 2008.

To represent the anode and cathode environments in the test, an acidic aqueous solution is chosen to represent the electrolyte. The central portion of the cell consists of platinum screens, electrodes, and carbon flow fields in contact with the BPP. Electrical current is passed through the conductors, and the resistance of the anode and cathode interfaces is measured. Bubbles of hydrogen (anode) and air (cathode) across the interface provide circulation between the BPP region and electrolyte reservoirs. Platinum catalyzed electrodes establish rest potentials between the BPP and electrolyte.



*The Corrosion Test Cell Unit*



## Technology History

- ◆ Developed at LANL and licensed to Fuel Cell Technologies, Inc.
- ◆ Commercialized and being marketed in 2008 by Fuel Cell Technologies with two units sold to date.

## Applications

Can be used to represent as closely as possible the conditions at the anode and cathode of an operating PEM fuel cell to test the BPP material.

## Capabilities

- ◆ Provides a long-term measurement of electrical resistance of the anode and cathode BPP interfaces.
- ◆ Allows soluble BPP dissolution products to be monitored in the electrolytes.

## Benefits

### Cost Savings

Reduces costs by using corrosion cells and accessory equipment rather than the traditional fuel cell test stands.

### Efficiency

Allows materials to be screened without fabrication of BPPs and multiple cells to screen multiple materials at the same time, reducing development time.

### Versatility

Provides an intermediate level of screening for BPP materials between potentiostatic measurements and long-term fuel cell tests.

**Contact Information:****Chuck Derouin***Email:* [chuck@fuelcelltechnologies.com](mailto:chuck@fuelcelltechnologies.com)*Phone:* (505) 821-4762**Fuel Cell Technologies, Inc.**

5620 Venice Ave., Suite F

Albuquerque, NM 87113

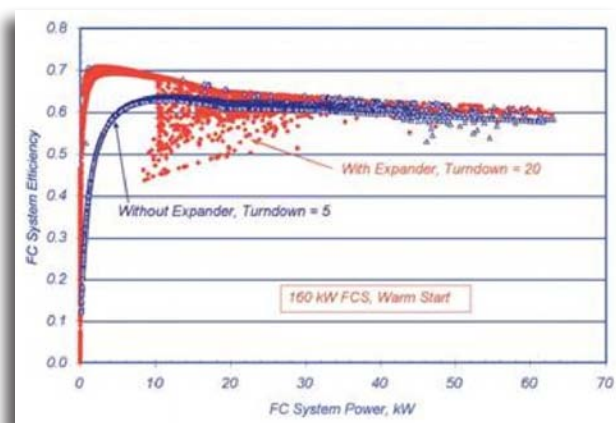
**Website:** [www.fuelcelltechnologies.com/fuelcell](http://www.fuelcelltechnologies.com/fuelcell)

## New Modeling Tool Allows System Designers a Flexible and Speedy Simulation of Fuel Cell Systems and Subsystems

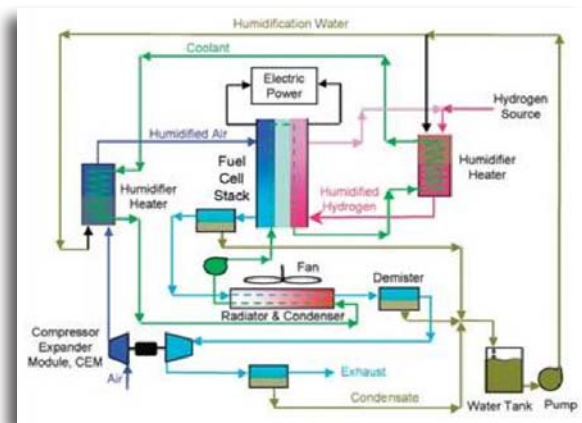
While developers are addressing improvements in components and subsystems in automotive fuel cell propulsion systems, such as fuel cells, stacks, fuel processors, and balance-of-plant components, Argonne National Laboratory, with support from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, has developed a modeling and analysis tool that allows system designers to manipulate and validate different configurations without having to build a functional prototype.

The Generational Computational toolkit (GCtool) software package offers speed, flexibility, and user-friendliness, allowing end-users to address issues of thermal and water management, design-point and part-load operation, in addition to component, system, and vehicle level efficiencies and fuel economies. Such analyses are essential for effective system integration while avoiding the expense and delays of building different fuel cell or power-plant configurations for evaluation.

The GCtool's strength lies in the flexibility of the program. Using a common C or C-linkable language, the GCtool enables developers to use existing libraries or modules to incorporate custom models of any desired level of sophistication (fidelity) created by end-users. Capable of performing both steady-state and dynamic analyses, the program allows for unlimited parameter sweeps and also performs constrained optimization where specific constraint definition is not a prerequisite for system operation.



*Effect of Expander on Dynamic System Efficiency over an Urban Drive Cycle*



*Schematic Diagram of a Hydrogen-Fueled Polymer Electrolyte Fuel Cell System for Automotive Applications*

## Technology History

- ◆ Developed and commercialized by Argonne National Laboratory.
- ◆ Sold more than 67 licenses since 1999.

## Applications

Can be used by end-users to develop component or system configurations and simulations that can be used to evaluate developmental components and systems against efficiency targets for fuel cell deployment.

## Capabilities

- ◆ Enables modeling and analysis of various fuel cell subsystems and portfolios, including polymer electrolyte, molten carbonate, phosphoric acid, and solid oxide fuel cells designs.
- ◆ Allows for simulations that can represent any duty cycles, such as the various automotive driving schedules, for the applications of interest.
- ◆ Allows users to change the baseline information and corresponding library details for alternative configurations.
- ◆ Can be used to model pressurized fluidized-bed combustion and integrated gasification/combined-cycle power plants and other coal combustion systems.

## Benefits

### Cost Savings

Enables users to test and validate models without incurring the time and costs of building a prototype.

### Efficiency

Allows modeling and simulation of systems with rapid turnaround time for analysis and troubleshooting.

### Flexibility

Offers a library of models for subcomponents and property tables common to many systems and allows users to add their own component models, if needed.

**Contact Information:**  
**Rajesh Ahluwalia**  
*Email:* [walia@anl.gov](mailto:walia@anl.gov)  
*Phone:* (630) 252-5979  
**Argonne National Laboratory**  
9700 South Cass Avenue  
Argonne, IL 60439  
**Website:** [www.anl.gov](http://www.anl.gov)

## Proven and Reliable Hydrogen Fuel Cell System Provides Backup Power for Electric Utility Substations and Telecommunication Stations

A fuel cell produces electricity through an electrochemical process that strips the electrons from hydrogen atoms using a catalyst and sends them through an electrical circuit while the protons pass through a membrane. They recombine with oxygen to form water as the only byproduct of the process. Unlike conventional diesel generators, the Plug Power Inc. GenCore fuel cell system provides instant power during a grid outage. Plug Power developed this zero emission fuel cell system with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, and it provides backup power to critical infrastructure, including computer and communications equipment.

Currently, 20 GenCore systems are being used at five New Mexico National Guard facilities in Santa Fe and Rio Rancho, New Mexico. This is the largest installation and demonstration of emergency backup power hydrogen fuel cells in the National Guard. Each unit has 6 cylinders of hydrogen and, in the event of a power failure, will operate for 11 hours on the current supply. Additional hydrogen extends the runtime of the system. The low-maintenance feature of these units increases their availability when needed. The use of hydrogen as a fuel reduces dependence on foreign oil.



*Plug Power's 5-kW GenCore Fuel Cell Provides Emergency Backup Power at the New Mexico National Guard Facility in Santa Fe*



*The GenCore Fuel Cell System*

## Technology History

- ◆ Developed and commercialized by Plug Power Inc.
- ◆ Deployed first units at New Mexico National Guard in 2008.

## Applications

Can be used to provide backup power that is fueled by clean hydrogen. The 5U series provides power for utility substations and the 5T series provides power for telecom stations.

## Capabilities

- ◆ Can be used anywhere backup power is required.
- ◆ Can be used in environmentally sensitive locations because of its silent operation and nontoxic byproduct, water.
- ◆ Starts up instantly when power is lost.

## Benefits

### Environmental

Provides a silent and nonpolluting system, with only water as a byproduct.

### Reliability

Offers low maintenance and provides instant startup.

### Versatility

Offers a modular design to enable multiple units to be installed for more power and allows more hydrogen cylinders to be added to increase the run duration.

#### Contact Information:

**Erin Lane**

Email: [erin\\_lane@plugpower.com](mailto:erin_lane@plugpower.com)

Phone: (202) 484-5300

**Plug Power Inc.**

968 Albany Shaker Road

Latham, NY 12110

Website: [www.plugpower.com](http://www.plugpower.com)

# Improved Catalyst Coated Membrane (CCM) Manufacturing

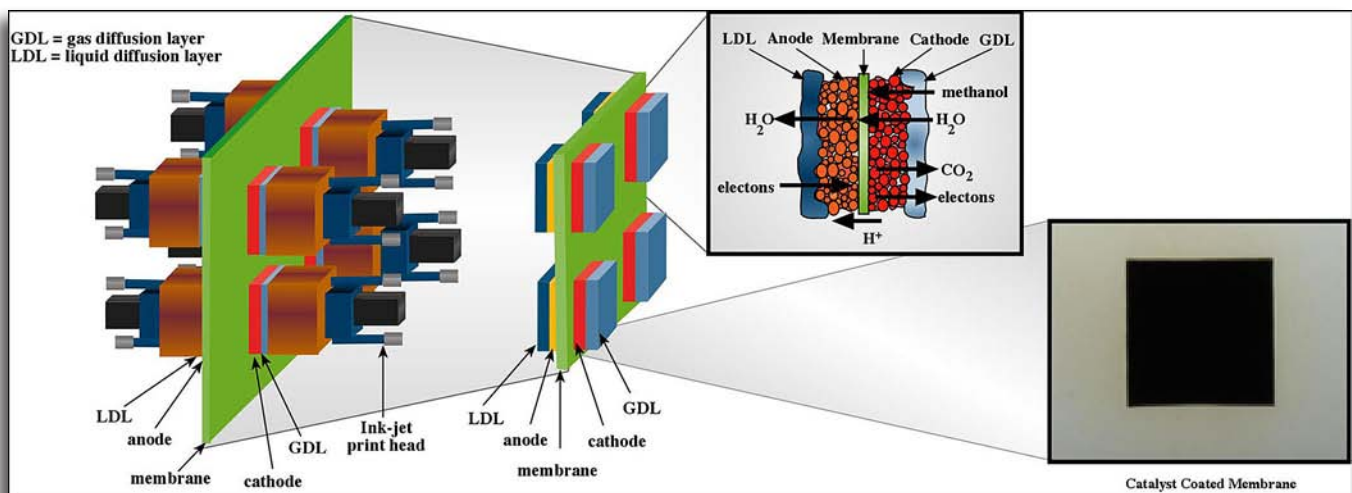
Commercial Technology

## New Spray Deposition Technique Results in Lower Manufacturing Costs at Higher Volumes

The conventional technologies for manufacturing catalyst coated membranes/membrane electrode assemblies (CCMs/MEAs) include screening printing, roller coating, decal transferring, and gravure coating. Each technology requires significant investment for the fuel cell CCM production application. The relatively complex manufacturing process associated with these technologies does not allow the flexibility to meet different direct methanol fuel cell (DMFC) equipment manufacturer's application requirements. In addition to the lack of flexibility, these technologies also suffer from low yields, further increasing the cost of the finished product.

To overcome these limitations, Cabot Corporation developed a revolutionary spray deposition manufacturing technology along with specialized inks and catalyst powders. Cabot received development funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program through the National Center for Manufacturing Sciences. This new manufacturing platform can be used for CCM/MEA production with existing printer or spray deposition systems. It uses special electrocatalyst inks with a limited amount of capital investment per volume demand and has a much simpler manufacturing process. It also improves CCM performance and possesses a high degree of flexibility to meet various DMFC customers' requirements.

This new manufacturing technology will help expedite the commercialization of DMFCs and impact fuel cell manufacturing costs and processes. It allows high-volume production of CCMs/MEAs with lower platinum content and higher fuel cell performance. This technology can be easily applied to other areas by printing catalysts on substrates for other industries, such as membrane reactors, gas separation membranes coated with selective catalysts, other types of fuel cells (e.g., solid oxide fuel cells), electrolyzers, ultracapacitors, batteries, and other coated membrane applications. This new manufacturing technology is now available for licensing, and the associated electrocatalyst inks and catalyst powders are commercially available.



*Cabot's Catalyst Coated Membrane Manufacturing Process*

## Technology History

- ◆ Developed and marketed by Cabot Corporation.
- ◆ Offers associated electrocatalyst inks and catalyst powders from Cabot Superior Micropowders, a division of Cabot Corporation.

## Applications

Can be used to manufacture CCMs/MEAs for DMFCs or other industries, e.g. membrane reactors, gas separation membranes coated with selective catalysts, other types of fuel cells (e.g., solid oxide fuel cells), electrolyzers, ultracapacitors, batteries, and other coated membrane applications.

## Capabilities

- ◆ Provides low-cost, high-volume manufacturing of CCMs for fuel cells.
- ◆ Reduces the amount of precious metals needed in fuel cells.

## Benefits

### Cost Savings

Reduces the cost of manufacturing CCMs and the amount of expensive precious metals used in a fuel cell.

### Productivity

Allows higher production and higher yields.

### Versatility

Can be used with existing spray deposition systems and allows quick changeover to different materials.

**Contact Information:****Hanwei Lei***Email:* [hanwei\\_lei@cabot-corp.com](mailto:hanwei_lei@cabot-corp.com)*Phone:* (505) 563-4419**Cabot Corporation**

5401 Venice Ave NE

Albuquerque, NM 87113

**Website:** [www.cabot-corp.com](http://www.cabot-corp.com)



## New Test Equipment Allows Rapid Testing of Fuel Cell Components

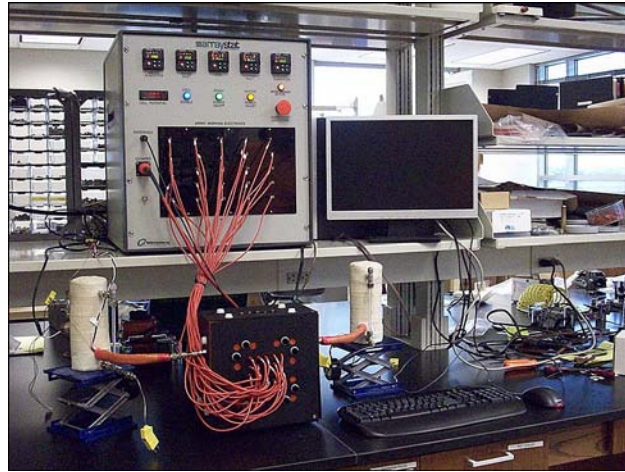
Platinum is currently used as a catalyst in fuel cell membrane electrode assemblies (MEAs). Unfortunately, platinum is an expensive precious metal and its use increases the overall cost of a fuel cell. Reducing the amount of platinum or substituting alternative materials requires time-consuming ex situ methods of analysis that do not consider the effects of the realistic catalyst environment and flowing reactant fuel and oxidant streams. A device is needed that evaluates the catalyst as it is incorporated into a real MEA in an operating fuel cell.

NuVant Systems Inc., with a U.S. Department of Energy Small Business Innovation Research (SBIR) grant, developed testing equipment that eliminates the need for multiple test stations and provides a convenient way to test MEAs realistically and rapidly. The Arraystat™ requires only one pair of mass flow controllers and a single operator to run the equivalent of 25 single-cell test stations. In addition, a separate parallel array fuel cell test fixture allows a membrane to be screened in an actual fuel cell environment. NuVant's patented technology uses an array MEA. The counter electrode of the array MEA consists of a single large area standard fuel cell electrode, while the array side consists of a library of 25 catalyzed spots. Each spot consists of a user-supplied gas-diffusion-layer disc that is catalyzed by the end user's method and is attached to the membrane. The assembly is then housed in the patented array fuel cell through which fuels and oxidants are delivered. The completed assembly may then be connected to the Arraystat, which can be routed to a computer using the associated software to gather and analyze the data. The Arraystat individually addresses each electrode disc. This method allows for the preparation and testing of various MEAs with high throughput under realistic catalyst loadings and reactant flow rates.



*NuVant's Array Potentiostat (Arraystat) and Parallel Array Flow-Field Fuel Cell*





*NuVant's Array Potentiostat (Arraystat) Connected to Parallel Array Fuel Cell*

## Technology History

- ◆ Started research in 2004.
- ◆ Sold first commercial Arraystat in 2006 and the first commercial parallel array fuel cell in 2007. To date, sold six Arraystats and seven parallel array fuel cell test units.

## Applications

Can be used to test MEAs using different combinations of catalysts as well as flow-field design, MEA degradation, parallel battery charge-discharge characteristics, and optimized plating conditions.

## Capabilities

- ◆ Measures and records data from 25 separate locations.
- ◆ Achieves high throughput through modular design and allows MEA component or flow-field evaluation.

## Benefits

### Accuracy

Eliminates random error introduced by multiple test stands because a single common counter electrode is used.

### Cost Savings

Reduces costs associated with testing MEAs because of the high throughput and single test station.

### Versatility

Allows maximum flexibility by having user-defined measurement discs.

**Contact Information:**  
**Eugene S. Smotkin**  
 Email: [esmotkin@nuvant.com](mailto:esmotkin@nuvant.com)  
 Phone: (219) 644-3231  
**NuVant Systems Inc.**  
 9800 Connecticut Drive  
 Crown Point, IN 46307  
 Website: [www.nuvant.com](http://www.nuvant.com)

# Integrated Manufacturing for Advanced Membrane Electrode Assemblies

Commercial Technology

## New Fabrication Process Reduces Costs and Improves Performance of Fuel Cells

BASF Fuel Cell, Inc., formerly PEMEAS Fuel Cell Technologies, E-TEK Division, with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, developed an advanced membrane electrode assembly (MEA) fabrication process using improved cathode structures and catalysts and a durable membrane. The assembly uses a new design for the gas diffusion electrode (GDE). The new design incorporates the "fine gradient" ELAT<sup>®</sup> electrode (trademark derived from Electrode, Los Alamos Type), resulting in assemblies that can run longer with stable voltages. By modifying the fine gradient structure, performance is improved when operating at lower relative humidity. The fine gradient approach has also decreased precious metal loading, which reduces the cost of the material. By reducing undesired variations in coating quality, fine gradients of architectural features can be created, such as pore size distribution and hydrophobicity within the gas diffusion layer structure.

All of these structures were initially fabricated on a sophisticated developmental coating machine to facilitate assessment for high-volume manufacturing. Roll-to-roll ion beam deposition methods resulted in greater stability compared with conventional supported catalysts. The fine gradient manufacturing approach lowers the amount of precious metal without a loss of power, provides greater ability for water elimination in the gaseous diffusion layer (GDL), and, with the proper design, greater water retention in the electrode for operating in dry conditions. This work generated new spin-off products for gas diffusion electrodes (fine gradient ELAT), MEAs (for direct methanol fuel cells), and electrocatalysts (next generation platinum and platinum-alloys).



*BASF Coating Machine for MEAs*

## Technology History

- ◆ Developed by BASF in partnership with DuPont Fuel Cells, Nuvera Fuel Cells, Spire Biomedical Corp, Northeastern University, and Case Western Reserve University.
- ◆ Manufactured products such as catalysts, GDEs/GDLs and MEAs for direct methanol fuel cells being marketed by BASF.

## Applications

Can be used in polymer electrolyte membrane fuel cells operating at higher temperatures and low water vapor pressures. The advanced MEA fabrication process is amenable to mass production.

## Capabilities

- ◆ Uses less platinum in cathode structures and catalysts without a loss in performance.
- ◆ Allows durable membrane to operate at high temperatures and low water vapor pressures.
- ◆ Allows mass production of MEAs.

## Benefits

### Cost Savings

Requires less precious metal in MEAs and reduces cost by using high-volume manufacturing methods.

### Durability

Displays greater stability of the ion-beam assisted deposition cathodes compared with supported catalysts.

### Efficiency

Offers conductivity at subfreezing temperatures as well as at high temperatures and low relative humidity.

**Contact Information:****Emory S. De Castro***Email:* [emory.decastro@basf.com](mailto:emory.decastro@basf.com)*Phone:* (732) 545-5199 x4114**BASF Fuel Cell, Inc.**

39 Veronica Ave.

Summerset, NJ 08873

**Website:** [www.basf.com](http://www.basf.com)

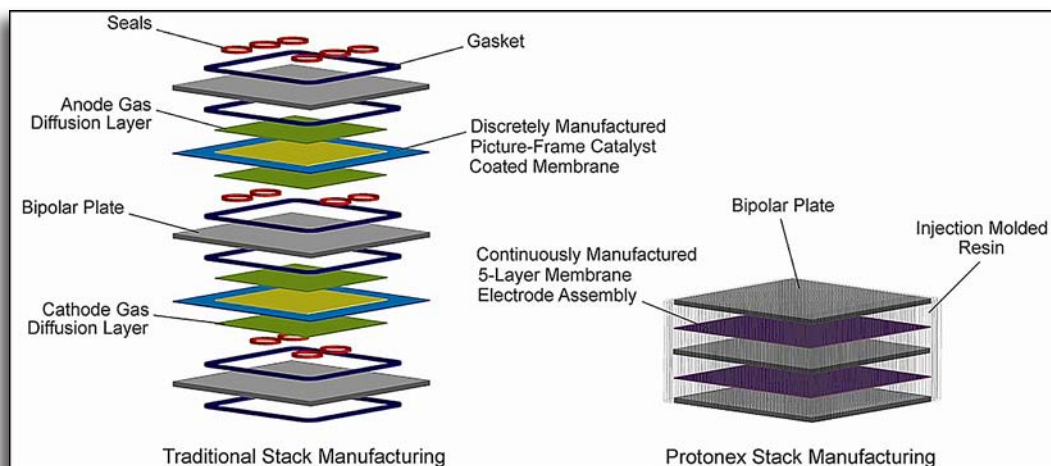
# Novel Manufacturing Process for PEM Fuel Cell Stacks

## One-Step Molding Process Reduces Manufacturing Costs and Improves Fuel Cell Stack and System Durability

The foremost hurdle facing fuel cell developers today is high manufacturing costs. Today's state-of-the-art stack fabrication technology has low manufacturing yields and poor stack reliability, resulting primarily from manual assembly methods and multiple sealing interfaces. Additionally, complicated product designs and gasket-reliant assembly increase production costs and reduce fuel cell durability. While economy-of-scale will address the cost issues for many ancillary components of integrated fuel cell systems, stack manufacture and reliability remain major concerns.

Protonex Technology Corporation has addressed these concerns with a novel manufacturing method that eliminates the labor-intensive stacking/alignment and multiple component design of conventional stack fabrications. This new process was refined with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program through the National Center for Manufacturing Sciences. Protonex uses a one-step molding process that creates the structure necessary to seal the stack and five-layer membrane electrode assemblies.

Two portable power system product lines have used this new manufacturing process. The Quantum™ line is for commercial users and the Pulse™ line is for military customers. Currently, 250-watt Pulse systems are being supplied to the U.S. military, and the U.S. Army has funded further improvements in the system.



*Protonex Injection-Molded Stack Versus Traditional Stack Assembly*



*Protonex Technology Fuel Cell Stacks*

## Technology History

- ◆ Developed and commercialized by Protonex Technology Corporation to manufacture the Quantum and Pulse portable power systems.
- ◆ Delivered 10 Pulse systems on a military contract in 2008.

## Applications

Can be used to manufacture polymer electrolyte membrane (PEM) direct methanol and alkaline-based fuel cells for consumer electronics, portable soldier power devices, residential utilities, and automotive engines.

## Capabilities

- ◆ Demonstrates that high-performance PEM stacks can be produced with a high degree of manufacturability.
- ◆ Reduces part count and complexity and manufacturing cycle time.

## Benefits

### Cost Savings

Lowers costs by using lower tolerance and fewer components.

### Efficiency

Offers significant part count reduction and improved (lower) manufacturing time.

### Reliability.Robustness

Uses adhesive-based seals to improve stack reliability and robustness over traditional compression-based seals.

### Versatility

Is easily automated, uses membrane electrode assemblies more efficiently, and reduces the need for tension members.

#### Contact Information:

**Michael McCarthy**

Email: [michael.mccarthy@protonex.com](mailto:michael.mccarthy@protonex.com)

Phone: (508) 490-9960

**Protonex Technology Corporation**

153 Northboro Road

Southborough, MA 01772

Website: [www.protonex.com](http://www.protonex.com)



# PureMotion® 120 Fuel Cell Powerplant

Commercial Technology

## New Hydrogen Fuel Cell System Being Sold to Power Next-Generation Zero-Emission Transit Buses

The PureMotion® 120 Fuel Cell Powerplant (FCPP) was developed by UTC Power using funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. One UTC Power project, entitled Motor Blower Technologies for Fuel Cell Automotive Power Systems, resulted in small, lightweight, motor-driven blowers to provide cathode air and reformer air for a near-ambient pressure fuel cell operating on gasoline. A second project, entitled Sensors for Automotive Fuel Cell Systems, resulted in the technology and commercial supplier base capable of supplying physical and chemical sensors required to optimize the fuel processing operation of polymer electrolyte membrane (PEM) fuel cell automotive power plants.

These projects, along with other programs combined with UTC Power's engineering, design and development, resulted in the PureMotion 120 FCPP, an integrated fuel cell power source for transportation applications. UTC Power is using this knowledge to continuously improve the performance of its products and to apply this technology to other areas of fuel cell development. The results of this application of knowledge will increase the utilization of fuel cells in transportation and allow the use of alternative fuels such as hydrogen.



*A Bus Using the PureMotion 120 Fuel Cell Powerplant*



*The PureMotion 120 Fuel Cell Powerplant*

## Technology History

- ◆ Developed and commercialized by UTC Power.
- ◆ Deployed first unit in 2005 with six units now in use on buses.

## Applications

Can be used as a power source for vehicles using hydrogen as a fuel or as a stationary 120-kW power source.

## Capabilities

Can be used anywhere a 120-kW power source is needed for vehicular transportation needs.

## Benefits

### Cost Savings

Reduces cost through mass manufacturing and better designs.

### Environment

Produces water as a byproduct when hydrogen is used as a fuel source.

### Versatility

Uses hydrogen produced from various sources, including renewable sources.

#### **Contact Information:**

**Mike Tosca**

Email: [mike.tosca@utcpower.com](mailto:mike.tosca@utcpower.com)

Phone: (860) 727-7324

**UTC Power**

195 Governor's Highway

South Windsor, CT 06074-2419

Website: [www.utcpower.com](http://www.utcpower.com)

# Scale-Up of Carbon-Carbon Composite Bipolar Plates

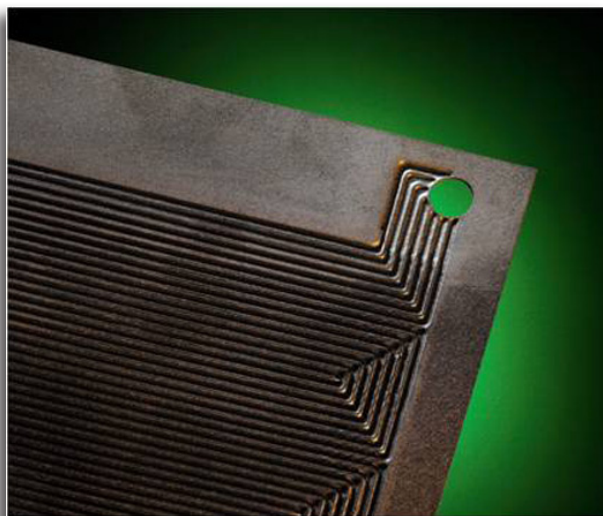
Commercial Technology

## New Molded, Porous Carbon-Carbon Composite Bipolar Plates Offer Fuel Cell Performance and Cost Advantages

In the past, it was not uncommon for fuel cell companies to pay up to \$400 per cell in bipolar plate costs. Even today, some bipolar plates are constructed of graphite, which requires expensive machining to fabricate. When a cost of \$400 per cell is extended to automotive applications where 300 or more cells are required, the cost becomes prohibitive. In addition to the expensive machining, weight and electrical contact resistance are also less than desirable in conventional graphite bipolar plates.

In April 2001, Porvair Advanced Materials, Inc., licensed from Oak Ridge National Laboratory a carbon-carbon composite bipolar plate formation technology that addressed these problems. Using funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, Porvair investigated transferring this technology from the laboratory to full-scale, low-cost mass production. This investigation also looked at refining the material and its composition to improve fuel cell properties and performance.

The result of this investigation was a new, commercial, fully molded, high-performance porous bipolar plate product that is easily scaled to high volumes. Cost analyses showed that the Porvair plate could meet automotive volume pricing of less than \$4 per kilowatt. Performance of the plates was found to be excellent, meeting or exceeding the performance of competitive products, including state-of-the-art, expensive machined graphite products. Since 2007, Porvair has manufactured more than 10,000 bipolar plates using this technology.



*Fully Molded Porvair Bipolar Plate*



## Technology History

- ◆ Developed and commercialized in 2003 by Porvair Advanced Materials, Inc.
- ◆ Manufactured more than 50,000 bipolar plates between 2003 and 2008.

## Applications

Can be used in polymer electrolyte membrane fuel cells instead of expensive machined plates.

## Capabilities

- ◆ Allows for molding of a wide array of product designs because of process flexibility.
- ◆ Minimizes contact resistance between cells.
- ◆ Resists the corrosive environment in the fuel cell.
- ◆ Reduces the weight of the fuel cell stack compared with graphite plates.

## Benefits

### Cost Savings

Provides high-volume manufacturing with no machining, reducing the cost of the plates.

### Performance

Resists the corrosive environment in the fuel cell.

### Weight Reduction

Provides an extremely lightweight product with a density of about 1.2 grams per cc.

**Contact Information:**  
**David P. Haack**  
*Email:* [dhaack@Pamus.com](mailto:dhaack@Pamus.com)  
*Phone:* (828) 697-2411  
**Porvair Advanced Materials, Inc.**  
700 Shepered St.  
Hendersonville, NC 28792  
**Website:** [www.porvair.com](http://www.porvair.com)

# XX25™: Portable Reformed Methanol Fuel Cell

Commercial Technology

## Lightweight, Rugged Fuel Cell Unit Provides Innovative Mobile Power for Soldiers in the Field

The XX25 portable reformed methanol fuel cell is a self-contained, 25-W output power system that uses a fuel cell in conjunction with a methanol fuel source to generate power. The XX25 was developed by UltraCell Corporation with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, through the Edison Materials Technology Center. The fuel source can be external or enclosed as an integral part of the unit as a replaceable cartridge. The XX25 contains a power button, an output connector, an LCD display (backlit and contrast adjustable), and a fuel cartridge that contains the methanol fuel.

The XX25 is ruggedized and has successfully passed extreme environmental testing that meets military standards. The testing subjected the XX25 to temperature extremes, vibration, dust, corrosive environments, and other extreme conditions. The lightweight system operates silently and may be operated continuously by hot swapping fuel cartridges. A larger external fuel source may be used for extended run times and a one-gallon fuel tank will supply 2,500 watt-hours of energy.



*The XX25 Fuel Cartridge and Portable Pack Unit*

## Technology History

- ◆ Developed and being marketed by UltraCell Corporation.
- ◆ Won “Best Soldier System Innovation & Technology” at the Soldier Technology USA 2008 Conference.
- ◆ Commercialized in 2007 and more than 200 units sold.

## Applications

Can be used by individual soldiers for portable power for laptops, communication devices, off-grid battery charging, etc.

## Capabilities

- ◆ Supplies up to 25 watts of power continuously with hot swapping of methanol fuel cartridges.
- ◆ Can be hybridized with external batteries for high power peaks and with up to 5 gallon fuel tanks for long run time.

## Benefits

### Durable

Has passed military standard testing (MIL-STD-810F Environmental Testing) for extreme conditions and contains no moving parts that can fail.

### Environmental

Provides fuel that is totally contained in the cartridge with no toxic byproducts during use.

### Portable and Versatile

Weights 1.24 kilograms and is about the size of a hardback book; can be used with different size fuel cartridges or an external fuel source; and offers various voltages (12 to 30 volts).

**Contact Information:****Ian Kaye***Email:* [ikaye@ultracellpower.com](mailto:ikaye@ultracellpower.com)*Phone:* (925) 455-9400 x103**UltraCell Corporation**

399 Lindbergh Avenue

Livermore, CA 94551

**Website:** [www.ultracellpower.com](http://www.ultracellpower.com)



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## Hydrogen Electrolysis System Provides High Purity Hydrogen for Fueling Vehicles in a Variety of Climates

The potential worldwide markets for hydrogen-fueled vehicles are broad, encompassing everything from passenger cars, scooters, and buses to trucks, forklifts, and military vehicles. Leading global manufacturers in each of these markets are developing products that require hydrogen. Proton Energy Systems, Inc., as part of a demonstration project managed by EVermont and funded by the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, developed FuelGen, a hydrogen fueling system. The demonstration fueling station in Burlington, Vermont, completed in 2006, uses wind-generated electricity as well as grid-supplied electricity to produce 8 to 12 kilograms of hydrogen fuel per day. This station demonstrates the ability of the FuelGen system to deliver 99.999% pure hydrogen fuel in a harsh, cold environment.

In the FuelGen polymer electrolyte membrane (PEM) electrolysis unit, water is electrolyzed and broken down into its molecular components of H<sub>2</sub> and O<sub>2</sub>. The H<sub>2</sub> is captured and stored as a compressed gas and used as a motor fuel. The FuelGen system is a fully integrated, packaged electrolysis system that includes support and safety systems for regulating electrolyzing operations. The system offers automated tank-topping operation and an on-board water purification system. The system also offers an integrated vent stack with automatic drain trap, hydrogen product line isolation solenoid valve, integrated dew point monitoring system, an outdoor rated enclosure with shrouds, and an option for remote monitoring.

A fueling station involving photovoltaic solar panels opened in Las Vegas, Nevada, in April 2007 to demonstrate the viability of fuel cell technology in a hot, dry climate. Another FuelGen system was sold in 2007 and is operating in White Plains, New York; and in 2008 a system started in Sacramento, California. Three or four more FuelGen systems are expected to be sold for the remainder of 2008.



*EVermont Demonstration Fuel Station in Burlington, VT*



*FuelGen Station in Las Vegas, NV*

## Technology History

- ◆ Developed by Proton Energy Systems, Inc., in partnership with EVermont.
- ◆ Commercially available from Proton Energy Systems, Inc., since 2007.
- ◆ Sold three units since 2007.

## Applications

Can be used to generate compressed hydrogen gas by splitting water (electrolysis) and takes advantage of renewable power sources such as wind and solar. The hydrogen is intended to displace traditional fuels such as gasoline as a motor fuel and replace it with hydrogen as a fuel.

## Capabilities

- ◆ Generates over 13 kg/day of hydrogen at up to 400 psi.
- ◆ Produces 99.999% purity hydrogen.
- ◆ Uses a power conservation mode during standby.

## Benefits

### Purity

Consistently produces 99.999% pure hydrogen without the need for additional cleanup of the hydrogen and via the same PEM technology used in the original equipment manufacturer automotive fuel cells.

### Simplicity

Installs and operates in a day with as little as 4 hours of maintenance per year.

### Sustainability

Creates transportation energy in a localized, decentralized, and sustainable manner and allows wind or solar energy to be used to produce the hydrogen.

#### Contact Information:

**Mark Schiller**

Email: [mschiller@protonenergy.com](mailto:mschiller@protonenergy.com)

Phone: (203) 678-2185

**Proton Energy Systems, Inc.**

10 Technology Drive

Wallingford, CT 06111

Website: [www.protonenergy.com](http://www.protonenergy.com)



# H2 ProGen: A Total Supply Solution for Hydrogen Vehicles

Commercial Technology

## Integrated, On-Site Hydrogen Generation/Dispensing Station Allows Hydrogen Fueling at Reduced Cost

The H2 ProGen System is an integrated, on-site hydrogen generation and dispensing system that provides a “turn-key” hydrogen infrastructure solution. Gas Technology Institute (GTI), working with GreenField Compression (a brand within the Atlas Copco Group), developed the system to include hydrogen generation, purification, compression, storage, and dispensing. The system was developed with funding from the U.S. Department of Energy’s Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program.

The first installation of the integrated system is at the University of Texas, Center for Electro Mechanics in Austin, Texas. The H2 ProGen hydrogen fueling station is skid-mounted, fabricated, and tested in the manufacturing plant, then delivered as a completed system to the site. It can be readily deployed with quick connection to water, gas, and electric utilities to easily provide on-site hydrogen production, storage, and dispensing. Natural gas is anticipated to be the most common feedstock for on-site hydrogen generation, but the GTI-developed reformer system can also use ethanol (E-85), biodiesel, and other renewable fuels to produce hydrogen. GTI and GreenField have also designed the system to use an electrolyzer for hydrogen generation.

GreenField’s G1E or G2E is a separate hydrogen dispenser that can be purchased individually or as part of the packaged system. The dispenser has integrated cascade storage sequencing valves, a precision mass flow meter, and a patented algorithm for achieving full fill performance without requiring a vehicle communications link. The dispenser relies on the GTI-developed and patented HydroFill™ technology. The dispenser is designed to service high-pressure, compressed-hydrogen vehicles. The core dispenser is based on a derivative of a Gilbarco gasoline dispenser and benefits from an ability to interface with commercial point-of-sale management systems.



*H2 ProGen Hydrogen Dispensing Station*





*H2 ProGen Unit in Transit*

## Technology History

- ◆ Developed by GTI and marketed by GreenField Compression (a brand within the Atlas Copco Group).
- ◆ Became commercially available in 2007 with one fuel station in use at the University of Texas in Austin.

## Applications

Can be used as a hydrogen supply station for all hydrogen-fueled vehicles that require high-pressure compressed hydrogen such as cars, trucks, buses, and industrial lift vehicles.

## Capabilities

- ◆ Produces hydrogen by reformation of hydrocarbon fuels such as natural gas, propane, ethanol, biodiesel, or Fischer-Tropsch liquids.
- ◆ Compresses and stores hydrogen in an on-board storage assembly.
- ◆ Produces and delivers 20 to 200 kg of hydrogen per day.

## Benefits

### Cost Savings

Integrates the key hydrogen station components at the factory into the H2 ProGen system, greatly reducing site engineering and construction costs.

### Emissions Reductions

Reduces emissions compared with trucked-in liquid or gaseous hydrogen and grid-supplied electrolyzer-based systems.

### Energy Savings

Achieves full-cycle energy savings compared with trucked-in liquid or gaseous hydrogen and electrolyzer-based systems.

#### Contact Information:

**Jared Hightower**

Email: [Jared.Hightower@us.atlascopco.com](mailto:Jared.Hightower@us.atlascopco.com)

Phone: (972) 889-2400

**GreenField Compression**

909 North Bowser Road

Richardson, TX 75081

Website: [www.greenfieldcompression.com](http://www.greenfieldcompression.com)

# High-Efficiency, High-Pressure Electrolysis via Photovoltaic Arrays

Commercial Technology

## Flexible, Innovative Hydrogen Production System Uses Renewable Power to Reduce Emissions and Costs

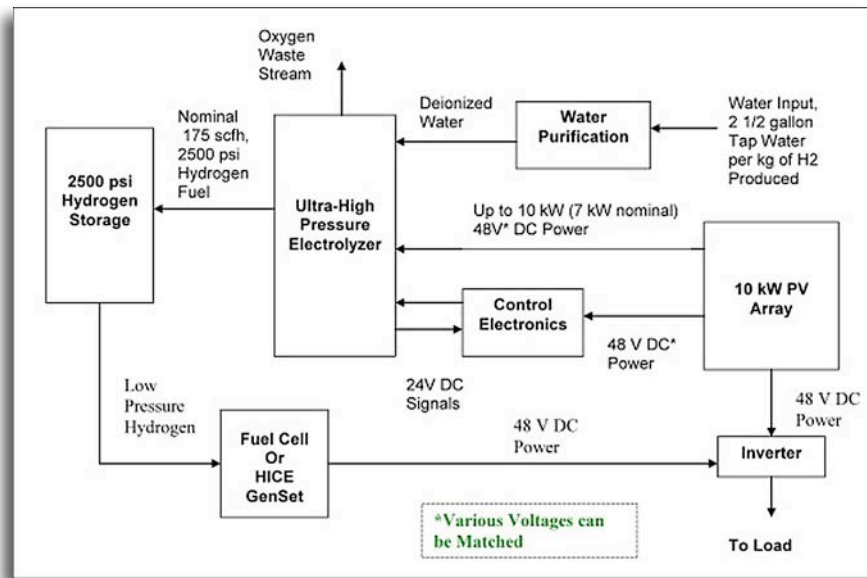
Producing hydrogen from renewable energy sources, such as solar and wind in distributed generation applications, provides an environmentally preferable option for the sustainable delivery of fuel-grade hydrogen. However, to gain commercial acceptance, the hydrogen generation systems must be reliable and cost-effective to deploy. Eliminating the complex and high maintenance mechanical compressor used to supply high-pressure hydrogen to the point-of-use is recognized as a significant goal in improving the reliability and cost position of hydrogen generating systems.

Avalence, LLC, with support from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, developed an innovative hydrogen generating system that links a photovoltaic power supply to an ultra-high-pressure electrolysis unit that can generate fuel-grade hydrogen at pressures consistent with point-of-use storage and delivery (5,000 to 10,000 psig). With the electrolysis cell producing fuel at delivery pressure, the need for additional mechanical compression is eliminated.

With several commercially installed and operational units, current work is building on previous research, development, and design efforts for units running at various pressures. With engineering and design flexibility, additional units are being built to custom specifications required by customers. Continuing product development is centered on detailed component analysis and parametric testing to determine production efficiencies with varying light conditions and electrolyzer cell configurations so that findings may be incorporated into future operating hydrogen production systems.



*The Avalence Electrolysis Unit with Photovoltaic Array*



*Avalence Solar Energy Electrolysis Schematic*

## Technology History

- ◆ Developed and being marketed by Avalence, LLC; commercialized in 2007, with 4 units sold and operating in the field and several more in production.

## Applications

Can be used to generate and deliver high-pressure hydrogen (over 5,000 psig) and can be coupled to a renewable energy generating source such as photovoltaic arrays.

## Capabilities

- ◆ Generates and delivers high-pressure hydrogen without additional compression.
- ◆ Can deliver 1 to 30 kg/day of hydrogen, with models up to 300 kg/day in development.

## Benefits

### Cost Savings

Cuts the point-of-use cost of hydrogen production up to 50% and operating expenses by 20%.

### Environmental

Provides flexible integration with renewable energy sources, which increases the use of "green" power, and provides an emission-free platform for hydrogen generation.

**Contact Information:**  
**Martin Shimko**  
 Email: [mas@avalence.com](mailto:mas@avalence.com)  
 Phone: (203) 701-0052  
**Avalence, LLC**  
 1240 Oronoque Road  
 Milford, CT 06460  
 Website: [www.avalence.com](http://www.avalence.com)

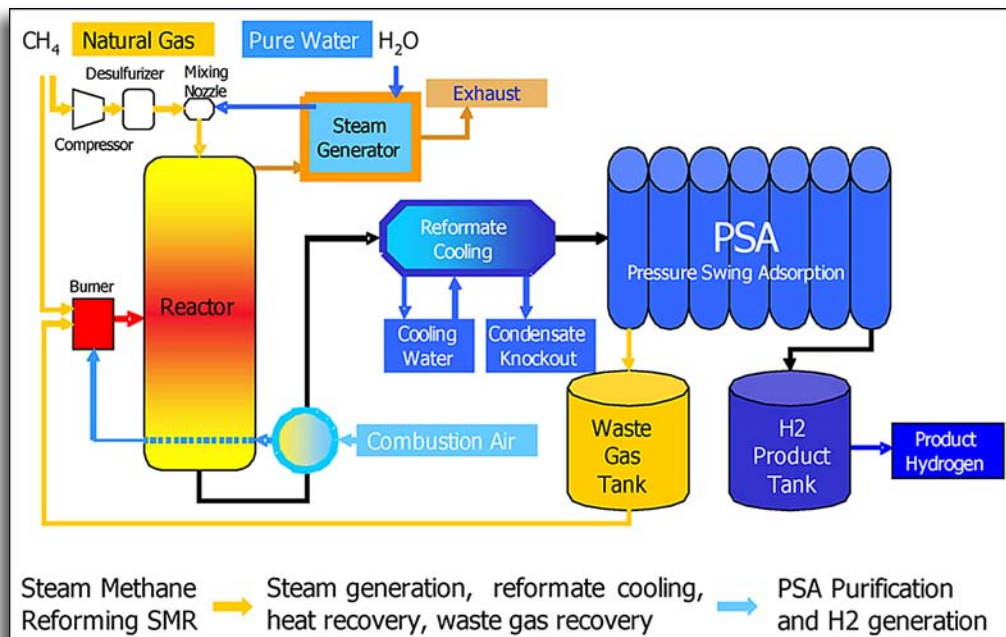
# Hydrogen Distributed Production System

## New Hydrogen Generation Module Reduces Production and Fuel Costs at Increased Capacities

H<sub>2</sub>Gen Innovations, Inc., has been building on their existing steam methane reforming platform to address many of the acknowledged technical barriers that exist in the hydrogen production marketplace. H<sub>2</sub>Gen, with support from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, has built and tested and is now selling a steam methane reformer with a built-in pressure swing adsorption (PSA) system that will achieve future DOE cost and efficiency targets.

To meet cost targets, H<sub>2</sub>Gen has developed a hydrogen generation module (HGM) that has 5 times the current capacity of their commercially available HGM-2000 model, which produces up to 113 kg/day of high purity hydrogen. Based on the extensive testing and validation of the HGM-2000, H<sub>2</sub>Gen designed and fabricated a 565 kg/day unit (HGM-10000) that incorporated optimized catalysts, a completely redesigned reactor, and associated boiler and heat exchange subsystems.

Initial system and field testing of the HGM-10000 unit began in 2007, and the unit has now run for 2,830 hours in the field, providing information on system efficiency and reliability. With the HGM-10000 ready for commercial deployment, H<sub>2</sub>Gen is identifying further areas of potential improvement and monitoring field operation to determine longer-term system reliability, maintenance requirements, and ultimately the catalyst and system lifetimes.



Components of the HGM-10000



*H<sub>2</sub>Gen Innovations' HGM-10000 Unit*

### Technology History

- ◆ Developed and being marketed by H<sub>2</sub>Gen Innovations, Inc., in partnership with Süd Chemie, Inc.
- ◆ Became commercially available in 2008.

### Applications

Can be used where high purity hydrogen is required, including industrial gas, chemical processing, pharmaceuticals, electronics, and hydrogen energy systems.

### Capabilities

- ◆ Achieves fuel efficiency of up to 78% high heating value and provides up to 99.999% pure hydrogen.
- ◆ Produces a 200 or 300 psig H<sub>2</sub> product and allows remote monitoring without the need for staffing.

### Benefits

#### Production Cost Savings

Cuts the cost of producing high purity hydrogen by up to 50% compared with trucking in either liquid or compressed hydrogen.

#### Increased Capacity and Reduced Fuel Costs

Has 5 times the capacity of the previous HGM-2000 model at a price increase of only 2.9 times.

#### Modular Design

Allows the introduction of hydrogen-powered vehicles when and where they are needed and eliminates the need for large-scale hydrogen infrastructure for vehicle fueling.

**Contact Information:**  
**Dr. C.E. (Sandy) Thomas**  
 Email: [thomas@h2gen.com](mailto:thomas@h2gen.com)  
 Phone: (703) 778-3122  
**H<sub>2</sub>Gen Innovations, Inc.**  
 4740 Eisenhower Ave.  
 Alexandria, VA 22304  
 Website: [www.h2gen.com](http://www.h2gen.com)



# Hydrogen Generation from Electrolysis

Commercial Technology

## New PEM-Based Electrolysis System Reduces the Cost and Increases the Efficiency of Hydrogen Generation

While the technology of using electricity to produce high purity hydrogen and oxygen from water has been available for many years, bringing to the market a product that uses the technology has been challenging. Proton Energy Systems, Inc., with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, took advantage of the polymer electrolyte membrane (PEM) used in many fuel cell applications to reduce the cost and increase efficiency to make the hydrogen generation process practical.

As a result of this research, Proton Energy Systems developed the HOGEN® S series of hydrogen generators that was commercialized in 1999. The HOGEN S meets hydrogen requirements of 20 to 40 SCF/hr or 24 to 48 grams/hr. After further funding from the HFCIT Program, Proton Energy Systems developed and commercialized the HOGEN H series in 2004. The HOGEN H series has an output capacity of 76 to 229 SCF/hr or 90 to 275 grams/hr.

Through 2007 over 1200 HOGEN systems have been commercialized worldwide. The HOGEN systems are installed in applications ranging from power plant turbine generator cooling, to heat treating, to meteorological applications. These systems have uptime availability of better than 99.9%.



*The Proton Energy Systems' Hogen S Series*

## Technology History

- ◆ Developed and marketed by Proton Energy Systems, Inc.
- ◆ Commercialized the HOGEN S series in 1999 and the HOGEN H series in 2004.
- ◆ Through 2007, sold 282 HOGEN S series units in the United States and 121 internationally and 82 HOGEN H series units in the United States and 37 internationally.

## Applications

Can be used to generate hydrogen that can be used for vehicle fueling, including forklifts, as well as electrical generator cooling and materials processing.

## Capabilities

- ◆ Takes potable water and electricity and produces high-purity hydrogen and oxygen with no other byproducts.
- ◆ Produces no pollutant output if the electricity is attained from renewable sources.
- ◆ Produces hydrogen at up to 400 psi without mechanical compression at a purity of 99.999%.

## Benefits

### Ease of Integration

Provides very compact and easy-to-integrate systems with fueling balance of plant and systems start-up in one day.

### Efficiency

Produces high purity hydrogen for fuel cells that exceeds fuel specifications.

### Environmental

Eliminates gas scrubbers, gas conditioners, and the potential for chemical contamination downstream because PEM electrolysis has no liquid electrolyte.

**Contact Information:****John Speranza***Email:* [jsperanza@protonenergy.com](mailto:jsperanza@protonenergy.com)*Phone:* (203) 678-2326**Proton Energy Systems, Inc.**

10 Technology Drive

Wallingford, CT 06492

**Website:** [www.protonenergy.com](http://www.protonenergy.com)

# ME100 Methanol Reforming Hydrogen Generator

Commercial Technology

## Hydrogen Generator System Provides High Purity Hydrogen Quietly and Reliably for Remote and Mobile Uses

Fuel cells are an attractive way to provide quiet, efficient electricity to remote and mobile users. REB Research & Consulting's ME100 hydrogen generator answers the need for efficient and effective delivery of high-purity hydrogen to the fuel cell. On-site hydrogen generation from methanol is far more cost effective than delivered hydrogen and more practical than hydrogen produced any other way. Further, the hydrogen purity remains high, even during startup and after a variable load.

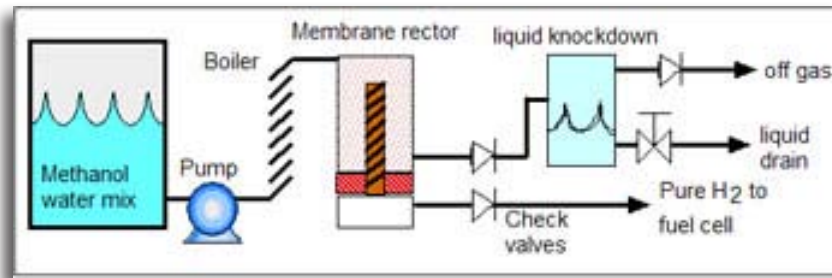
REB developed the membranes used in hydrogen generation reactors with support from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program and a grant from the Small Business Innovation Research (SBIR) Program. REB designed and developed a unique form of membrane reactor steam reformer that allows easy heat transfer so that quantities of high purity hydrogen could be generated in a small volume process by reforming methanol and water. Ordinary shift catalysts are used to convert methanol to hydrogen, and while the hydrogen is formed, it is extracted and purified through palladium-coated metal membranes within the reaction zone. By removing hydrogen, the conversion reaction is driven to completion far faster and in a much smaller volume, increasing the effective catalyst activity and thermodynamic equilibrium as a result of increasing the reactant concentration and residence time.

Because the membranes are 100% selective to hydrogen, the REB hydrogen generator can ensure very high hydrogen purity independent of back-pressure changes caused by varying fuel cell demand. Both hydrogen delivery pressure and flow can self-adjust to accommodate fuel cell load almost instantaneously.



*The ME100 Generator System*





*Schematic of ME100 Reactor and Flows*

## Technology History

- ◆ Developed and marketed by REB Research & Consulting to provide improved delivery of high-purity hydrogen.
- ◆ Sold more than 350 hydrogen membrane reactors since 2002.
- ◆ Sold more than 15 ME100 hydrogen generator systems since 2002.

## Applications

Can be used to make ultrapure hydrogen from methanol reforming and where high purity hydrogen is required.

## Capabilities

- ◆ Produces very high purity hydrogen (99.99995% pure) at a cost far lower than bottled gas.
- ◆ Delivers continuous hydrogen output at a variable rate of up to 10 kg per day and at pressures up to 40 psig.

## Benefits

### Efficiency

Uses readily available methanol feedstock for hydrogen generation at a power density consistent with bottled hydrogen.

### Flexibility

Demonstrates fuel cell load following characteristics while maintaining high hydrogen purity.

### Versatility/Safety

Provides quiet, reliable hydrogen generation that can be developed in remote and mobile applications where size and weight are a premium. Is safer and lighter than hydrogen bottles, eliminating the need for hydrogen inventory.

#### Contact Information:

**Robert Buxbaum**

Email: [buxbaum@rebresearch.com](mailto:buxbaum@rebresearch.com)

Phone: (248) 545-0155

**REB Research & Consulting**

3259 Hilton Rd.

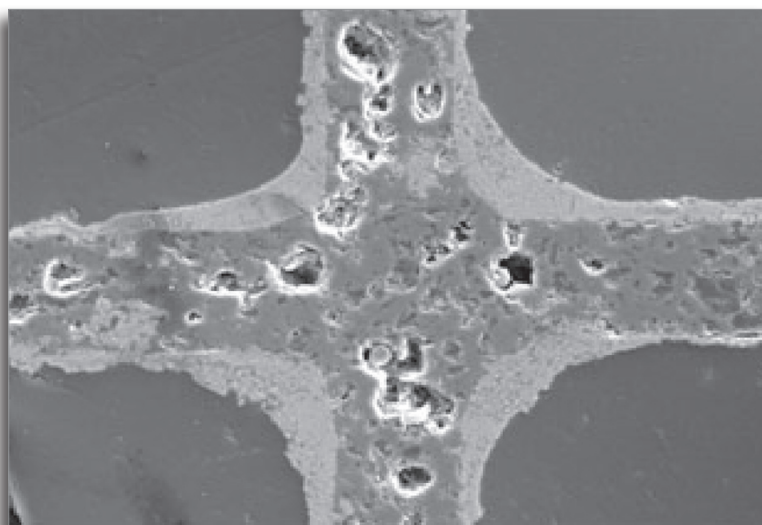
Ferndale, MI 48220

Website: [www.rebresearch.com](http://www.rebresearch.com)

## New Catalysts Operate at High Temperatures and Activity Levels, Improving Fuel Processor Performance

NexTech Materials, Ltd., established synthesis processes for preparing highly active water gas shift (WGS) catalysts based on ceria-supported precious metals using funding provided in part by the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program. The primary advantages of the WGS catalysts are their high activity, nonpyrophoric nature, and capability to operate over a wide temperature range. NexTech has extended the synthesis processes to a family of ceria-based catalysts that are useful for several important fuel-processing reactions.

Improved catalysts are required for a number of fuel cell and distributed hydrogen production applications. High activity ceria-based catalysts are being used for applications where small reactor size and/or multiple startup/shutdown cycles are important requirements. The ceria-based catalysts are prepared from nanoscale ceria-based mixed oxides using synthesis methods that provide exceptionally high dispersion of catalytic metals. By varying the catalyst synthesis conditions and the specific catalytic metals, the activity of these ceria-based catalysts are tailored for specific reactions and operating temperatures, depending on customer requirements. Two grades of WGS catalyst formulations are available, one for higher-temperature WGS reactions (350°C to 450°C) and one for lower-temperature WGS reactions (250°C to 350°C). NexTech began selling these catalysts commercially in 2005 and continues development work to improve functionality, increase durability, and reduce cost.



*Micrograph of a Washcoated Pt/Ceria Catalyst Layer on a Cordierite Monolith*

## Technology History

- ◆ Developed and commercialized by NexTech Materials, Ltd.
- ◆ Became commercial in 2005 with more than \$200,000 in sales to date.

## Applications

Can be used in fuel processing systems for polymer electrolyte membrane fuel cells, reforming reactors for solid oxide fuel cells, and hydrogen production systems.

## Capabilities

- ◆ Has high activity that allows WGS reactions.
- ◆ Can be used for steam reforming of methane, diesel, and ethanol.
- ◆ Enables the catalytic partial oxidation of methane and other hydrocarbons.

## Benefits

### Efficiency

Can perform at high activity over wide temperature ranges.

### Versatility

Can be tailored for specific reactions and operating temperatures, depending on customer requirements, and are available in multiple forms (e.g., pellets and monoliths).

**Contact Information:**  
**Scott L. Swartz**  
*Email:* [s.swartz@nextechmaterials.com](mailto:s.swartz@nextechmaterials.com)  
*Phone:* (614) 842-6606  
**NexTech Materials, Ltd.**  
404 Enterprise Dr.  
Lewis Center, OH 43035  
**Website:** [www.nextechmaterials.com](http://www.nextechmaterials.com)



D.3 Storage Technologies..... D-47

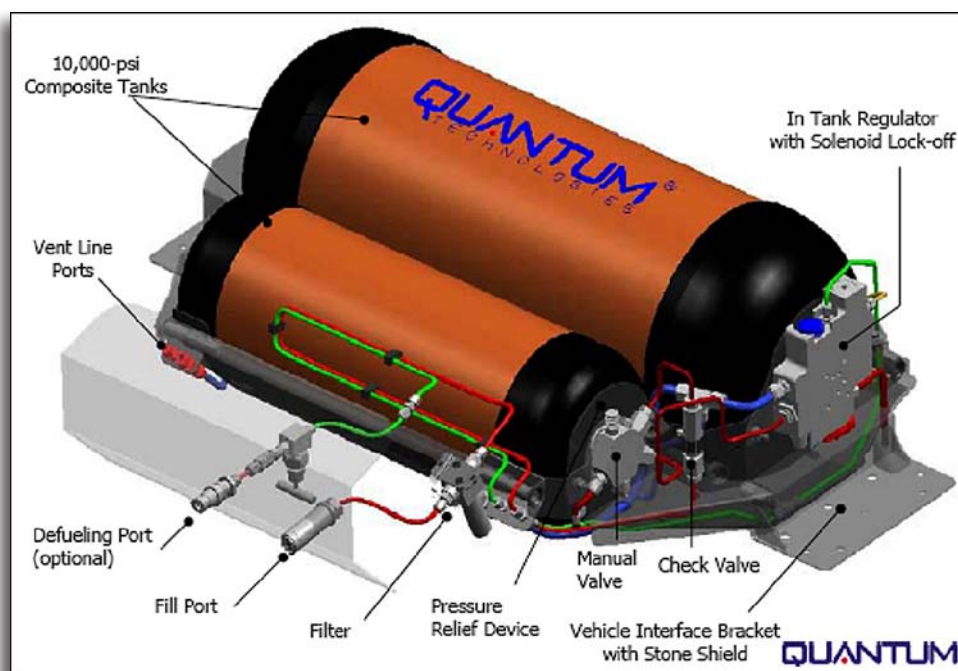
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- ◆ Non-Destructive Ultrasonic Scanning Technology..... D-50

## Lightweight, All-Composite Tank Improves the Range of Hydrogen-Powered Fuel Cell Vehicles

Previous approaches to hydrogen storage have included compression (3,600 psi), liquefaction, chemical storage, metal hydride storage, and adsorption. While each storage method has positive attributes, no single approach has effectively addressed the multiple requirements for transportation use. These requirements include energy density, size, weight, cost, durability, and strict safety-related items.

Quantum Fuel Systems Technologies Worldwide, Inc., in cooperation with the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program, designed, manufactured, and validated hydrogen fuel tanks and hydrogen fuel delivery systems running at 5,000 and 10,000 psig. The TriShield™ cylinder is comprised of a seamless, one-piece, permeation-resistant, cross-linked, ultra-high molecular weight polymer liner that is overwrapped with multiple layers of carbon fiber/epoxy laminate and a proprietary external protective layer for impact resistance. The tank also includes an in-tank regulator, which confines high gas pressures within the tank, thus eliminating high-pressure fuel lines downstream of the fuel storage subsystem.

As the first company in the world to develop and deploy 10,000 psig hydrogen systems, Quantum Technologies has enabled global automakers to offer driving ranges acceptable for early-market hydrogen vehicles. Quantum continues to research strategies on advanced storage solutions that offer currently established safety and performance metrics, while reducing the overall cost, weight, and size.



*Schematic of the Quantum Hydrogen Storage System*

## Technology History

- ◆ Developed by Quantum Fuel Systems Technologies Worldwide, Inc., and commercially offered in 2001.
- ◆ Sold more than 2,000 storage tank systems, primarily to major automobile manufacturers.

## Applications

Can be used for compressed hydrogen fuel storage applications at 5,000 and 10,000 psig (700 bar).

## Capabilities

- ◆ Increases a vehicle's driving range by more than 55% compared with equivalent-sized storage tanks at 5,000 psig.
- ◆ Increases the safety and reliability of hydrogen storage and fuel delivery systems, exceeding current regulatory qualification requirements.
- ◆ Delivers a fully validated 10,000 psig hydrogen storage system for automotive equipment manufacturers.

## Benefits

### Capacity

Offers high capacity, lightweight and fully validated high-pressure hydrogen storage systems that have been field proven under real world conditions.

### Product Quality

Designed and manufactured to strict automotive and high-pressure safety standards, reduces the potential for hydrogen embrittlement in the presence of high-pressure hydrogen, as is the case with metal-lined alternative technologies.

**Contact Information:****Neel Sirosh***Email:* [nsirosh@qtww.com](mailto:nsirosh@qtww.com)*Phone:* (949) 399-4698**Quantum Fuel Systems Technologies Worldwide, Inc.**

17872 Cartwright Road

Irvine, CA 92614

**Website:** [www.qtww.com](http://www.qtww.com)

# Non-Destructive Ultrasonic Scanning Technology

Commercial Technology

## Innovative System Allows Rapid and Accurate Testing of High-Pressure Hydrogen Cylinders

One of the main components of an automobile powered by fuel cells is the hydrogen storage system. A large amount of hydrogen storage is needed to generate the power and range for an automobile. Currently, large amounts of hydrogen are stored by using high-pressure cylinders operating at 12,000 psi or more. This large amount of flammable hydrogen stored at this high pressure could become dangerous if the cylinder had flaws that could allow a catastrophic release. Therefore, it is critical that hydrogen cylinders meet stringent Department of Transportation safety targets before they are used in automobiles.

Meeting these targets requires new materials and production methods. One of the most promising methods uses composite pressure vessels. These vessels could include plastic-lined composite over-wrapped pressure vessels and composite over-wrapped steel-lined pressure vessels as well as other materials such as ceramics. However, these vessels are hard to inspect with traditional ultrasound and x-rays because of the materials used in their construction. A technology is needed to inspect these new types of vessels non-destructively. Ideally, the technology should identify the location of flaws and detect a wide variety of damage types in a wide variety of materials, including metals, polymers, ceramics, and composites.

Digital Wave Corporation, with funding from the U.S. Department of Energy's Hydrogen, Fuel Cells & Infrastructure Technologies (HFCIT) Program through the National Center of Manufacturing Sciences, has developed a revolutionary non-destructive testing method that is effective on these different types of materials. By using stacked polyvinylidene film (PVDF) piezoelectric transducers in modal acoustic emission phased arrays and proprietary data analysis software, Digital Wave's ultrasonic scanning technology is adaptable to a wide range of cylinder geometries and material types while providing rapid analysis and accurate flaw location. The PVDF piezoelectric film used in the technology is inexpensive, mechanically rugged, low profile, and easily attached to the test item.



*Pressure Tank with Digital Wave's Stress Transducers Attached*





*Digital Wave's Mobile Scanning System*

## Technology History

- ◆ Began research in April 2006.
- ◆ Commercialized in 2008.

## Applications

Can be used to non-destructively test high-pressure hydrogen cylinders for vehicles powered by fuel cells.

## Capabilities

- ◆ Identifies location of flaws using non-destructive sound waves.
- ◆ Provides increased safety by identifying flaws prior to failure.

## Benefits

### Cost Savings

Detects flaws before they cause catastrophic failure.

### Performance

Provides rapid analysis and accurate flaw location.

### Versatility

Tests a wide range of cylinder geometries and material types.

#### Contact Information:

**Steve Ziola**

Email: [Stevez@digitalwavecorp.com](mailto:Stevez@digitalwavecorp.com)

Phone: (303) 790-7559

**Digital Wave Corporation**

6555 S. Kenton Street, Suite 304

Centennial, CO 80111

Website: [www.digitalwavecorp.com](http://www.digitalwavecorp.com)



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# Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells

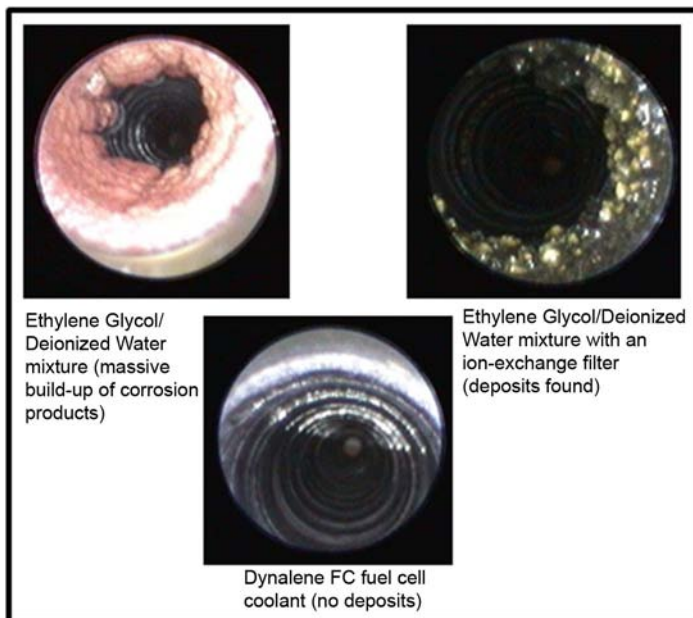
Emerging Technology

## Advanced Coolant Reduces Weight, Size, and Operating Costs of Fuel Cells

Fuel cell developers currently using water and water/glycol blends depend on the de-ionizing filter in the coolant loop to maintain acceptably low levels of electrical conductivity. However, the filter needs frequent replacement, leading to downtime and increased operating costs of the fuel cell system. An additional concern is the eventual transition to aluminum heat exchangers. Although aluminum is lighter weight, has a lower purchase cost, and exhibits better heat transfer capabilities, the de-ionizing filters used today will not be able to manage the excess of aluminum ions in the coolant if the fluid itself is not designed to substantially buffer the ion build-up.

Dynalene, Inc., with HFCIT and private industry support, has developed an advanced complex coolant fluid (CCF) that addresses these issues. Consisting of a base compound (glycol and water mixture), the CCF incorporates a non-ionic corrosion inhibitor with ion-suppressing nanoparticles, enabling the coolant to maintain low electrical conductivity while protecting fuel cell metallurgy and reactor channels. Modeling and simulation have been completed for fluid performance for short-term and long-term durations and have culminated with field testing in a fuel cell system that has operated continuously for four months.

Further work is being conducted to optimize the nanoparticle chemistry and to develop a steric stabilization method that will prevent flocculation and deposition of the particles. Compared with non-inhibited coolant mixtures, the CCF mixture demonstrates a 70% improvement in the rate of change of electrical conductivity. Extrapolated to 3,000 hours of operation, the conductivity of the cooling solution would exceed the design target established by polymer electrolyte membrane fuel cell manufacturers; through optimization, Dynalene intends to reduce the conductivity by at least one order of magnitude, enabling fuel cell stacks to operate 2 to 3 years without replacing the coolant.



Fuel Cell Coolant Channels with and without Dynalene CCF

## Technology History

- ◆ Developed by Dynalene, Inc., with HFCIT and private industry support.
- ◆ Patent granted to Dynalene for this coolant in 2006; long-term field tests continue in fuel cells to corroborate lab results.
- ◆ Working on production issues centered on manufacturing the nanoparticle used in the coolant.

## Applications

Can be used in fuel cells that have stainless steel, carbon steel, aluminum, copper, and brass heat exchangers and piping that require very low electrical conductivity over extended run times.

## Capabilities

- ◆ Maintains acceptably low corrosion rates on steel and aluminum heat exchangers.
- ◆ Demonstrates three times lower rate of increase in electrical conductivity during continuous operation.
- ◆ Works to stabilize particles, which can lead to flocculation and deposition on flow channels.

## Benefits

### Cost Savings

Eliminates the need for de-ionizing filters in fuel cells, reducing the overall cost of ownership and maintenance.

### Productivity

Enables fuel cells to stay on-line without frequent changing of the de-ionizing filter.

### Contact Information:

**Dr. Satish Mohapatra**

Email: [satishm@dynalene.com](mailto:satishm@dynalene.com)

Phone: (610) 262-9686 ext. 102

**Dynalene, Inc.**

5250 West Coplay Rd.

Whitehall, PA 18052

Website: [www.dynalene.com](http://www.dynalene.com)

# Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)

Emerging Technology

## New Modular Hydrogen Generation Method Allows for On-Site Production at Reduced Cost

Hydrogen is a clean fuel source and, when used in a fuel cell, the only byproduct is water. However, compressed hydrogen in cylinders is an expensive fuel source, requiring storage, shipping, handling, and frequent bottle changeouts. Industrial hydrogen generation systems run at elevated pressures and are designed and operated to endure on the order of 100 thermal cycles. In addition to the durability problem, high-pressure systems introduce other issues related to the system's high-pressure components.

If any hydrogen-based system is to succeed, these issues need to be addressed in a cost effective manner. A system is needed to operate reliably and preferably at the point of use to minimize or eliminate transportation of the hydrogen gas or travel time. Meeting these needs requires a new approach to designing a hydrogen generation system that will challenge the technical limitations of existing systems.

Nuvera Fuel Cells, Inc., with funding from HFCIT, is developing a steam reforming module for hydrogen production using a new approach to system design. The knowledge gained from the Cost Effective, High-Efficiency Advanced Reforming Module (CHARM) project is being used to develop the new PowerTap™ reforming module. This system aims to provide customers with pure hydrogen at the lowest life-cycle cost. The CHARM reformer is designed to be cyclable (daily start/stop for 5 years). The reformer runs at low pressure and its materials of construction were selected using a combination of coupled fluid/stress analysis and an accelerated testing campaign. The PowerTap reforming module is designed to be used as a hydrogen fuel supply in forklift fleets. It operates on natural gas (or propane) and water, which allows it to be used on-site closest to the point of use, minimizing travel time.

## Technology History

- ◆ Developed by Nuvera Fuel Cells, Inc.
- ◆ Incorporated into PowerTap, a pre-commercial, integrated hydrogen generation, storage, and dispensing system.

## Applications

Can be deployed at point of use such as Nuvera's PowerFlow™ fuel cell "engine," which replaces a forklift's motive battery, and at fuel cell vehicle refueling stations.

## Capabilities

- ◆ Provides low-pressure (100 psi) hydrogen with minimal operating costs.
- ◆ Eliminates the need for hydrogen bottle storage and transportation.

## Benefits

### Cost Savings

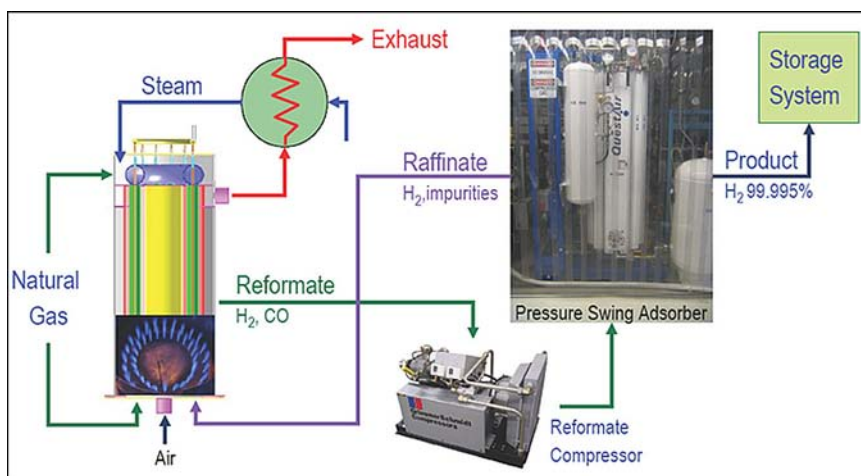
Reduces the cost of supplying hydrogen compared with bottles and trucked tubes.

### Durability

Mitigates detrimental effects of thermal cycling and supports long life.

### Product Quality

Generates pure (99.995%) hydrogen at rates up to 56 kg per day.



PowerTap H<sub>2</sub> Generation Unit Using CHARM

### Contact Information:

**Darryl Pollica**

Email: [dpollica@nuvera.com](mailto:dpollica@nuvera.com)

Phone: (617) 245-7637

**Nuvera Fuel Cells, Inc.**

129 Concord Road, Building 1  
Cambridge, MA 02140

Website: [www.nuvera.com](http://www.nuvera.com)



# Dimensionally-Stable High-Performance Membrane

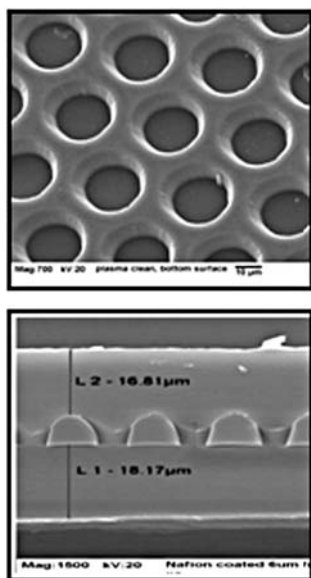
Emerging Technology

## New Fuel Cell Membrane Exhibits Improved Mechanical Properties

Devices that use fuel cell technology, such as vehicles, portable devices, and remote installations, require frequent startup and shutdown cycles, which are stressful on the polymer electrolyte membrane (PEM) structure. The water/ice expansion associated with the freeze/thaw cycle, low humidity, and high temperatures involved in the technology increases the stress and can result in dimensional instability in the PEM structure. These stresses may dry out the membrane, cause early failure because of cracks and structural fatigue, and can lead to loss of the fuel cell itself.

A membrane material and structure are needed that can be exposed to freeze/thaw cycles and operating conditions that include wide temperature ranges and varying relative humidity conditions and cycles. The membrane also needs to be highly conductive while maintaining superior mechanical properties and dimensional stability. Ideally, this PEM membrane should be able to be manufactured by a low cost, continuous process.

With the help of DOE SBIR grants, Giner Electrochemical Systems, LLC, is developing an easily manufactured membrane that improves performance and longevity in suboptimal operating conditions. Improved mechanical properties of their dimensionally stable membrane are achieved by using a high-strength support structure fabricated from high-performance engineering plastics. The pattern design of the support structure is completely customizable so that the weak areas, such as edges, can be specifically reinforced to further enhance durability. Employing the high-strength support structure allows lower-equivalent-weight ionomers, which are too mechanically weak to be implemented in the fuel cells, to be used without sacrificing mechanical durability. Thus, higher performance, especially at lower relative humidity levels, can be achieved. Based on microfabrication technology, support structures can be fabricated with a low-cost, continuous process. The membrane's property can be completely controlled by design and engineering of the patterns.



Micrographs of Giner's Dimensionally Stable Membrane

## Technology History

- ◆ Developed by Giner Electrochemical Systems, LLC.
- ◆ Continuing work on the Phase II SBIR grant with a focus on improving membrane fabrication processes and scalability to larger stacks.

## Applications

Can be used in fuel cells for vehicles, portable devices, and remote installations.

## Capabilities

- ◆ Improves membrane durability/lifetime during relative humidity cycling.
- ◆ Enhances fuel cell performance at low humidity and high temperature.
- ◆ Facilitates the operation of fully automated fabrication of membrane electrode assemblies.

## Benefits

### Durability

Prevents stress-induced failure because of the membrane's high-strength design.

### Performance

Improves performance at low humidity and high temperature.

### Contact Information:

**Dr. Han Liu**

Email: [hliu@ginerinc.com](mailto:hliu@ginerinc.com)

Phone: (781) 529-0531

**Giner Electrochemical Systems, LLC**

89 Rumford Avenue

Newton, MA 02466-1311

Website: [www.ginerinc.com](http://www.ginerinc.com)



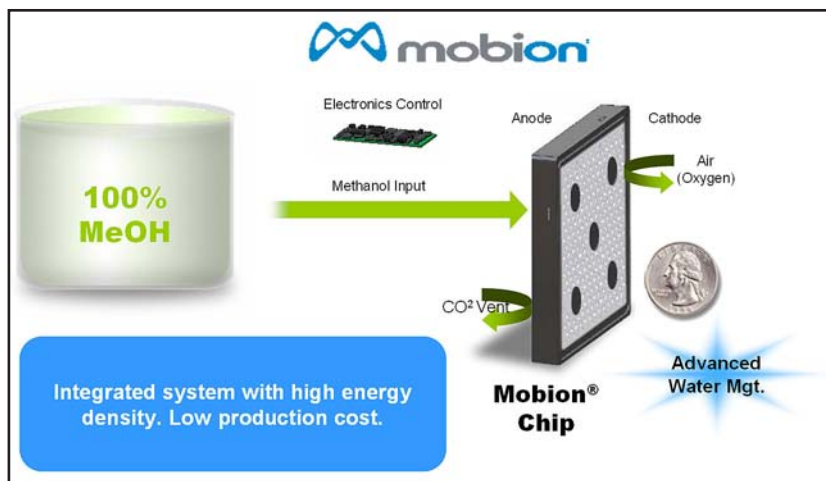
# Direct Methanol Fuel Cell for Handheld Electronics Applications

## New Power Source Eliminates Need to Plug into Electrical Wall Outlet

Consumers are increasingly relying on handheld devices, whether for their business use or personal needs. As more and more features are added to portable devices, the amount of power being consumed also increases. Batteries are not keeping up with increased power demands and consumers are forced to choose between turning off some features to conserve battery power or searching for a wall outlet to recharge. The problem is that outlets may not always be available in remote areas. In addition, connecting to an outlet negates the portable nature of these devices and restricts their operation to an area limited by the length of the power cord. A system is needed that generates its own power so that portable devices can be used anywhere.

To address this need for a portable power source without the drawbacks associated with batteries, MTI Micro Fuel Cells, Inc., with HFCIT funding, has developed a technology called Mobion®. The Mobion technology is a direct methanol fuel cell chip that generates power from methanol while eliminating the conventional fuel cells need for active water recirculation pumps or the inclusion of water as a fuel dilutant. Fuel cells are different from batteries in that they consume reactant, which can be replenished, while batteries store electrical energy chemically in a closed system. While the electrodes within a battery react and change as a battery is charged or discharged, a fuel cell's electrodes are catalytic and relatively stable, resulting in long life.

Because of this improved technology, micro fuel cells have a significant advantage as handheld portable energy sources. As a standalone product, it can be carried just like the devices it was meant to power and used as needed to keep the device batteries charged. As the technology continues to improve, the micro fuel cell will also get embedded in devices and double or triple the time between charges. The consumer will get more use out of their device and be less inconvenienced by the need to find an outlet. MTI Micro has demonstrated prototypes for applications including a universal power source with removable/replaceable cartridges, a handheld GPS unit, a camera grip for a digital SLR camera, and a smart phone.



MTI Micro Fuel Cells' Mobion Technology

## Technology History

- ◆ Developed by MTI Micro Fuel Cells, Inc., in partnership with the Methanol Foundation.
- ◆ Continued testing of prototype units occurring while efforts are underway to increase the durability and reliability of the system. Codes and standards work and approval are proceeding with a number of government agencies.

## Applications

Can be used as a complement for current handheld electronic devices to keep their batteries charged.

## Capabilities

- ◆ Eliminates the need for a wall outlet to keep devices charged for true mobile power.
- ◆ Operates in any orientation.
- ◆ Operates over a wide temperature range (0°C to 40°C) and at any humidity level.

## Benefits

### Manufacturability

Can be fabricated using high-volume, cost-effective manufacturing processes due to reduced parts count and smaller system design.

### Performance

Achieves a power density of over 62 mW/cm<sup>2</sup> with a fuel energy of over 1800 Whr/kg.

### Versatility

Allows fuel cartridge to be changed out while the device is operating, with no loss in power.

### Contact Information:

**Jim Frawley**

Email: [JimF@mechtech.com](mailto:JimF@mechtech.com)

Phone: (518) 533-2235

**MTI Micro Fuel Cells, Inc.**

431 New Karner Road

Albany, NY 12205

Website: [www.mtimicrofuelcells.com](http://www.mtimicrofuelcells.com)

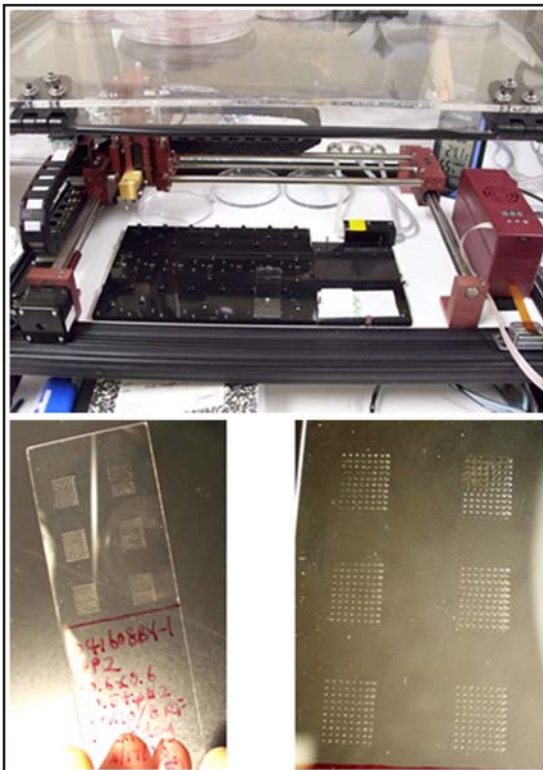
# Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors

Emerging Technology

## New Technology Uses Inkjet Methods to Mass-Produce Hydrogen Sensors, Reducing Assembly Costs

Safety is an important concern in the production, delivery, and storage of hydrogen for transportation, distributed stationary power, and portable power applications. Because hydrogen can neither be seen nor smelled, a reliable hydrogen sensor is needed in all aspects of the hydrogen economy. The sensor also should be intrinsically safe to prevent the hydrogen from igniting. A method is needed to fabricate these sensors in high volume, which will require existing technologies to be modified.

With the help of DOE SBIR grants, InnoSense, LLC, is developing innovative manufacturing processes, based on direct-write inkjet technology, for the high-volume fabrication of both the components and the complete sensor system. A less expensive high-volume fabrication process is being developed that will eliminate the individual calibration of each sensor by making many identical sensors in one batch. InnoSense has established the fabrication protocols so multiple sensors can be developed in a single batch and perform reversibly and reproducibly. InnoSense sensors are all-optical and therefore intrinsically safe, producing no arc or spark. After fine-tuning for high-volume manufacturing, sensors will be manufactured that meet customer specifications for cost, reliability, response time, operational life, and desired sensitivity.



*InnoSense's Sensor Fabrication Process Using Pin-Printing Techniques*

## Technology History

- ◆ Developed by InnoSense, LLC, starting in 2006.
- ◆ Continuing work centered on fine-tuning the technologies for high-volume fabrication.

## Applications

Can be used to produce inexpensive hydrogen sensors for hydrogen storage facilities and other applications using hydrogen.

## Capabilities

- ◆ Achieves high-volume fabrication speeds.
- ◆ Produces hydrogen sensors with improved consistency batch to batch.
- ◆ Uses inexpensive pin-printing technology to fabricate hydrogen sensors.

## Benefits

### Cost Savings

Reduces manual assembly costs by using pin-printing technology.

### Performance

Allows sensors to be mass-produced by using a high-volume fabrication process.

### Contact Information:

**Dr. Kisholoy Goswami**

*Email:* [Kisholoy.goswami@innosense.us](mailto:Kisholoy.goswami@innosense.us)

*Phone:* (310) 530-2011 Ext. 105

**InnoSense, LLC**

2531 West 237th Street, Suite 127

Torrance, CA 90505-5245

**Website:** [www.innosense.us](http://www.innosense.us)

# Fuel Cell Membrane Measurement System for Manufacturing

Emerging Technology

## New High-Throughput System Rapidly Measures Fuel Cell Membrane Resistance

Successful commercialization of fuel cells in the high-volume transportation market requires that cost be reduced and the consistency of polymer electrolyte membranes be improved. Fabricating a membrane electrode assembly (MEA) and testing it in a completed fuel cell are costly and time consuming. Current technology does not support testing the “bare” membrane prior to assembly in an MEA. Ionomer material is produced in a wide sheet and is subject to both longitudinal and lateral variations. Therefore, guaranteeing consistency and repeatability in the finished product is difficult and can increase waste and costs. A tool is needed to measure the ionic resistance of the “bare” membrane prior to assembly in the finished product. This tool needs to be combined with the necessary software and methodology to enhance the product quality assurance/quality control (QA/QC). Tools and methods for accurate measurement of the through-thickness ionic resistance of fuel cell membranes, a key property, are required to support high-volume production QA/QC programs.

Scribner Associates, Inc., with funding from DOE SBIR grants, is developing a high-throughput membrane measurement system to support fuel cell membrane manufacturing operations. Scribner Associates has a pending patent application for a novel electrode design and measurement apparatus that is compatible with bare membrane and MEA samples. The ability to test bare membranes significantly reduces the analysis time and increases the throughput of the measurement system. Possible future markets might include a membrane test device designed for the research and development community. Researchers developing new membrane materials need to characterize their materials before they go through the time-consuming and costly effort of fabricating and testing an MEA in a fuel cell.



*Scribner Associates' Rapid Membrane Measurement System Prototype*

## Technology History

- ◆ Developed by Scribner Associates, Inc.
- ◆ Working on developing a second-generation prototype system for evaluation by a leading fuel cell membrane developer and manufacturer.

## Applications

Can be used to rapidly measure the through-thickness ionic resistance of bare, as-manufactured fuel cell membranes under controlled environmental conditions.

## Capabilities

- ◆ Achieves consistent and accurate measurement results.
- ◆ Uses bare, as-manufactured membrane or MEA samples.
- ◆ Performs analyses significantly faster than previous methods.

## Benefits

### Cost Effectiveness

Achieves consistent results, thus lowering manufacturing costs through less waste.

### Performance

Improves fuel cell membrane manufacturing efficiency by using high throughput testing.

### Contact Information:

**Dr. Kevin R. Cooper**

*Email:* kevin@scribner.com

*Phone:* (910) 695 8884 ext. 32

**Scribner Associates, Inc.**

150 East Connecticut Ave.

Southern Pines, NC 28387

**Website:** [www.scribner.com](http://www.scribner.com)



# High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure

Emerging Technology

## New System Optimizes Discovery and Testing of Fuel Cell Electrocatalysts

The development and high-volume manufacture of durable, low-cost oxygen reduction electrocatalysts with high activity and utilization are critical remaining challenges for the successful introduction of fuel cells into mass markets. Meeting the challenges has two issues: the high cost of platinum (Pt) used in the current generation membrane electrode assemblies (MEAs) and lack of sufficient durability under load-cycling conditions.

To address these problems, Cabot Superior MicroPowders (CSMP) and partners, with funding from HFCIT, has developed a complete system for combinatorial discovery of high-performance fuel cell electrocatalysts consisting of rapid powder synthesis, primary electrochemical testing screen, automated electrode printing, and rapid testing in MEA configurations. This system allows different catalyst mixtures to be formulated and then tested to determine their performance. This is achieved by applying the catalyst mixtures to MEAs and then testing them in different configurations.

As a result of this effort, six Pt-alloy compositions were identified that demonstrate up to a two-fold improvement in Pt mass activity compared with that of pure Pt electrocatalysts. Through Pt-alloy catalysts composition, production optimization, and layer structure development, the best CSMP Pt-alloy electrocatalyst demonstrates performance in MEA configurations equivalent to 0.6 g Pt/kW at 0.8 V, meeting the DOE target. Single-cell MEA operation at lower voltages (0.7 V and 0.6 V) lead to performance of 0.3-0.4 mg Pt/kW, exceeding the DOE targets set at the beginning of the project. Selected Pt-alloy compositions also demonstrate significantly improved durability when tested under load cycling protocols. The improved performance of MEAs incorporating Pt-alloy compositions was also validated by testing in short stacks.

## Technology History

- ◆ Developed by Cabot Superior MicroPowders in partnership with DuPont Fuel Cells, CFD Research Corporation, and Hydrogenics Corporation.
- ◆ Undertaking long-term durability testing under cycling protocols production of the new catalysts.

## Applications

Can be used to develop and test new MEAs to improve performance in automotive fuel cells.

## Capabilities

- ◆ Provides rapid electrochemical testing.
- ◆ Provides a combinatorial electrocatalyst synthesis platform based on spray conversion.
- ◆ Allows platinum to be reduced while maintaining performance.

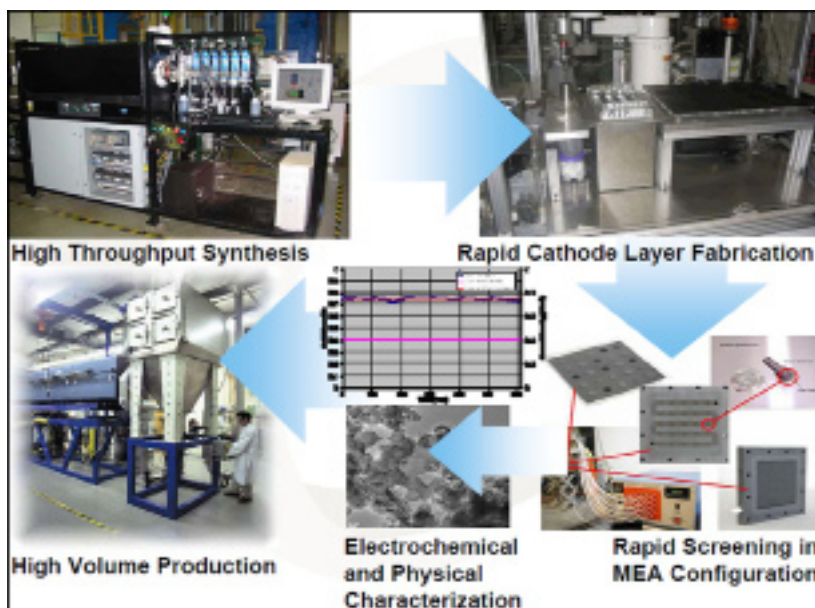
## Benefits

### Cost Savings

Allows rapid synthesis and testing of electrocatalysts and reduces research costs.

### Performance

Demonstrates up to two-fold improvement in Pt mass activity compared with that of pure Pt electrocatalysts from the production of six Pt-alloy compositions.



*Cabot's High Throughput Catalyst Discovery Platform*

### Contact Information:

**Paolina Atanassova**

*Email:*

paolina\_atanassova@cabot-corp.com

*Phone:* (505) 563-4379

**Cabot Superior MicroPowders**

5401 Venice NE

Albuquerque, NM 87113

**Website:** [www.cabot-corp.com](http://www.cabot-corp.com)

# High-Temperature Membrane with Humidification-Independent Cluster Structure

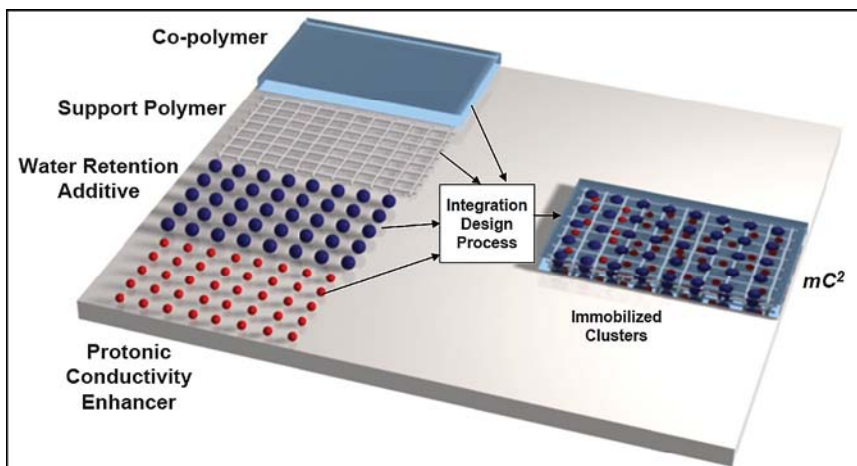
Emerging Technology

## Novel Fuel Cell Membrane Can Operate at Varying Humidity Levels Over a Wide Temperature Range

A major challenge for fuel cell membranes operating at high temperatures (up to 120°C) and low relative humidity is loss of proton conductivity due to loss of water. Another problem is that fuel cells must operate over a wide temperature range (-20°C to 120°C), which results in conditions ranging from dry to condensing atmospheres within the fuel cell. This poses a challenge not only to the conductivity but also to the mechanical integrity of the membrane. Membranes that can operate at lower relative humidity at elevated temperatures up to 120°C will reduce the fuel cell system complexity and cost.

To address these requirements, FuelCell Energy, Inc., with HFCIT funding, is developing a composite membrane in which both the ionic conductivity and mechanical properties are enhanced to meet DOE's goals for transportation fuel cells. The main focus is to increase the proton conductivity at 120°C and 25% to 50% relative humidity without decreasing the mechanical properties. A multicomponent composite membrane concept is being developed to address conductivity and mechanical issues. This multicomponent approach provides basic building blocks and functionalized additives to solve these technical problems.

FuelCell Energy's composite membrane (mC<sup>2</sup>) consists of four components: a co-polymer, a support polymer, a water retention additive, and a protonic conductivity enhancer. The co-polymer provides the basic building block for the membrane. It is an advanced perfluoro sulfonic acid with significantly higher conductivity than state-of-the-art polymers. The support polymer is designed to give a stable cluster structure and enhance mechanical properties. The functionalized additives are designed to retain water at low relative humidity conditions and enhance the composite membrane's proton conductivity by providing an alternate proton conduction path. This path is designed to efficiently transport protons at high temperature as well as subfreezing conditions. Moreover, the additives further reinforce the mechanical properties of the composite membrane. Conductivity and durability testing of the mC<sup>2</sup> is continuing.



FuelCell Energy's Composite Membrane Concept

## Technology History

- ◆ Developed by FuelCell Energy, Inc., in partnership with BekkTech LLC and the University of Central Florida.
- ◆ Continuing work on improving additive dispersion, conducting conductivity testing, and durability testing of the mC<sup>2</sup>.

## Applications

Can be used to improve the performance of polymer electrolyte membrane fuel cells over a wide temperature and humidity range.

## Capabilities

- ◆ Allows use of fuel cell membranes at higher temperatures.
- ◆ Operates independent of inlet humidity.
- ◆ Can be used in fluctuating humidity environments.

## Benefits

### Cost Savings

Lowers overall system cost by reducing fuel cell system complexity.

### Durability

Increases mechanical strength.

### Contact Information:

**Dr. Ludwig Lipp**

Email: [llipp@fce.com](mailto:llipp@fce.com)

Phone: (203) 205-2492

**FuelCell Energy, Inc.**

3 Great Pasture Road

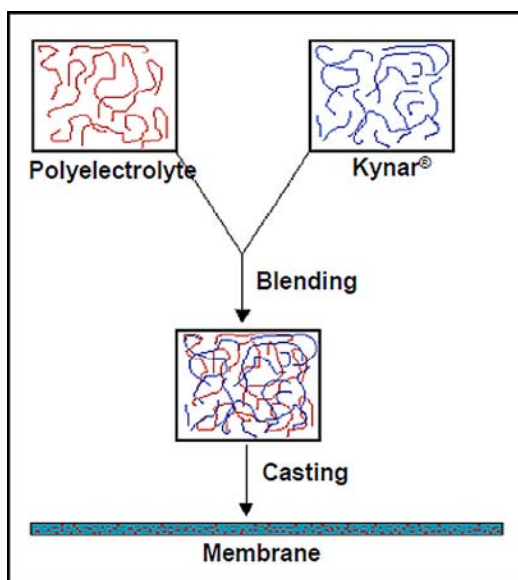
Danbury, CT 06813

Website: [www.fuelcellenergy.com](http://www.fuelcellenergy.com)

## New Blended Membrane has Improved Electrochemical Stability and Mechanical Toughness

Low-cost, durable polymer electrolyte membranes are critical components that require improvement to realize the viability of fuel cells for automotive and stationary applications. In a typical commercially-available membrane – a perfluorinated sulfonic acid (PFSA) membrane – all mechanical, chemical, electrochemical, and transport properties are “packaged” into a single macromolecule. PFSA membranes require complex synthesis for production, leading to high cost, and have insufficient durability under fuel cell operating conditions. One way to advance the state-of-the-art of fuel cell membranes is to decouple the membrane’s proton conductivity properties from the other requirements. This approach allows the use of various, separate materials to fulfill mechanical and transport properties.

Arkema Inc., conceived a new approach based on the blending of polymer materials, Kynar® poly(vinylidene fluoride) (PVDF) for enhanced mechanical toughness and sulfonated polyelectrolytes for proton transport. In this approach, proton conductivity is decoupled from other requirements. Kynar PVDF provides an ideal matrix for the membrane as it offers exceptional chemical resistance in highly oxidative and acidic environments, outstanding electrochemical stability, and mechanical toughness. Arkema, with HFCIT funding, demonstrated beginning-of-life performance equal to or better than PFSA materials, and greatly improved durability in accelerated tests (open-circuit voltage hold, relative humidity cycling, and voltage cycling). Also, these novel materials potentially offer a lower-cost membrane than the PFSA membrane (at equal production volume) because their preparation process is simpler. Arkema and its partners are now focusing on improving membrane performance at low relative humidity and temperatures above 80°C to meet and exceed DOE’s 2015 performance and durability targets.



Arkema's Membrane Production Process

## Technology History

- ◆ Developed by Arkema Inc., in partnership with Johnson Matthey Fuel Cells, Inc., Oak Ridge National Laboratory, Virginia Polytechnic Institute and State University, and the University of Hawaii.
- ◆ Continuing new membrane production, screening, and testing as well as improving membrane performance at low relative humidities and higher temperatures.

## Applications

Can be used in membrane electrode assemblies in fuel cells suitable for both automotive and stationary applications.

## Capabilities

- ◆ Increases the durability of membrane electrode assemblies in fuel cells.
- ◆ Can be mass-produced because of simpler preparation process.

## Benefits

### Cost Savings

Results in lower cost membranes at high production volumes.

### Durability

Features exceptional electrochemical stability and high durability.

#### Contact Information:

**Michel Foure**

Email: [Michel.Foure@arkema.com](mailto:Michel.Foure@arkema.com)

Phone: (610) 878-6790

**Arkema Inc.**

900 First Avenue

King of Prussia, PA 19406-0936

Website: [www.arkema.com](http://www.arkema.com)

# Low-Cost Co-Production of Hydrogen and Electricity

Emerging Technology

## New Technology Combines Electricity with Hydrogen Generation

Widespread adoption of new hydrogen technology and its commercial viability rest on early technical validation and volume manufacturing processes. One of the challenges facing this transition is the production of hydrogen for use in fuel cells. Present technology uses natural gas in steam reformers to convert the natural gas to hydrogen. This converted natural gas contains gases other than hydrogen that cause problems in non-solid oxide fuel cells (SOFCs) such as polymer electrolyte membrane (PEM) fuel cells which require high purity hydrogen. In addition, the waste gas exiting the SOFC anode still contains hydrogen although it is mixed with other gases and therefore unsuitable for reuse.

To use this waste gas, Bloom Energy Corporation, with HFCIT funding, is integrating an SOFC and an electrochemical hydrogen pump to co-produce hydrogen and electricity. The fuel exhaust from the natural-gas-fueled SOFC could be processed in a hydrogen separation subsystem to provide PEM fuel-cell-grade hydrogen fuel to an external user. Alternatively, the hydrogen separation subsystem could raise the overall electric generating efficiency of the SOFC by 3% to 4% in the electric-only mode by circulating recovered anode exhaust hydrogen back to the inlet of the SOFC. The process uses an electrochemical hydrogen pump which takes the waste gas from the anode of the SOFC and converts it to pure hydrogen through the use of an electric current and an electrolyte. The resulting pure hydrogen can be used by a PEM fuel cell or recycled to increase the efficiency of the SOFC. A field demonstration of the SOFC system with co-production of hydrogen and electricity is planned to start within a year at the Ted Stevens Anchorage International Airport in Alaska.

## Technology History

- ◆ Developed by Bloom Energy Corporation in partnership with the University of Alaska and H2 Pump, LLC.
- ◆ Testing and field demonstration of a full-scale H<sub>2</sub> pump and integration with a prototype SOFC scheduled to begin in less than one year.

## Applications

Can be used to increase the efficiency of SOFCs or to generate pure hydrogen for use by PEM fuel cells.

## Capabilities

- ◆ Uses waste gas from SOFCs to generate pure hydrogen.
- ◆ Increases the efficiency of SOFCs when the pure hydrogen gas is recycled.

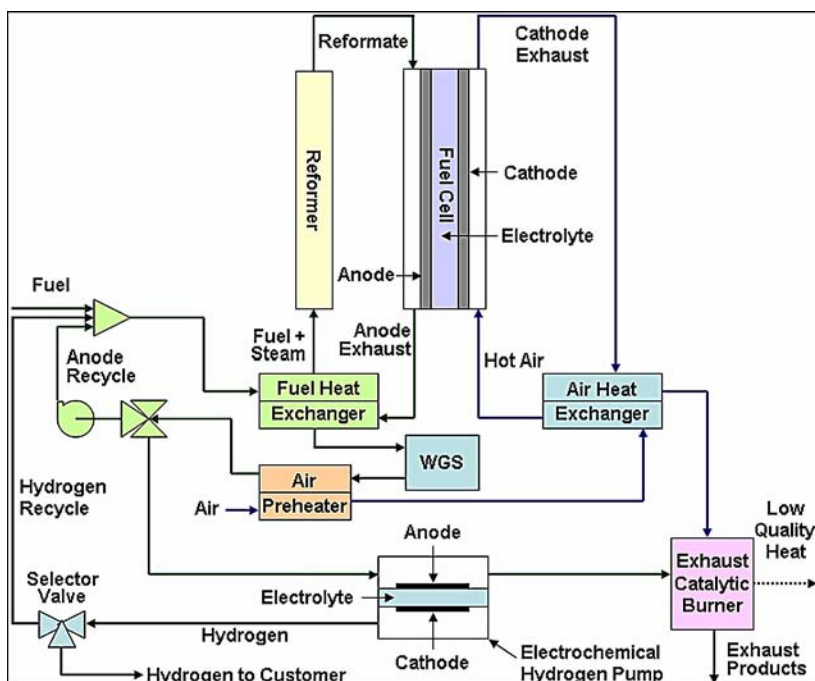
## Benefits

### Cost Savings

Reduces the amount of natural gas used by extracting pure hydrogen from waste gas and recycling it through the SOFC.

### Versatility

Can use hydrogen output to generate electricity from a PEM fuel cell or to increase the efficiency of the SOFC through recycling of the pure hydrogen.



Flow Diagram of Bloom Energy's SOFC System

### Contact Information:

**Fred Mitlitsky**

Email: [fmitlitsky@bloomenergy.com](mailto:fmitlitsky@bloomenergy.com)

Phone: (408) 543-1500

**Bloom Energy Corporation**

1252 Orleans Drive

Sunnyvale, CA 94089

Website: [www.bloomenergy.com](http://www.bloomenergy.com)



# Low-Cost Hydrogen Sensor for Transportation Safety

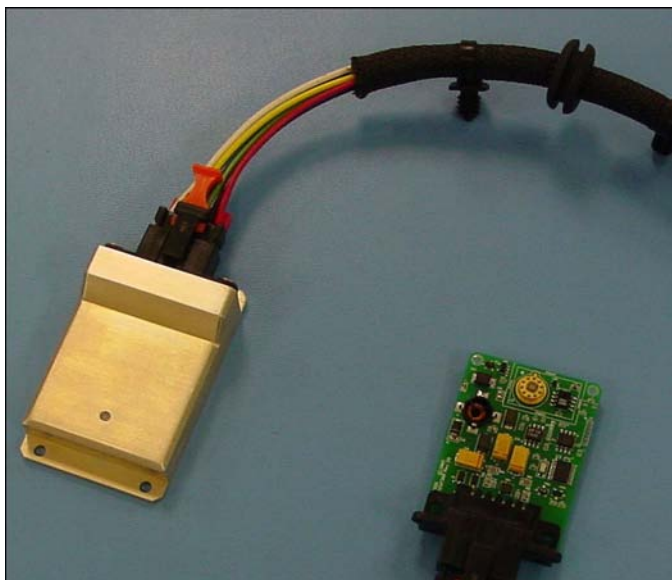
Emerging Technology

## Compact, Versatile Sensor Increases Hydrogen Safety at Low Cost

The use of hydrogen fuel in transportation applications requires the development of compact, reliable, low-cost instrumentation for safe operation and process control. Additionally, a sensor system for the vehicle and power generation markets must provide monitoring capability at all times, such as when the vehicle is parked and requires ultralow power operation. An integrated sensor system needs to be developed for prototype production and eventual transfer/licensing to a Tier 1 automotive supplier for volume production. A low-cost, compact, and high-performance hydrogen detection system is also positioned well for the fuel cell/power generation, nuclear safety, and transformer monitoring markets.

Makel Engineering, Inc., has developed, with funding from HFCIT through the Edison Materials Technology Center, a micro electromechanical systems (MEMS) hydrogen sensor system for hydrogen-powered transportation applications. This MEMS-based sensor technology provides the means for low-cost, compact, low-power consumption, miniaturized systems, suitable for mass production. The system was designed around Makel's current state-of-the-art hydrogen sensor that incorporates a highly sensitive Schottky diode made of a palladium (Pd) alloy on a silicon substrate for measurements in the low concentration range (50 ppm to a few percent). Additionally, sensor elements with a resistive structure incorporating Pd-based nanoclusters or nanowires are under development for ultra-fast time response and wide concentration range measurements.

This sensor will allow low-cost monitoring of hydrogen leaks in fuel cell automobiles, stationary power supplies, and other areas where hydrogen leakage poses a safety concern. This project won a 2006 R&D 100 award. Automotive testing of the sensor is now underway, and work is starting on using hydrogen-sensitive nanomaterials to provide lower sensor cost, simplified manufacturing, and improved detection capabilities.



*Makel's Low-Cost Hydrogen Sensor for Transportation Safety*

## Technology History

- ◆ Developed by Makel Engineering, Inc., in collaboration with Argonne National Laboratory and Case Western Reserve University.
- ◆ Continuing sensor testing with automotive companies and work on nanomaterial enhancements to the sensor.

## Applications

Can be used anywhere hydrogen gas leakage is a concern, such as fuel cell powered automobiles and stationary power systems.

## Capabilities

- ◆ Allows miniaturized detection systems to be created because of the sensor's small size.
- ◆ Can be used for continuous monitoring applications.

## Benefits

### Cost Savings

Reduces sensor cost due to mass-production manufacturing.

### Safety

Detects hydrogen from 50 ppm up to 100% in oxygen and inert backgrounds.

#### Contact Information:

**Dr. Benjamin Ward**

*Email:* [bward@mackelengineering.com](mailto:bward@mackelengineering.com)

*Phone:* (408) 543-1500

**Makel Engineering, Inc.**

15505 Neo Parkway

Cleveland, OH 44128

**Website:** [www.mackelengineering.com](http://www.mackelengineering.com)



# Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells

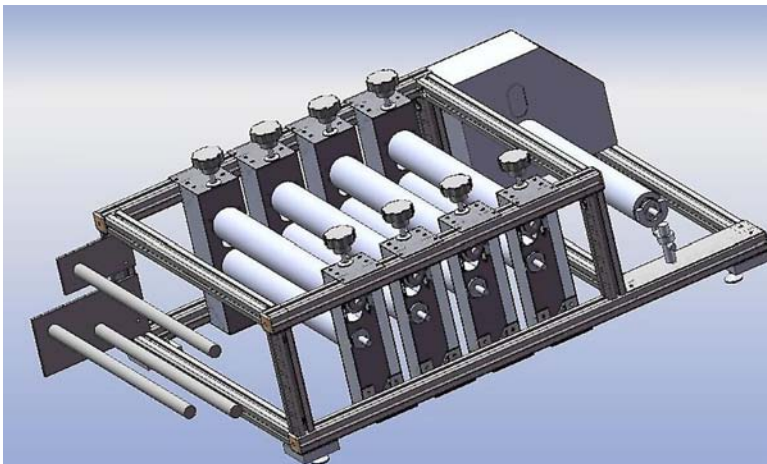
Emerging Technology

## New Technology Allows Large-Scale Manufacturing of Fuel Cell Plates

The bipolar plate is known to significantly impact the performance, durability, weight, and cost of a fuel cell system, the four technical barriers identified by DOE. The bipolar plate is one of the most costly components in a polymer electrolyte membrane (PEM) fuel cell (typically 33% of the stack cost). Bipolar plates typically account for more than 80% of the weight and 95% of the volume of a fuel cell stack and therefore dictate the gravimetric and volumetric power density of a fuel cell stack.

Bipolar plates need to be constructed from inexpensive starting materials that (1) are easily formed into any plate configuration with surface flow channels, preferably using a continuous molding process; (2) are corrosion resistant in a fuel cell environment; (3) have adequate strength and flexibility; and (4) do not require further processing such as pyrolyzation or machining. Any laminated or multi-layer plate should have adequate bonding between layers to ensure structural integrity and reduced contact resistance (reduced power loss due to joule heating).

Responsive to these challenges, Nanotek Instruments, Inc., with the help of DOE SBIR grants, developed new highly conductive sheet molding compound (SMC) compositions, bipolar plates from these SMC compositions, and related processing technologies. Work is continuing to finalize the R&D and precommercialization activities, including (1) process scale-up (e.g., to construct a pilot-scale roll-to-roll apparatus that can be readily scaled up to become a commercial-scale system); (2) complete performance characterization and analysis of flexible graphite (FG)-SMC bipolar plates to establish product specifications (e.g., to experimentally measure and compare the strength, flexibility, electrical conductivity, gas permeation, and corrosion rates of the bipolar plates with theoretical predictions); (3) market validation and expansion (e.g., to proactively conduct direct marketing activities in selected market sectors); (4) business development, marketing, and sales (e.g., to prepare FG-SMC bipolar plate samples that will be evaluated by potential customers, investors, and strategic partners); and (5) sourcing of materials, components, and subsystems.



*Nanotek's Roll-to-Roll System for Producing Multiple-Layer Bipolar Plates*

## Technology History

- ◆ Developed by Nanotek Instruments, Inc.
- ◆ Started in 2007 with sales expected in the second quarter of 2009.
- ◆ Continuing work on establishing product specifications, construction of a pilot-scale unit, and marketing and other business activities.

## Applications

Can be used to develop low-cost/high-performance bipolar plates for fuel cells using sheet molding compound manufacturing techniques.

## Capabilities

- ◆ Produces low-cost fuel cell bipolar plates.
- ◆ Achieves high performance with low cost.
- ◆ Allows for large-scale manufacturing of sheets of bipolar plate material.

## Benefits

### Efficiency

Optimizes the composition and forming process, improving the performance of SMC bipolar plates.

### Productivity

Reduces manufacturing costs through large-scale sheet manufacturing and significantly reduces fuel cell weight, dimensions, and contact resistance.

### Contact Information:

**Bor Z. Jang**

*Email:* Bor.Jang@Wright.edu

*Phone:* (937) 331-9881

**Nanotek Instruments, Inc.**

1240 McCook Ave.

Dayton, Ohio 45404

**Website:** [www.nanotekinstruments.com](http://www.nanotekinstruments.com)

# Low Platinum Loading Fuel Cell Electrocatalysts

Emerging Technology

## New Catalyst Resists Carbon Monoxide Poisoning With Less Platinum

In hydrogen fuel cells the performance of the catalysts is extremely sensitive to small amounts of carbon monoxide (CO) contamination. The CO contamination causes poisoning of the catalyst, rendering it unable to convert the hydrogen gas into electricity and therefore shortening the life of conventional fuel cells. In addition, conventional fuel cell catalysts can contain platinum, which is extremely expensive. A catalyst that resists CO contamination and uses less platinum is needed.

Brookhaven National Laboratory (BNL), with funding from HFCIT, has developed patented anode electrocatalysts having low platinum loading that resist CO poisoning. The anode includes an electrocatalyst that has an electrically conductive support material, ruthenium nanoparticles, and a Group VIII noble metal. The ruthenium nanoparticles are deposited on a support material, heated in a hydrogen atmosphere, cooled, and then coated with the Group VIII noble metal compound. The weight ratio of platinum to ruthenium is from 0.02:1 to about 0.15:1. The conductive support material is made of finely divided carbon material, such as carbon black, graphitized carbon, graphite, or activated carbon. The ruthenium nanoparticles are about 1 nm to about 50 nm, preferably about 2 nm to 20 nm.

For oxygen reduction, BNL is also developing a novel class of cathode electrocatalysts consisting of platinum monolayers deposited on the surfaces of noble metal/non-noble metal core-shell nanoparticles. These new electrocatalysts have been demonstrated to have high activities and a very low platinum mass in the monolayer. The platinum mass activities are about an order of magnitude higher than those of commercial electrocatalysts. The platinum monolayers were electrodeposited on metal or alloy nanoparticles using galvanic displacement of a copper monolayer. Future work is focused on fuel cell tests of several types of platinum monolayer electrocatalysts, stability studies, and further reduction in platinum content using core-shell nanoparticle and oxide supports.

## Technology History

- ◆ Developed by BNL in collaboration with Los Alamos National Laboratory, Battelle Memorial Institute, 3M Company, Plug Power Inc., and General Motors Company.
- ◆ Is seeking industrial partners to license and further develop these technologies.

## Applications

Can be used in fuel cells to enhance their performance by eliminating CO poisoning at a lower platinum cost.

## Capabilities

- ◆ Survives in a CO environment without degradation.
- ◆ Allows the use of less platinum while maintaining performance.

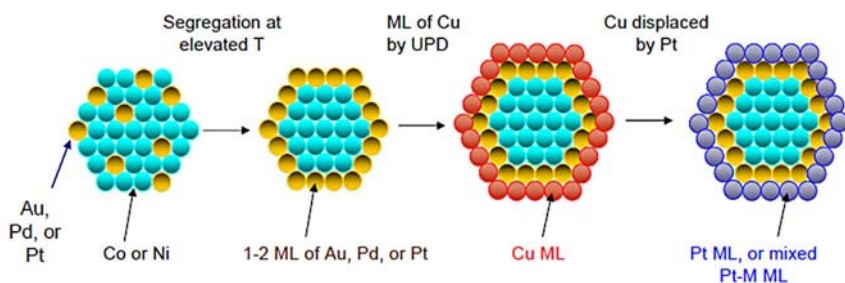
## Benefits

### Cost Savings

Reduces costs due to lower content of noble metal.

### Durability

Resists CO poisoning for increased lifespan.



*Synthesis Route for BNL's New Class of Cathode Electrocatalysts*

### Contact Information:

**Dr. Christine Brakel**

Email: [brakel@bnl.gov](mailto:brakel@bnl.gov)

Phone: (631) 344-7134

**Brookhaven National Laboratory**

Building 185

Upton, NY 11973-5000

Website: [www.bnl.gov](http://www.bnl.gov)

# Manufacture of Durable Seals for PEM Fuel Cells

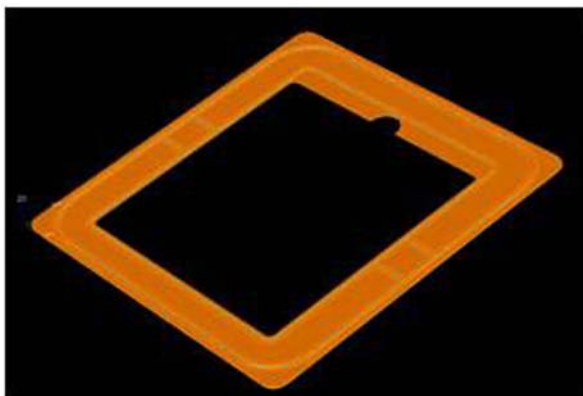
Emerging Technology

## New Manufacturing Method and Material Reduces Fuel Cell Assembly Cost

Considerable efforts are being spent to build a hydrogen infrastructure for automotive and stationary power. Mature polymer electrolyte membrane (PEM) fuel cell technology is a requisite for harnessing this infrastructure. To provide sufficient power and voltage, individual PEM fuel cells are stacked in series to yield a cell stack assembly (CSA). At the basic level, each cell contains an anode, cathode, membrane separator, and interfacial seal. The lifetime of the CSA is limited by the repeat elements. With careful control of the operating conditions, lifetimes equal to that of the interfacial seals and membranes can be achieved. Efforts are currently underway to improve membrane lifetimes. However, very little is being done in the area of seal durability.

Freudenberg-NOK General Partnership (FNGP) is developing durable seals for PEM fuel cells with funding from HFCIT through the National Center for Manufacturing Sciences. Seals for PEM fuel cells pose an enormous challenge compared with traditional industry sealing designs and manufacturing methods. Traditional sealing materials such as silicone are known to break down in the fuel cell environment. The resulting compounds can migrate to adjacent fuel cell components, causing water, reactant, and ionic transport poisoning issues. Careful elastomer material selection for the new seal will eliminate the poisoning risks, dramatically improving durability and reliability.

FNGP uses a custom elastomer material that exhibits vastly superior chemical and mechanical properties compared with conventional silicones. In addition to eliminating concerns of silicone catalyst contamination, the elastomer, developed for fuel cell applications, has improved compression set resistance and a low level of ionic contaminants. A low-cost, long-life alternate carrier material has also been identified. Based on the new elastomer and carrier material, FNGP arrived at an advanced interfacial seal design by molding the elastomer onto the carrier material. A high-volume manufacturing process is needed to make this design feasible. Combining disciplined material selection and lean manufacturing methods, FNGP is working to commercialize this new seal.



*Freudenberg-NOK's Durable Seal for PEM Fuel Cells*

## Technology History

- ◆ Developed by FNGP in partnership with UTC Power.
- ◆ Continuing durability testing of the new seals at UTC Power.

## Applications

Can be used for PEM fuel cell stacks to improve power plant efficiency and durability for bus/transportation applications; may also be used in stationary power sources.

## Capabilities

- ◆ Survives the electrochemical environment while eliminating catalyst poisoning concerns in the fuel cell.
- ◆ Covers a large region (50 cm x 35 cm) and accommodates large flange variations ( $\pm 0.4$  mm) with very low contact pressures (less than 3 N/mm).

## Benefits

### Cost Savings

Results in warranty cost savings because of improved durability.

### Efficiency

Reduces both assembly times and costs because of ability to be mass-produced.

### Contact Information:

**B Mark Belchuk**

*Email:* [MXB@FNGP.com](mailto:MXB@FNGP.com)

*Phone:* (734) 354-5309

**Freudenberg-NOK General Partnership**

47690 East Anchor Court

Plymouth, MI 48170-2455

**Website:** [www.freudenberg-nok.com](http://www.freudenberg-nok.com)



# Multi-Fuel Solid Oxide Fuel Cell (SOFC) System

Emerging Technology

## New Fuel Cell System Produces Heat and Electricity from Renewable Biofuels

Although fuel cell technology has been under serious development for over three decades, progress has been hampered by the need to have highly purified gaseous fuels (primarily hydrogen) to produce electricity. Reforming hydrocarbon fuels, particularly high molecular weight liquids, has been difficult. Yet operation on common, available fuels are required to enter mass-markets, and higher efficiencies are required to reduce the cost of overall electric generation efficiency and greenhouse gas emissions. Solid oxide fuel cells (SOFCs) are high-temperature ceramic devices that produce power electrochemically by transporting oxygen ions through a ceramic electrolyte from the air side to the fuel side, inducing an electric current in an external circuit. The products of the electrochemical conversion are heat and water. The residual high-temperature heat exhaust, when used for cogeneration with other processes, can enhance overall system efficiency.

Technology Management, Inc. (TMI), with funding from HFCIT through the Edison Materials Technology Center, has developed and demonstrated an integrated high efficiency reformer/SOFC system that can operate on multiple renewable and conventional fuels, including biodiesel, vegetable oils, ethanol, diesel, kerosene, natural gas, and propane. The 1-kW modular, multi-fuel SOFC system is designed to produce electricity and heat for multiple mobile and on-site stationary applications in rural and remote parts of the world, particularly where infrastructure may be marginal or not available. Simplicity is a key feature of the patented TMI SOFC cell and stack design. The simple design allows the use of high-volume, low-cost fabrication techniques, ease of cell and stack assembly, and straightforward thermal integration of the catalytic steam reforming with the fuel cell stack. The system is expected to achieve electrical efficiencies of >40% with overall energy efficiencies >80%.



TMI's Multi-Fuel SOFC 1-kW System Operating on Soybean Oil

## Technology History

- ◆ Originally developed SOFC by Standard Oil of Ohio and BP and technology platform by TMI.
- ◆ Now engineering full-scale system for manufacturing and field testing at end-user sites in preparation for original equipment manufacturer licensing.

## Applications

- ◆ Can be used for both stationary residential-scale and mobile applications such as on-board auxiliary power units for anti-idling of long-haul truck engines.
- ◆ Can be used in remote locations on indigenous fuels such digester biogas and vegetable oils.

## Capabilities

- ◆ Provides continuous 24/7 power.
- ◆ Operates interchangeably between fossil and renewable biofuels without shutdown.

## Benefits

### Cost Savings

Offers a simple cell and system design for low-cost, automated manufacturing. Is two to three times more efficient than a comparable-sized diesel-driven generator.

### Versatility

Is scalable for more power by using multiple modules in parallel that also provide redundancy. Is field upgradeable and compatible with multiple fuels, including high sulfur fuels and renewable biofuels.

#### Contact Information:

**Benson P. Lee**

*Email:* [tmi@stratos.net](mailto:tmi@stratos.net)

*Phone:* (216) 541-1000

**Technology Management, Inc.**

9718 Lake Shore Blvd.

Cleveland, Ohio 44108

**Website:** [www.tmifuelcellsystems.com](http://www.tmifuelcellsystems.com)

# Nitrided Metallic Bipolar Plates for PEM Fuel Cells

Emerging Technology

## Process Makes Corrosion-Resistant Stainless Steel Bipolar Plates for Fuel Cells

Bipolar plates are a key component for polymer electrolyte membrane (PEM) fuel cells. They electrically connect individual fuel cells into a stack to achieve a useful voltage and separate and distribute hydrogen and air flow streams. Stainless steels are of great interest for bipolar plates because they can be readily made into thin foils amenable to low-cost/high-volume manufacturing methods such as stamping. However, in the highly corrosive fuel cell service environment, most stainless steels exhibit borderline corrosion resistance, which can result in metal contamination of the fuel cell membrane and a loss of performance. They also exhibit high values of interfacial contact resistance (ICR) because oxide surface layers can form, further contributing to performance degradation. To address these problems, Oak Ridge National Laboratory (ORNL), with funding from HFCIT, is developing low-cost stainless steel bipolar plate alloys designed to be thermally (gas) nitrided to form an electrically conductive and corrosion-resistant Cr-nitride surface layer.

The Cr-nitride coating is naturally formed by heating the manufactured part to elevated temperature (>800°C) in a nitrogen-containing gas. The stainless steel alloy is specifically designed so that the Cr in the alloy moves to the surface of the part where it forms a thin (micron range) Cr-nitride surface layer. Low ICR and excellent corrosion resistance have been demonstrated for thermally nitrided Ni-Cr base alloys in PEM fuel cell environments. A key advantage of the ORNL thermal nitridation approach is the potential to form continuous, defect-free surface nitride layers on complex-shaped components at relatively low cost. Nitridation is also an industrially established process, primarily used for surface hardening. Currently, scale-up evaluation and demonstration are in progress in partnership with a stainless steel manufacturer, ATI Allegheny Ludlum Corp., and a metal bipolar plate producer, GenCell Corp, in collaboration with Arizona State University, the National Renewable Energy Laboratory (NREL), and Los Alamos National Laboratory (LANL).



*ORNL's Nitrided Metallic Bipolar Plates  
(Produced in collaboration with DANA Corporation, Tennessee  
Technological University, and the University of South Carolina)*

## Technology History

- ◆ Developed by ORNL, in collaboration with Arizona State University, ATI Allegheny Ludlum Corp., GenCell Corp, LANL, and NREL.
- ◆ Continuing work on characterizing the corrosion and electrical properties of nitrided foils and single-cell testing of stamped and nitrided alloys compared with untreated stainless steel and graphite plates.

## Applications

Can be used for PEM fuel cell bipolar plates but may be applicable to any electrochemical device component requiring high electrical conductivity and corrosion resistance (e.g., batteries, sensors, and supercapacitors).

## Capabilities

- ◆ Allows formation of continuous, defect-free surface nitride layers on complex-shaped components.
- ◆ Lowers ICR in fuel cells.
- ◆ Reduces corrosion in fuel cells.

## Benefits

### Cost Savings

Extends the life of fuel cell bipolar plates by reducing corrosion.

### Productivity

Increases the efficiency of fuel cells by reducing ICR.

#### Contact Information:

**Dr. Michael P. Brady**

Email: [bradymp@ornl.gov](mailto:bradymp@ornl.gov)

Phone: (865) 574-5153

**Oak Ridge National Laboratory**

P.O. Box 2008-03-25

Oak Ridge, TN 37831-6115

Website: [www.ornl.gov](http://www.ornl.gov)

## New Research Tests Fuel Cells in Rugged Applications

Previously, all off-road vehicles were powered by either gasoline or diesel fuel engines, causing pollution and noise. Although battery-powered vehicles have been used for some off-road applications, they are charged from conventional grid power and have limited range. Getting adequate range with battery-powered vehicles has been difficult because of the extra weight of the large batteries. While vehicles such as electric forklifts have very large batteries, they are not designed to operate on rough surfaces encountered in off-road applications.

An off-road vehicle is needed that has adequate range with a power source that is durable enough to withstand the shock and vibration (S&V) of off-road use without a large amount of additional weight. In addition, the power source needs to be simple and nonpolluting. One possible power source is a fuel cell, but little data exist on the effect of air pollutants on the fuel cell system and whether the system can be designed and constructed to survive S&V typical to off-road applications.

To meet these challenges, IdaTech, LLC, with funding from HFCIT, is researching the effect of air pollutants and S&V on fuel cells and off-road vehicles. They are incorporating a high-efficiency, liquid-fueled fuel cell system into a mid-duty golf course maintenance vehicle as a test vehicle to verify the system's operating characteristics in off-road use. The maintenance vehicle is very quiet compared with gasoline vehicles, and the fuel cell system has nearly zero pollution. The high efficiency of the fuel cell system and the lower cost of methanol compared with gasoline and diesel fuels are added benefits. The vehicle is projected to survive the S&V and pollution inherent on golf courses and similar off-road applications. Through this research, an engineering database is being developed that may be used for comparing off-road vehicle propulsive power requirements with proton exchange membrane fuel cell system capabilities. The off-road fuel cell vehicle is undergoing field trials.



*IdaTech's Off-Road Fuel Cell Test Vehicle*

## Technology History

- ◆ Being developed by IdaTech, LLC, in collaboration with the Toro Company, the University of California-Davis, and River's Edge Golf Course.
- ◆ Continuing work on shock and vibration testing and field testing of the prototype vehicle. Based on these tests a second prototype will be built and then demonstrated at selected venues.

## Applications

Can be used in off-road vehicles of all types, including golf carts and maintenance vehicles.

## Capabilities

- ◆ Uses methanol to fuel off-road fuel cell vehicles.
- ◆ Achieves increased range in a fuel cell vehicle by using liquid fuel.
- ◆ Protects fuel cells from shock, vibrations, and airborne pollution.

## Benefits

### Energy Efficiency

Uses a clean, highly efficient fuel cell instead of a gasoline engine.

### Versatility

Operates in a wide range of situations involving shock, vibration, and air pollution.

### Contact Information:

**Richard J. Lawrance**

Email: [rlawrance@idatech.com](mailto:rlawrance@idatech.com)

Phone: (541) 322-1112

**IdaTech, LLC**

63065 NE 18th Street

Bend, OR 97701

Website: [www.idatech.com](http://www.idatech.com)

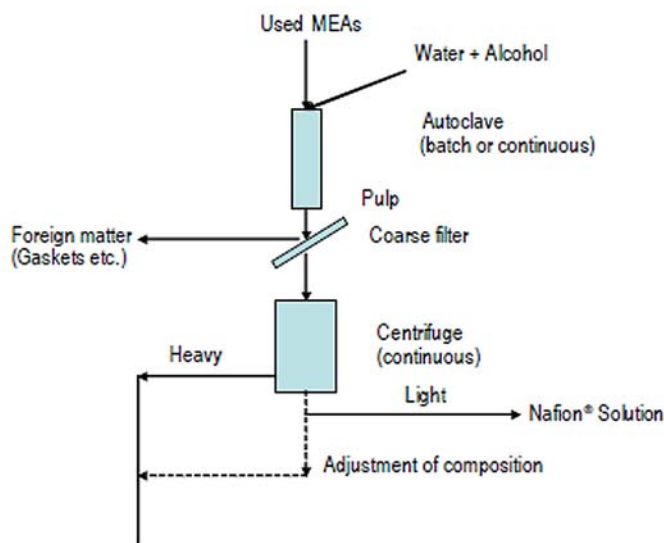


# Platinum and Fluoropolymer Recovery from PEM Fuel Cells

## Patented Process Recovers High Value Materials from Used Fuel Cells

Polymer electrolyte membrane (PEM) fuel cells are currently targeted for widespread back-up power and transportation applications. Current fuel cells contain valuable platinum (Pt), which can be recovered for reuse. The Pt is in the form of a Pt-carbon-ionomer mixture coated onto a Nafion® membrane to form a catalyst coated membrane (CCM) or membrane electrode assembly (MEA). Because the loading of Pt is about 2 g/kW, large systems contain enough material to make recycling economically feasible. The commercialization of fuel cell systems will increase demand for Pt group metals (PGMs). Without recycling PGMs, the long-term availability of Pt becomes a serious limitation. Therefore, Pt recycling is critical to the long-term economic sustainability of PEM fuel cells. Unfortunately, conventional Pt recovery processing is ill-suited for fuel cell components because the acid solvent method has a low recovery rate; the Pt particles are covered by the ionomer; and the Nafion® fluorine-containing polymer decomposes at high temperature, resulting in toxic and corrosive hydrogen fluoride gas being released. Thus, an advanced process is needed that enables the extraction and reuse of both the Pt and the ionomer in current fuel cell components.

Ion Power, Inc., has developed and patented, with HFCIT funding, a process that allows for the remanufacture of new MEAs made from used CCMs extracted from failed fuel cell stacks. The first step in this process is to remove the CCMs from the disassembled stacks and then dissolve the CCMs in an autoclave reactor to form a slurry of dissolved Nafion and the carbon-supported, Pt-catalyst particles. The second step is to separate these two valuable ingredients and allow the Nafion-containing solution to be reprocessed into a new fuel cell membrane. Ideally, the recovered Pt catalyst will be re-deposited on the remanufactured membrane so that a completely remanufactured CCM is the final product. To do this, recovered catalyst and Nafion are characterized to examine the changes of properties and structures during the component's life. The proper manufacturing process will be developed based on the properties and structures of recovered materials to realize a completely remanufactured CCM.



Ion Power's Recycling Process for MEAs

## Technology History

- ◆ Developed by Ion Power, Inc., in conjunction with DuPont Fuel Cells and Delaware State University.
- ◆ Continuing work on effective recovery of trace amounts of PGMs in the process and the commercialization of the process.

## Applications

Can be used for fuel cells that have reached the end of their useful life to recover the valuable raw materials that remain in the fuel cell membrane.

## Capabilities

- ◆ Allows for recycling of valuable platinum from used fuel cells.
- ◆ Prevents the formation of dangerous hydrofluoric acid fumes during recycling.
- ◆ Allows for remanufacturing of CCMs for fuel cells from the recovered fluoropolymer material.

## Benefits

### Cost Savings

Reduces the replacement cost of fuel cells by recovering valuable materials from used cells.

### Environmental

Eliminates the emission of hydrofluoric acid to the environment.

### Contact Information:

**Dr. Stephen Grot**

Email: [s.grot@ion-power.com](mailto:s.grot@ion-power.com)

Phone: (302) 832-9550

**Ion Power, Inc.**

720 Governor Lea Road

New Castle, DE 19720

Website: [www.ion-power.com](http://www.ion-power.com)



# Platinum-Group-Metal Recycling Technology

Emerging Technology

## New Method Recovers Platinum from Various Membrane Types

Fuel cell manufacturers are using different platinum-containing materials for membrane electrode assemblies (MEAs) in polymer electrolyte membrane (PEM) fuel cells. In addition, designs use either catalyst-coated membranes (CCMs) or gas diffusion electrodes (GDEs). These fuel cell components contain platinum (Pt) metal in their design; as the fuel cell ages, some of the Pt metal migrates throughout the membranes but is not consumed in the process. Because Pt is a valuable precious metal, recycling used fuel cells is worthwhile to recover the precious metal. However, the various types of fuel cell designs and materials make recovery difficult with a single process. Conventional recovery methods involve incineration, which creates undesirable by-products such as hydrogen fluoride gas from the MEA layers. The gas itself is poisonous and unsafe in the environment and combines with water vapor to form an extremely corrosive acid that dissolves glass and corrodes machinery used in the recycling process.

BASF Catalysts LLC, with HFCIT funding, is addressing these problems by developing a uniform process to recover and recycle precious metals (primarily Pt) used in constructing PEM fuel cell MEAs. This process is superior to the conventional Pt reclamation practice of MEA combustion, which liberates hydrogen fluoride gas from the perfluoropolymers used in the MEA. Instead, BASF has developed a process that leaches the precious metal from the MEA, eliminating the need for combustion. The process is applicable to CCM and GDE MEAs, as well as next-generation base-metal alloyed electrocatalysts. The process can be used for used MEAs and production scrap. In addition to the work done with Nafion®-based MEAs, the process has also been validated with MEAs that have polybenzimidazole membranes.

## Technology History

- ◆ Developed by BASF Catalysts LLC, in partnership with Ceralink, Inc.
- ◆ Continuing work on installing an agitated glass reactor and an agitated titanium-lined reactor to determine the Pt yield in each at different pressures and temperatures.

## Applications

Can be used to provide a recycling option for used fuel cells that eliminates the formation of hydrogen fluoride fumes.

## Capabilities

- ◆ Allows for single process batching of multiple fuel cell types.
- ◆ Achieves high process yields independent of MEA aging history, membrane construction, or electrocatalyst composition.

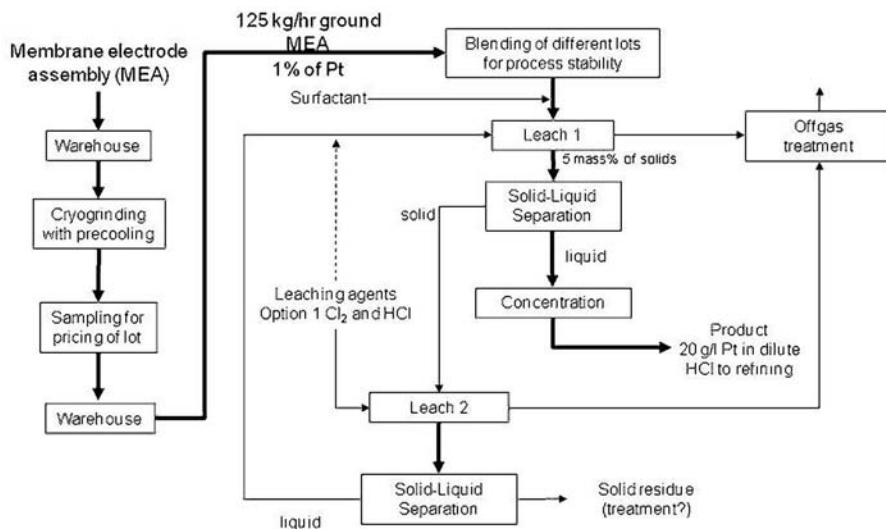
## Benefits

### Cost Savings

Achieves economy of scale by facilitating batching of recycled fuel cell lots.

### Efficiency

Recovers >98% of the platinum in MEAs.



BASF's Platinum Recycling Process

### Contact Information:

**Lawrence Shore**

Email: [larry.shore@basf.com](mailto:larry.shore@basf.com)

Phone: (732) 205-5447

**BASF Catalysts LLC**

25 Middlesex Turnpike

Iselin, NJ 08830

Website: [www.basf.com](http://www.basf.com)

# Polymer Electrolyte Membrane (PEM) Fuel Cell Power Plant Development and Verification

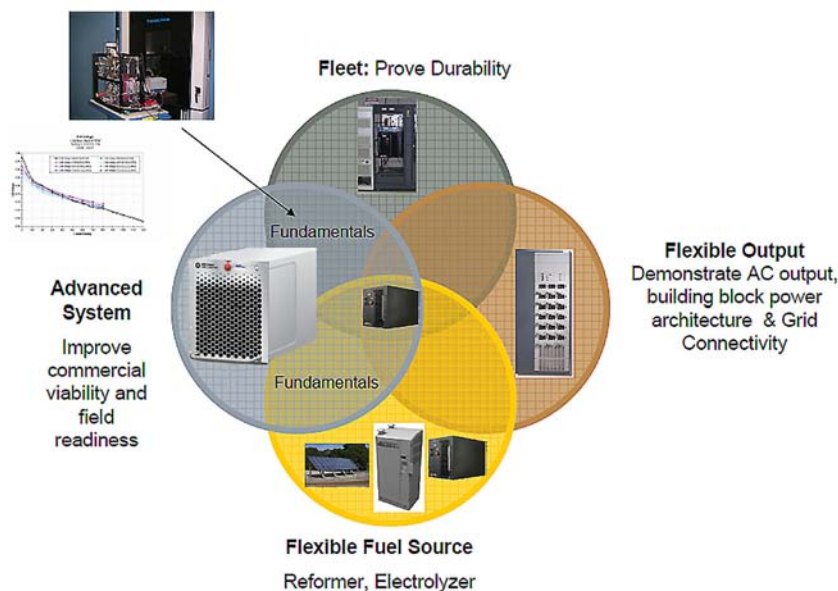
Emerging Technology

## New PEM Fuel Cell for Stationary Power Plant Applications

Commercialization of fuel cells for stationary power applications requires high availability and multiple grid connections. High availability requires that the mean time between forced outages (MTBFO) should be at least 5,000 hours. Multiple grid connections require control systems to ensure compatibility with any U.S. grid. Power requirements range from 5 kW to 150 kW or more for stationary applications, exceeding the capacity of most current technologies.

The problem is large-scale fuel cells (e.g., 150 kW) are difficult to build. The PEM for a 150-kW fuel cell would be very difficult to fabricate because of its large size and requirement for even gas flow and support. Large membranes are prone to early failure if the surface has any defects, which reduces the MTBFO. Higher power control circuits increase the complexity of ensuring compatibility with any U.S. grid.

To address these challenges, UTC Power, with HFCIT funding, is focusing on demonstrating technology for low-cost, high-durability stationary fuel cells using a 5-kW system platform to verify fundamental technologies in a complete system environment. The 5-kW platform is an efficient method to evaluate and build on lessons learned during early 150-kW power plant demonstration activities. Because durability is a requirement of stationary power supplies, the project is working towards a goal of a 40,000-hour fuel cell stack life. This goal is being accomplished by developing accelerated testing strategies to characterize the mechanical and chemical stability of seal materials. In addition, an accelerated chemical-mechanical test was developed to screen membranes for durability. The end result will be an affordable, durable PEM-fuel-cell based power plant for stationary applications.



UTC Power's Approach for the 5-kW Fuel Cell Development

## Technology History

- ◆ Developed by UTC Power in partnership with the Houston Advanced Research Center, U.S. Hybrid Corporation, TDI Power, and Avalence, LLC.
- ◆ Continuing work on system refinement, certification, and endurance testing and seeking field demonstration partners with potential commercial customers.

## Applications

Can be used to provide clean, efficient power for stationary applications.

## Capabilities

- ◆ Provides 5 kW to 20 kW of electrical power with path to large-scale power output (150 kW).
- ◆ Provides an alternative to conventional internal combustion power sources.
- ◆ Eliminates noise and pollution associated with conventional supplies.

## Benefits

### Cost Savings

Reduces development costs to close technology gaps by using a 5-kW platform for the powerplant. System cost is significantly reduced with advanced cell stack and balance-of-plant technology.

### Productivity

Exceeds program requirements for membrane internal resistance, open circuit voltage, falloff time, and conductivity.

### Contact Information:

**Eric Strayer**

Email: [Eric.Strayer@UTCPower.com](mailto:Eric.Strayer@UTCPower.com)

Phone: (860) 727-7238

**UTC Power**

195 Governor's Hwy

South Windsor, CT 06074

Website: [www.utcpower.com](http://www.utcpower.com)

# Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates

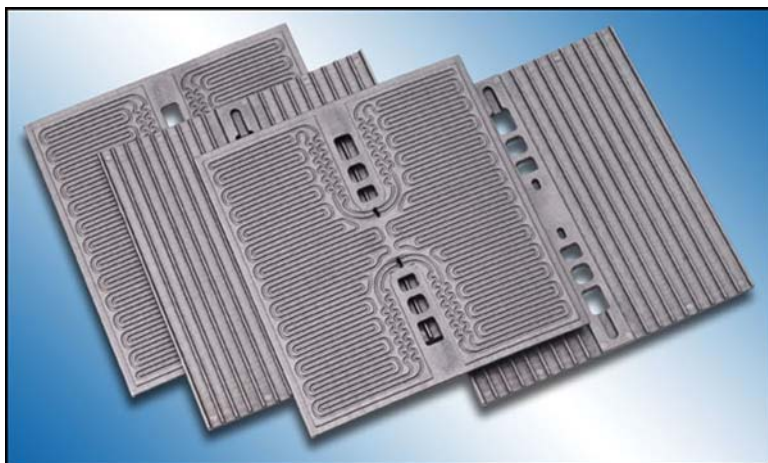
Emerging Technology

## New Lower-Cost Plates Operate at Higher Temperatures for Improved Performance

One of the main components by weight and volume of a polymer electrolyte membrane (PEM) fuel cell is the bipolar flow-field plate. A large number of these plates are required to produce a stack with the power and performance needed for automotive applications. Existing bipolar plate technology requires improved corrosion resistance, higher power density, improved gas impermeability, higher electrical and thermal conductivity, and lower production costs to meet stringent automotive and materials-handling performance targets.

Meeting these targets requires new materials and production methods. GrafTech International Ltd., with funding from HFCIT, is developing a new generation of GRAFCELL® bipolar flow-field plate technology that meets all of these needs. This technology uses expanded graphite in conjunction with an advanced high-temperature resin system to form PEM bipolar plates that are designed for high-volume production. High-volume production, combined with increased performance and durability, results in lower-cost PEM fuel cells, which meet the demanding requirements of automotive and materials-handling applications.

To meet these demanding requirements, the resin-impregnated flexible graphite composite has graphite as its continuous phase, allowing the material to retain the low contact resistance, high thermal conductivity, and high electrical conductivity of bulk graphite. High-temperature resins provide mechanical strength and structural stability and allow continuous operation of the composite bipolar plates at temperatures up to 120°C.



Typical Resin-Impregnated, Flexible-Graphite GRAFCELL Composite Flow-Field Plates (Used with Permission of Ballard Power Systems)

## Technology History

- ◆ Developed by GrafTech International Ltd., in collaboration with Ballard Power Systems, Inc., Huntsman Advanced Materials, and Case Western Reserve University.
- ◆ Producing full-size flow-field plates and then performing high temperature short-stack testing of these plates.

## Applications

Can be used in high-temperature PEM fuel cells for transportation, materials handling, and stationary power.

## Capabilities

- ◆ Provides continuous PEM fuel cell operation at 120°C.
- ◆ Achieves high process yields independent of aging history, membrane construction, or electrocatalyst composition of the membrane electrode assembly.

## Benefits

### Cost Savings

Can be fabricated using high-volume, cost-effective manufacturing processes.

### Performance

Operates at temperatures up to 120°C.

### Contact Information:

**Jeff Gough**

Email: [Jeff.Gough@graftech.com](mailto:Jeff.Gough@graftech.com)

Phone: (216) 676-2665

**GrafTech International Ltd.**

12900 Snow Road

Parma, OH 44130

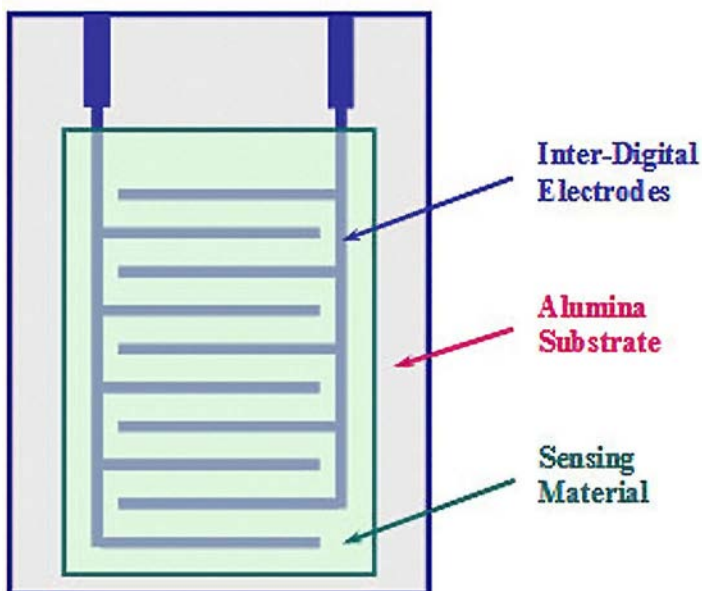
Website: [www.graftech.com](http://www.graftech.com)

## Advanced H<sub>2</sub>S Sensor Protects Fuel Cell Stack from Damage

Fuel cells use hydrogen to generate electrical power. One of the ways to generate hydrogen is by using a hydrocarbon fuel in a steam reformer. However, hydrocarbon fuel can contain sulfur, which forms hydrogen sulfide (H<sub>2</sub>S) gas after it passes through the steam reformers. This H<sub>2</sub>S gas is difficult to detect in the hydrogen-rich stream, and even extremely low levels can damage the fuel cell stack, reducing the stack's life. To avoid these problems, an H<sub>2</sub>S detector is needed, which can be located in a fuel cell power plant to provide continuous data signals to protect the stack from damage.

In an HFCIT-funded project, completed in 2005, NexTech Materials, Ltd., developed gas sensors required for automotive fuel cell systems. As a subcontractor to UTC Fuel Cells, NexTech pursued the development of sensors for three different gases, including carbon monoxide, ammonia, and H<sub>2</sub>S. The key requirement for these sensors was that the gases of interest needed to be detected in hydrogen-rich gas streams typical of reformed hydrocarbons. A key outcome of this project was the development a H<sub>2</sub>S sensor that can detect extremely low levels of H<sub>2</sub>S in a hydrogen-rich gas.

NexTech's H<sub>2</sub>S sensor operates by a reversible change in resistance caused by adsorption and desorption of H<sub>2</sub>S in a film of an H<sub>2</sub>S sensitive material. The patent-pending H<sub>2</sub>S sensing material has two oxide components: one that is stable in reducing environments and a second that reversibly forms a sulfide in the presence of H<sub>2</sub>S. The sensing material is deposited as a thick film on a substrate. The sensors can detect H<sub>2</sub>S from 25 ppb to 10 ppm, with response times of less than 30 seconds. Application requirements for H<sub>2</sub>S sensors in fuel cell systems vary greatly with respect to the type of fuel cell, the level of H<sub>2</sub>S detection required, the ambient gas composition and temperature.



*NexTech's H<sub>2</sub>S Sensor*

## Technology History

- ◆ Developed by NexTech Materials, Ltd., starting in 2002 as part of DOE's Partnership for a New Generation of Vehicles Program.
- ◆ Filed patent application on the sensor and continues to customize the sensor for specific applications.

## Applications

Can be used for fuel cell power plants using hydrogen generated from hydrocarbon fuels through reforming.

## Capabilities

- ◆ Maintains pure hydrogen streams for fuel cells by continuously monitoring for extremely low levels (25 ppb) of damaging H<sub>2</sub>S gas.
- ◆ Provides a response time of less than one minute.
- ◆ Allows for early detection of hydrogen gas purity problems.

## Benefits

### Cost Savings

Reduces the replacement cost of fuel cells by increasing the life of membranes.

### Product Quality

Enables fuel cells to stay on-line without frequent changing of fuel cell components due to damage from H<sub>2</sub>S.

### Productivity

Extends the life of guard beds, which are used to remove sulfur from hydrocarbon fuels, before being processed into hydrogen to feed a fuel cell.

### Contact Information:

**Lora B. Thrun, Ph.D.**

Email: [l.thrun@nextechmaterials.com](mailto:l.thrun@nextechmaterials.com)

Phone: (614) 842-6606

**NexTech Materials, Ltd.**

404 Enterprise Drive

Lewis Center, OH 43035-9423

Website: [www.nextechmaterials.com](http://www.nextechmaterials.com)





<b>E.2 Production/Delivery Technologies .....</b>	<b>E-27</b>
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## New Membrane Allows Cost-Effective Separation of Hydrogen for Fuel Cell Vehicles

The natural gas reforming process is a well established method for converting natural gas ( $\text{CH}_4$ ) to hydrogen ( $\text{H}_2$ ) and carbon monoxide ( $\text{CO}$ ). Additional  $\text{H}_2$  can be produced by the water gas shift reaction (WGSR) that converts  $\text{CO}$  and  $\text{H}_2\text{O}$  to carbon dioxide ( $\text{CO}_2$ ) and  $\text{H}_2$ . However for proper long-term operation, fuel cell vehicles require high purity hydrogen that is free of other gasses. One solution is to integrate a palladium (Pd) metal alloy membrane into this process to separate and purify the  $\text{H}_2$  for use in a fuel cell vehicle. Pall Corporation, with funding from HFCIT, is developing a Pd-based membrane that is designed to work as a selective barrier to only let  $\text{H}_2$  pass through. A mixed gas stream comes into the membrane device and is separated into two outlet streams, one containing near pure  $\text{H}_2$  at low pressure and the other containing  $\text{CO}_2$  and other components of the incoming gas at high pressure. The near pure  $\text{H}_2$  is the end product or fuel for fuel cell vehicles.

Developing this membrane requires research in the fields of Pd-membrane technology, high-temperature material analysis, and inorganic membrane product development and manufacturing. The resulting membrane will enable the design of a cost-effective natural gas reforming system. Combining the reforming process with the WGSR to create a membrane reactor could realize additional cost savings. The membrane device will also have a relatively small footprint, minimizing the overall plant size. The membrane design effort is focused on the unique requirements of distributed hydrogen production for fuel cell vehicles. These stations would produce up to 1,500 kg per day of  $\text{H}_2$  by reforming natural gas, which is equivalent to 300 cars per day. This is the average number of cars serviced by a typical gasoline fueling station today.



*Pall High-Performance Palladium-Based Membrane*

## Technology History

- ◆ Being developed by Pall Corporation in partnership with the Colorado School of Mines and the Oak Ridge National Laboratory.
- ◆ Building test stands to determine the durability and performance of the membranes under various operating conditions.

## Applications

Can be used to produce hydrogen using natural gas and steam.

## Capabilities

- ◆ Allows for near ideal separation of  $\text{H}_2$  from other gas stream components.
- ◆ Achieves extremely high rates of gas transport as well as high separation factors/high purity.
- ◆ Offers high-temperature and high-pressure operation.

## Benefits

### Cost Effective

Can be economically integrated into the overall  $\text{H}_2$  production process.

### Versatility

Is readily amenable to small-, medium-, or large-scale industrial commercialization.

#### Contact Information:

**Jim Acquaviva**

Email: [Jim\\_Acquaviva@Pall.com](mailto:Jim_Acquaviva@Pall.com)

Phone: (516) 801-9210

**Pall Corporation**

25 Harbor Park Drive

Port Washington, NY 11050

Website: [www.pall.com](http://www.pall.com)



# Hydrogen Generation from Biomass-Driven Carbohydrates via Aqueous-Phase Reforming

Emerging Technology

## New Process Uses Carbohydrates to Cost Effectively Produce Hydrogen

Generation of hydrogen traditionally involves using natural gas in a reforming process. However, natural gas is a nonrenewable resource, and the reforming process generates other products that must be removed from the gas stream to achieve pure hydrogen. The reforming process itself operates at high temperature and needs steam for the chemical transformation, increasing the total energy cost and the cost of the resulting hydrogen. Using renewable resources requires a technology that performs economical bioreforming in an aqueous state at a lower temperature than traditional reforming. Such a technology would also need to be flexible and to be able to use a wide variety of feedstocks for generating hydrogen.

Virent Energy Systems, Inc., with funding from HFCIT, is adapting their BioForming™ process, a patented aqueous-phase reforming (APR) process, to economically produce hydrogen. A range of biomass-derived feedstocks, including glycerol and sugars, is being tested as feedstocks. The key breakthrough in the BioForming process is a proprietary catalyst that operates in the aqueous phase and has high hydrogen selectivity at low temperature. The process reforms water-soluble oxygenated-hydrocarbons in a single step and produces a hydrogen-rich gas that is easily purified. The BioForming process can be used to produce fuel stock for energy systems requiring a clean source of hydrogen, including for transportation. The process applications are broad, given that hydrogen is a key chemical building block used in many chemical processes, predominately ammonia fertilizer production and, in oil refineries, to upgrade lower quality oil fractions into gasoline and diesel and to remove sulphur contaminants. Other applications include the manufacture of glass, vitamins, personal care products, lubricants, refined metals, and food products.



Virent's Hydrogen Pilot Plant

## Technology History

- ◆ Being developed by Virent Energy Systems, Inc., in partnership with Archer Daniels Midland Co. and the University of Wisconsin.
- ◆ Focusing on developing the APR catalyst and reactor system that converts glucose to hydrogen.

## Applications

Can be used to produce hydrogen using biomass-derived carbohydrates.

## Capabilities

- ◆ Uses renewable biomass-derived feedstock to generate hydrogen.
- ◆ Produces hydrogen at low temperatures without forming carbon monoxide.
- ◆ Uses various sugars and sugar alcohols in addition to feedstocks.

## Benefits

### Energy Efficiency

Does not require fossil fuels and generates carbon-neutral hydrogen from widely available biomass-derived feedstocks.

### Versatility

Produces hydrogen from various renewable feedstocks as well as various sugars and sugar alcohols.

### Contact Information:

**Dr. Randy D. Cortright**

Email: [Randy\\_Cortright@virent.com](mailto:Randy_Cortright@virent.com)

Phone: (608) 663-1630

**Virent Energy Systems, Inc.**

3571 Anderson St.

Madison, WI 53704

Website: [www.virent.com](http://www.virent.com)

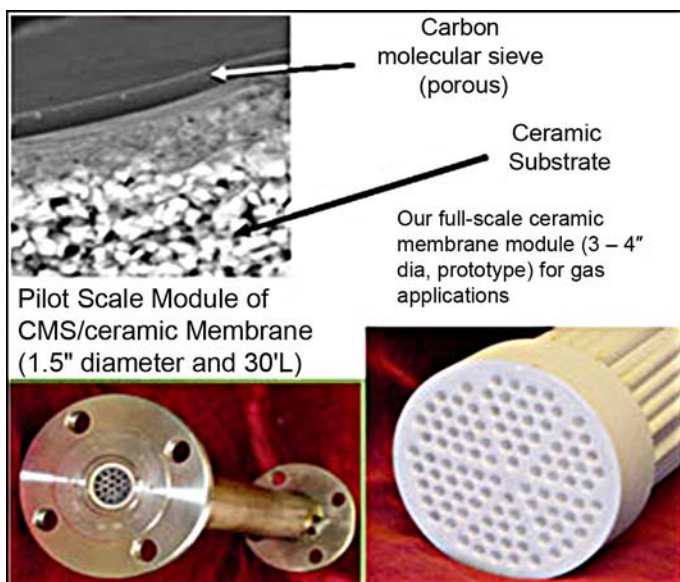
# Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor

Emerging Technology

## New Carbon Molecular Sieve Separates Hydrogen in Harsh Environments

The production of hydrogen often involves the production of syngas from coal. The syngas contains hydrogen and carbon monoxide as well as sulfur and heavy hydrocarbons. Existing methods to separate out the hydrogen involve two stages. The first stage is a water gas shift reaction using steam and high temperature with a catalyst to initiate a reaction that transforms the carbon monoxide to carbon dioxide and additional hydrogen. The second stage separates the hydrogen from the carbon dioxide and the other contaminants (sulphur and heavy hydrocarbons). Both stages are problematic because of the high temperatures involved and the contamination effect of the sulphur and heavy hydrocarbons. The contaminants can cause plugging, which can decrease the efficiency of the process. A method is needed to remove the contaminants and reduce the process from two steps to one step. Ideally, reducing the temperature of the reaction from the current 400°C to 200°C to 250°C would be beneficial. At high temperatures, the current catalyst membrane is prone to stability problems, and the corrosion effects of the contaminants are increased.

Media and Process Technology (M&P), Inc., with HFCIT funding, has overcome these problems and developed a commercially viable carbon molecular sieve (CMS) membrane. Although CMS membranes were introduced in 1980, no commercially viable product was available because of the lack of a technically viable module and potential surface poison by contaminants. M&P's robust CMS membrane can function as a hydrogen separator as well as a membrane reactor for the water gas shift reaction, thereby combining two process steps into one. Its inertness offers excellent opportunities for intermediate temperature applications under harsh environment, such as syngas from coal, and hydrogen recovery from sulfur and heavy hydrocarbon containing streams. The CMS membrane has been incorporated into a distributed hydrogen production process called HiCON, which is being pilot-scale tested now and will be field tested.



Media and Process Technology's CMS Membrane

## Technology History

- ◆ Being developed by M&P with support from Johnson Matthey, Inc., the University of Southern California, and Chevron Energy Technology Company.
- ◆ Running pilot-scale unit to demonstrate the optimized HiCON process and constructing field-demonstration unit.

## Applications

Can be used to produce hydrogen using syngas from coal and hydrogen recovery from sulfur and heavy hydrocarbon containing streams.

## Capabilities

- ◆ Uses coal syngas and hydrocarbon waste streams to generate hydrogen.
- ◆ Achieves production and separation of hydrogen at low temperatures in one step.
- ◆ Operates under harsh environments, such as sulfur and heavy hydrocarbon containing streams.

## Benefits

### Durability

Delivers burst pressure in excess of 1500 psi.

### Versatility

Produces hydrogen from syngas from coal and recovers hydrogen from sulfur and heavy hydrocarbon containing streams.

### Contact Information:

**Paul K. T. Liu**

Email: [pliu@mediaandprocess.com](mailto:pliu@mediaandprocess.com)

Phone: (412) 826-3721

**Media and Process Technology, Inc.**

1155 William Pitt Way

Pittsburgh, PA 15238

Website: [www.mediaandprocess.com](http://www.mediaandprocess.com)

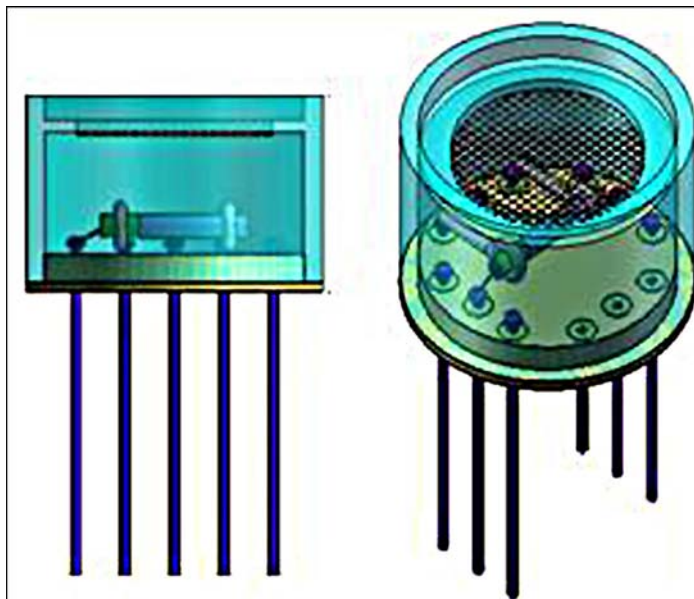
# Hydrogen Safety Sensor for Advanced Energy Applications

Emerging Technology

## New Low-Cost, Durable Ceramic-Based Sensor Reliably Detects Hydrogen in the Presence of Other Gases

With the anticipated growth of the hydrogen sensor market for advanced energy applications, a number of hydrogen sensor technologies have emerged. No single technology, however, meets the key requirements of the advanced energy community. Most commercial sensors suffer from cross-sensitivity to gases such as carbon monoxide and methane, have very slow recovery times, drift over time, or are cost-prohibitive. A hydrogen sensor is needed that can operate in a wide variety of other gases without false readings, that is stable, and that can be mass-produced to reduce costs. Such a sensor would have wide-scale implementation in any application requiring the safe use or handling of hydrogen gas.

To meet these requirements, NexTech Materials, Ltd., with funding from HFCIT through the Edison Materials Technology Center, developed a new family of hydrogen sensitive materials based on a three-phase ceramic composite. The composite is sensitive to hydrogen over a wide concentration range and is unaffected by varying humidity and background combustible gases such as carbon monoxide and methane. The NexTech hydrogen sensor detects the presence of hydrogen in air at concentrations as low as 500 ppm, even in widely varying environmental conditions. NexTech's hydrogen sensor is based on a three-phase composite ceramic material, which was developed using sensor elements comprised of a thick film deposited on electroded substrates. After evaluating several element designs, NexTech selected a tubular sensor design in which electrode and active sensor coatings are deposited onto the exterior of a tubular substrate. A heater is inserted in the center of the tube to efficiently heat the sensor to its operating temperature with minimal power consumption. A protective cap with a flame-arrestor gas sampling mesh physically protects the sensor element and further reduces thermal losses. The net result is a durable and reliable hydrogen sensor design with minimal power consumption requirements. Because of its low materials and fabrication cost, this product lends itself to wide-scale implementation in any application requiring the safe use or handling of hydrogen gas.



*NexTech's Ceramic-Based Hydrogen Sensor*

## Technology History

- ◆ Developed by NexTech Materials, Ltd.
- ◆ Developing the integrated electronics and packaging for the sensor and third-party testing for certification prior to prototype testing.

## Applications

Can be used to detect hydrogen for the safe handling and implementation of hydrogen among fuel cell developers, electrolysis system developers, and at distribution points in the emerging hydrogen infrastructure.

## Capabilities

- ◆ Detects the presence of hydrogen in air at concentrations as low as 500 ppm, even in widely varying environmental conditions.
- ◆ Can be used in the presence of carbon monoxide, methane, and volatile organic compounds.
- ◆ Can be used in fluctuating humidity environments.

## Benefits

### Cost Savings

Offers low materials and fabrication cost at high production volumes.

### Productivity

Provides durability and reliability with fast response and recovery times.

### Contact Information:

**Dr. Lora Thrun**

*Email:* [l.thrun@nextechmaterials.com](mailto:l.thrun@nextechmaterials.com)

*Phone:* (614) 842-6606 x129

**NexTech Materials, Ltd.**

404 Enterprise Dr.

Lewis Center, OH 43035

**Website:** [www.nextechmaterials.com](http://www.nextechmaterials.com)



# Integrated Ceramic Membrane System for Hydrogen Production

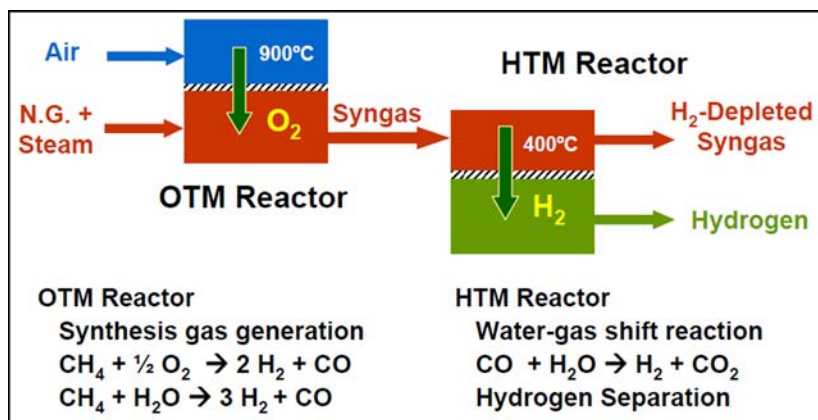
Emerging Technology

## New Palladium-Based Membrane System Produces High-Purity Hydrogen at Reduced Capital Cost

Hydrogen is expected to play a vital role in the transportation sector for fuel cell vehicles (FCVs). One of the crucial factors for successfully introducing FCVs on U.S. roadways is a low-cost supply of hydrogen. The near-term demand for hydrogen at FCV fueling stations is projected to be less than 10,000 standard cubic feet per hour (scfh). To be competitive with gasoline, the cost of hydrogen delivered to a vehicle must be below \$20/MMBtu. A key challenge in achieving this price is to reduce the capital cost of an onsite plant.

One approach to lower capital costs is to reduce both the complexity of the process and the equipment needed to generate hydrogen. The equipment needed to produce hydrogen depends on the hydrogen production process used. In this system, the two main components are the oxygen transport membrane (OTM) and the hydrogen transport membrane (HTM). Air at low pressure (25 psi) is passed to one side of the OTM, and compressed natural gas (200 – 300 pisa) and steam are passed to the other side of the OTM. Oxygen is transported across the OTM to the permeate side, where it reacts with natural gas to form syngas. A portion of natural gas also reacts with steam to form syngas. Hydrogen is formed by the water-gas shift reaction in the HTM reactor where CO reacts with steam to form more hydrogen and CO<sub>2</sub>. The proper membrane support material and catalysts could reduce the complexity of this process

Praxair, Inc., with funding from HFCIT, is researching a hydrogen transport membrane integrated in a water-gas-shift reactor to increase hydrogen yield from the reactor by shifting the equilibrium composition to produce more hydrogen and less CO. The palladium-based membrane has the added advantage of producing hydrogen with extremely high purity, appropriate for polymer electrolyte membrane (PEM) fuel cells. Small on-site hydrogen generators, such as those that would be located at fueling stations, are the target production units for this technology.



*Praxair's Conversion Process for Hydrogen Production*

## Technology History

- ◆ Being developed by Praxair, Inc., in partnership with the Research Triangle Institute.
- ◆ Continuing work to improve the palladium-based membrane, reducing its cost, and testing the performance of the system.

## Applications

Can be used to generate hydrogen for use in hydrogen-powered vehicles.

## Capabilities

- ◆ Increases hydrogen yield from any synthesis gas generator, including OTM processes and reforming.
- ◆ Achieves strength with porosity through advanced ceramic substrate technology.
- ◆ Increases production of high-purity hydrogen from syngas

## Benefits

### Capital Cost

Produces hydrogen in a less capital-intensive system because of the simpler integrated membrane system.

### Performance

Produces hydrogen at sufficient purity for PEM fuel cells without further purification.

### Versatility

Combines uniform small pores on the surface to support a thin membrane layer with larger pores in the bulk of the substrate to allow unrestricted flow.

### Contact Information:

**Joseph Schwartz**

Email: joseph\_schwartz@praxair.com

Phone: (716) 879-7455

**Praxair, Inc.**

175 East Park Drive

PO Box 44

Tonawanda, NY 14151

Website: [www.praxair.com](http://www.praxair.com)

# Integrated Hydrogen Production, Purification and Compression System

Emerging Technology

## New Technology Produces Pure, High Pressure Hydrogen at Reduced Cost

One of the major hurdles to a hydrogen economy is demonstrating a low-cost option for producing fuel-cell-quality hydrogen that can meet DOE cost and efficiency targets for distributed production of hydrogen. DOE has determined that the delivered cost of hydrogen must be equivalent to \$2 to \$3/gallon of gasoline for hydrogen to be competitive as a fuel for vehicles. For small, on-site hydrogen plants being evaluated for refueling stations, capital cost is the main challenge to delivered hydrogen cost. Existing systems have high capital cost because of the complexity of the present reforming, purification, and compression stages.

A technology is needed that uses fewer stages and uses excess heat for compression. One of the main components in existing systems is the hydrogen compressor, which is needed to develop the high pressures required for efficient storage of hydrogen in the vehicle. The compressor requires electrical energy to run the motor, which reduces the system's overall efficiency. System efficiency gains are also affected by the number of separate stages needed prior to compression.

Linde Inc., with funding from HFCIT, is developing a technology to reduce the number of stages needed and is working to achieve the target hydrogen cost by combining unit operations for the entire generation, purification, compression, and delivery system. Their system uses a membrane reformer, developed by Membrane Reactor Technologies (MRT), Ltd. The reformer has elevated-temperature, hydrogen (H<sub>2</sub>)-selective, palladium-alloy membrane modules immersed in a fluid bed reformer vessel, thereby directly producing high purity hydrogen in a single step. The continuous removal of pure hydrogen from the reformer pushes the equilibrium forward, thereby maximizing reactor productivity. Further, H<sub>2</sub> flux through the membrane is increased by using the suction capabilities of the novel hydride compressor developed by Ergenics Corporation. The integrated reformer-compressor package is envisaged to provide additional gains by compressing H<sub>2</sub> from 0.5 bar to 350 bar or higher in a single unit and using waste heat from the reformer to supply more than 20% of the compression energy, thus reducing operating costs.



Linde's Prototype Hydrogen Generator Unit

## Technology History

- ◆ Being developed by Linde Inc. in collaboration with Membrane Reactor Technologies, Ltd., and Ergenics Corporation.
- ◆ Testing the proof-of-concept prototype unit to validate design improvements and demonstrate that DOE cost and efficiency targets are achievable.

## Applications

Can be used to generate hydrogen directly for vehicle fueling or other fuel cell and industrial applications.

## Capabilities

- ◆ Improves heat and mass transfer because of inherent advantages of the fluid bed reformer design.
- ◆ Achieves increased H<sub>2</sub> flux as a result of suction provided by the hydride compressor on the permeate side.
- ◆ Uses excess heat from the reformer to provide over 20% of the compression energy.

## Benefits

### Capital Cost

Lowers capital cost compared with conventional fuel processors by reducing component count and subsystem complexity.

### Performance

Increases energy efficiency by directly producing high-purity hydrogen using high-temperature, H<sub>2</sub>-selective membranes.

#### Contact Information:

**Satish Tamhankar**

Email: [Satish.Tamhankar@linde.com](mailto:Satish.Tamhankar@linde.com)

Phone: (908) 771-6419

**Linde Inc.**

575 Mountain Avenue

Murray Hill, NJ 07974

Website: [www.linde.com](http://www.linde.com)

# Integrated Short Contact Time Hydrogen Generator

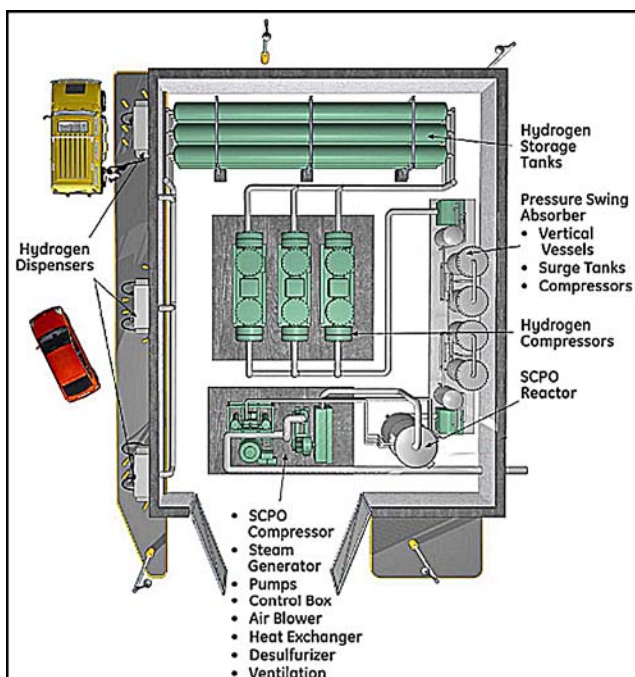
Emerging Technology

## New Technology Uses Novel Staged Catalytic Partial Oxidation (SCPO) Technology for Hydrogen Production

One challenge for the realization of the hydrogen economy is the development of a low-cost, compact reforming technology that is fuel flexible and can produce hydrogen ( $H_2$ ) from fossil fuels and renewable fuels. Analysis of existing systems has shown that efficiency is just one of many factors that affect the cost of a  $H_2$  generation system. For example, some system configurations have a higher than expected system efficiency but also have more components, which leads to higher capital cost and lower reliability. Thus, the most efficient system is not necessarily the best technology choice for  $H_2$  production.

A technology is needed that uses fewer components to reduce the cost of  $H_2$  production. Ideally, the technology should be modular for mass production and should be thermally integrated as much as possible to reduce the cost and improve the efficiency.

GE Global Research Center, with funding from HFCIT, is developing an efficient, unique technology based on integrating four catalysts zones: pre-steam methane reforming (pre-SMR), catalytic partial oxidation (CPO), steam methane reforming (SMR), and water gas shift (WGS). The resulting SCPO technology generates  $H_2$  from natural gas to meet DOE cost and efficiency targets for distributed  $H_2$  generating and dispensing systems of less than 1,500 kg/day. Using this novel system and short-contact time catalysts allows for greater reformer compactness and therefore lower capital costs than conventional approaches. The unique system design, as well as modular component design, will reduce the manufacturing cost after mass production and ease the operation and maintenance for  $H_2$  production. The project has demonstrated that it is a leading technology for  $H_2$  production from natural gas and with minor modifications will allow the use of biofuels, gasoline, or diesel as feedstock.



GE Global Research Center's Hydrogen Generator

## Technology History

- ◆ Being developed by GE Global Research Center in partnership with Argonne National Laboratory and the University of Minnesota.
- ◆ Continuing work on SCPO catalyst testing to increase the sulfur tolerance of the system and refinement of the system analysis for updated costs.

## Applications

Can be used in different industries when syngas and hydrogen production are needed.

## Capabilities

- ◆ Can be mass-produced because of its modular design.
- ◆ Achieves  $H_2$  production of 60 Kg/day using test units and working on a system to produce 1,500 kg/day.
- ◆ Reduces peak metal temperature in entire system to  $<600^\circ C$  to allow the use of low cost stainless steel

## Benefits

### Cost Effectiveness

Allows cost-effective mass production because of its integrated, modular design.

### Performance

Combines the efficiency advantage of steam reforming and the low capital cost advantage of autothermal reforming.

### Contact Information:

**Dr. Ke Liu**

Email: [liuk@research.ge.com](mailto:liuk@research.ge.com)

Phone: (949) 330-8977

**GE Global Research Center**

18A Mason

Irvine, CA 92618

**Website:**

[www.ge.com/research/grc\\_4\\_5\\_11.html](http://www.ge.com/research/grc_4_5_11.html)



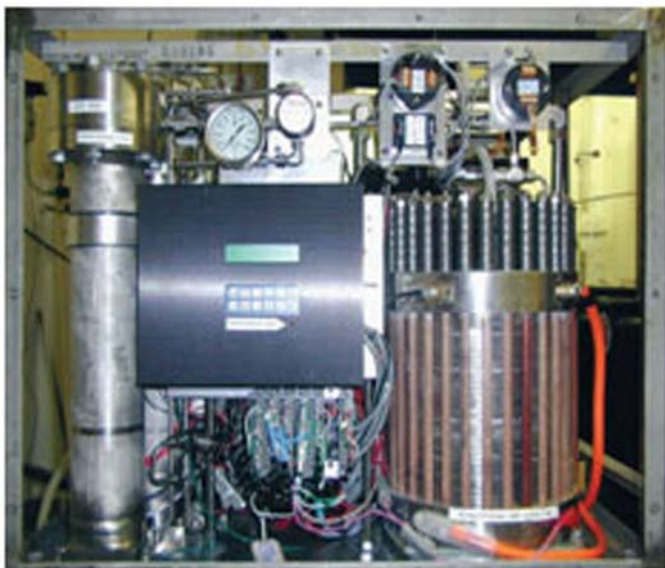
# Low-Cost, High-Pressure Hydrogen Generator

Emerging Technology

## New Technology Displays Improved Stack Energy Efficiency and Power Density for Hydrogen Production

Demand for high purity hydrogen is increasing in industrial sectors, such as microchip manufacturing, ammonia production, and metallurgy. Utility use of hydrogen for generator cooling is also increasing. Utilities are also interested in using electrolysis to capture otherwise lost energy from renewable power-generating sources, such as wind during low demand time, for peak shaving. High purity, low-cost hydrogen is essential for the hydrogen economy. Electrolysis can produce high purity hydrogen, but current technologies have high capital costs because of complex designs, high parts count, and expensive materials. Significant reductions in the capital cost and complexity of electrolysis systems are required to make this technology competitive for the hydrogen economy and other applications.

Giner Electrochemical Systems, LLC, with funding from HFCIT, is working to make electrolysis competitive by improving the electrolyzer design, manufacturing techniques, and materials. One of the design improvements is Giner's anode-side membrane support structure (ASMSS). In prior designs, the ASMSS was a complex structure consisting of nine layers of metallic components, with each layer processed and assembled by hand. This structure had the highest parts count and labor requirements of the cell components. Giner is developing technology to revise this structure into a single piece component having the required properties and tolerances. This technology, combined with other improvements, will result in lower-cost cell components through design simplification along with less expensive materials and lower-cost fabrication methods.



*Giner's Electrolyzer Module System*

## Technology History

- ◆ Being developed by Giner Electrochemical Systems, LLC, in partnership with General Motors Corporation and the Center for Technology Commercialization.
- ◆ Continuing testing of a prototype unit at the National Renewable Energy Laboratory and developing advanced membranes.

## Applications

Can be used to produce high purity hydrogen anywhere electricity is available from wind, solar, or other means.

## Capabilities

- ◆ Operates in remote locations with renewable energy sources.
- ◆ Achieves hydrogen production by using water and electricity.
- ◆ Offers higher power density and stack efficiency than conventional systems.

## Benefits

### Cost Effectiveness

Results in lower labor costs for assembly because of reduced parts count.

### Performance

Results in stable electrolyzer performance over long periods of time because of improved stack design.

### Contact Information:

**Monjid Hamdan**

*Email:* [mhamdan@ginerinc.com](mailto:mhamdan@ginerinc.com)

*Phone:* (781) 529-0526

**Giner Electrochemical Systems, LLC**

89 Rumford Avenue

Newton, MA 02466

**Website:** [www.ginerinc.com](http://www.ginerinc.com)

# Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures

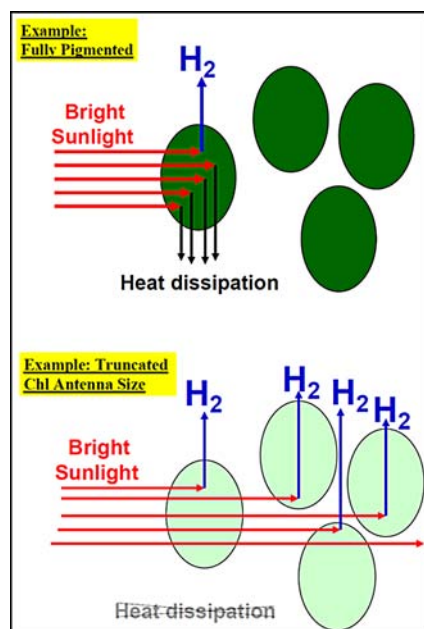
Emerging Technology

## New DNA Research Improves the Ability of Algae to Produce Hydrogen

Hydrogen can be produced in a number of different ways. Unfortunately, only a few of them involve renewable energy sources. Renewable energy sources are preferred whenever possible, but most of the existing renewable energy hydrogen generation technologies involve a large amount of capital outlay and are technically complicated. In addition, some of them create unwanted byproducts such as carbon dioxide or carbon monoxide. The conversion and sequestering of these unwanted byproducts require the use of additional energy and technology.

A simple, low energy, low technology process is needed that uses natural materials and does not produce unwanted byproducts. Ideally, this technology would use a nonpolluting source of energy such as sunlight and a plant type of material that could be grown in a water media.

The University of California (UC)-Berkeley is developing, with funding from HFCIT, this type of technology by genetically engineering a strain of algae that is proving to be highly efficient at converting sunlight to hydrogen. UC-Berkeley's preliminary investigation discovered that the normal type of algae that grows in the wild suffers from a characteristic that limits efficient conversion of sunlight into hydrogen. This limiting characteristic is the high-density green color resulting from the presence of chlorophyll in the algae. The chlorophyll tends to over-absorb sunlight in individual cells at the surface of the culture, causing heat dissipation and failure of the sunlight to penetrate deeper into the culture. This over-absorption limits the conversion efficiency of the algae, resulting in lower production of hydrogen. By genetically engineering the size of the chlorophyll "antenna," UC-Berkeley has prevented this over-absorption at the surface, which allows the sunlight to penetrate deeper into the culture, thereby decreasing the heat dissipation and increasing the light utilization efficiency of hydrogen production from 3% to 15%.



## Technology History

- ◆ Being developed by the UC-Berkeley Plant & Microbial Biology Department.
- ◆ Continuing work on developing genetic strains of truncated chlorophyll antenna algae and advancing the biochemical and molecular characterization of several promising strains that show high utilization of sunlight for hydrogen production.

## Applications

Can be used to produce hydrogen using algae and sunlight.

## Capabilities

- ◆ Uses renewable algae to generate hydrogen.
- ◆ Produces hydrogen in normal sunlight without undesirable byproducts.
- ◆ Increases sunlight utilization in algae from 3% to 15%.

## Benefits

### Energy Efficiency

Requires no fossil fuels and generates carbon-neutral hydrogen from algae and sunlight.

### Versatility

Produces hydrogen from algae in an easily scalable system.

### Contact Information:

**Tasios Melis**

Email: [melis@nature.berkeley.edu](mailto:melis@nature.berkeley.edu)

Phone: (510) 642-8166

**University of California at Berkeley**

Berkeley, CA 94720-3102

Website: [www.berkeley.edu](http://www.berkeley.edu)

# Membrane Structures for Hydrogen Separation

Emerging Technology

## New Low-Cost Membranes Supply Ultra-Pure Hydrogen for Fuel Cells

Achieving a hydrogen economy requires new devices and technology. One of the devices needed is a hydrogen purifier to separate hydrogen from other gases. Purifiers have three basic requirements: mechanical support of a thin membrane, effective sealing, and pore-free membranes. Existing designs can often do two out of the three, but achieving all three is very difficult, particularly at low cost. Because existing purifiers are expensive and mechanically fragile, incorporating them into devices such as reformers to produce hydrogen increases the overall cost and decreases the reliability of the complete system.

A low-cost membrane to separate hydrogen is needed. The membrane is the portion of the purification system that separates mixed gases from the desired purified hydrogen gas. These gases are under pressure, so the membrane needs to be both mechanically robust and free of pores. Its architecture needs to allow for effective sealing and membrane support to create a low-cost purifier module.

Genesis Fueltech, Inc., with the help of DOE SBIR grants, is developing a thin, pore-free membrane to be used in a purifier module. The planar architecture will allow for scaling to larger sizes to increase the capacity while maintaining the low-cost design features. Genesis Fueltech has refined the design for improved mechanical support, sealing, and other processing steps, and includes improved alloys for higher hydrogen flux.



*Genesis Fueltech's Model 20L Reformers*

## Technology History

- ◆ Developed by Genesis Fueltech, Inc., starting in 2005.
- ◆ Testing is ongoing with potential commercialization in 2009.

## Applications

Can be used in Genesis methanol reformers to supply pure hydrogen for fuel cells.

## Capabilities

- ◆ Maintains higher hydrogen output than existing conventional units.
- ◆ Handles mechanical stress without failure.
- ◆ Achieves high manufacturing rates.

## Benefits

### Cost Savings

Allows purifiers using these membranes to be an order of magnitude less expensive than conventional units.

### Productivity

Can scale existing designs for industrial applications.

#### Contact Information:

**David DeVries**

*Email:* david@genesisfueltech.com

*Phone:* (509) 534-5787

**Genesis Fueltech, Inc.**

528 S. Cannon

Spokane, WA 99201

**Website:** [www.genesisfueltech.com](http://www.genesisfueltech.com)

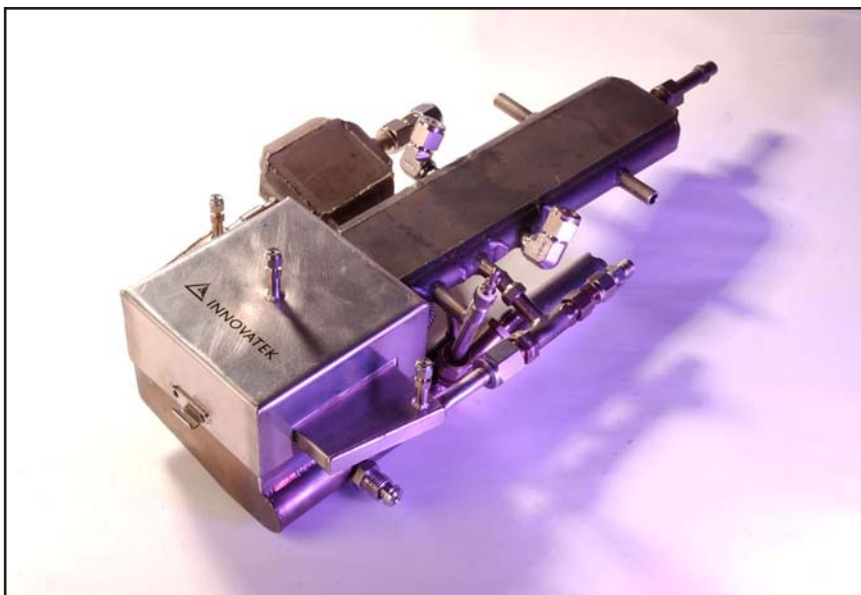
# Novel Catalytic Fuel Reforming

Emerging Technology

## New System Generates Hydrogen from Multiple Fuels

Hydrogen generation from existing fuel production and distribution networks (i.e., natural gas, gasoline, diesel, or jet fuels) offers a significant cost advantage in the final generation and delivery of power compared with using compressed hydrogen. Reforming hydrocarbon fuel provides high energy density, contributes to increased run times per unit of fuel consumed, and reduces the need for increased on-site fuel storage concerns. However, conventional reformers do not handle multiple fuel types, especially fuels containing sulfur. A reformer is needed that can handle multiple fuels with higher sulfur content and is easy to control and safe to operate. The reformer needs to have a reasonable initial capital cost and must operate with minimal maintenance.

To address these challenges, InnovaTek, Inc., with HFCIT funding, has developed a novel hydrogen generator that reforms multiple fuel types (natural gas, gasoline, and diesel) to produce pure hydrogen by integrating microreactor and microchannel heat exchanger technology with advanced sulfur-tolerant catalysts and membranes. Microstructured components, especially an integrated system of catalytic and heat exchange microchannels, produce a compact, thermodynamically efficient fuel processor design. The integrated prototype can produce 12 to 60 liters per minute of hydrogen that can fuel a 1- to 5-kW polymer electrolyte membrane (PEM) fuel cell, or other auxiliary power unit. Current work is focused on developing and delivering prototype systems for testing with various types of fuel cells. InnovaTek has partnered with commercial firms to further develop and test the unit for defense missions and for backup or auxiliary power for large trucks that have emissions control restrictions but still need power while idling.



*InnovaTek's Catalytic Fuel Reformer*

## Technology History

- ◆ Developed by InnovaTek, Inc.
- ◆ Continuing work with commercial partners on prototype testing of the unit for use in defense missions and as an auxiliary power unit in large trucks.

## Applications

Can be used to produce hydrogen from multiple fuel sources, including natural gas, gasoline, diesel, or jet fuels.

## Capabilities

- ◆ Produces 30 to 150 grams per hour of hydrogen.
- ◆ Provides an integrated package of reformer components.
- ◆ Allows use of multiple fuel sources to generate hydrogen.

## Benefits

### Cost Savings

Increases the efficiency of the reformer by integrating the microstructured steam reformer, heat exchangers, and fuel injector.

### Performance

Demonstrates thermal efficiency >65%.

### Contact Information:

**Patricia Irving**

*Email:* [irving@tekkie.com](mailto:irving@tekkie.com)

*Phone:* (509) 375-1093

**InnovaTek, Inc.**

350 Hills Street, Suite 104  
Richland, WA 99354

**Website:** [www.tekkie.com](http://www.tekkie.com)



# Novel Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production

Emerging Technology

## New Device Replaces Loose Ceramic Catalyst Media for Increased Efficiency in Hydrogen Production

For many years bulk hydrogen has been made from natural gas using a steam reforming process. In this process, many stainless steel tubes are suspended vertically in a furnace that operates at 850°C to 900°C. These tubes are normally 3" to 6" in diameter and up to 40 feet tall. The tubes are filled with loose ceramic media that is impregnated with catalyst materials. To maximize surface area, the ceramic media is shaped as balls, small saddles, wheels, and similar configurations. Steam and natural gas are fed to one end of the tubes; as the steam and gas pass over the catalyst-impregnated ceramic shapes, they generate hydrogen (as syngas), which is extracted from the opposite end.

The problem with the process is that it is fundamentally limited by the ability of the ceramic media to transfer heat. Also, the ceramic shapes break down and deteriorate over time, requiring the ceramic catalyst bed be replaced every three to five years.

To address the process limits and need for periodic replacement, Catacel Corp., with HFCIT funding through the Edison Materials Technology Center, has developed the Catacel SSR as a drop-in replacement for the loose ceramic catalyst media in the stationary steam reforming process. This replacement consists of a cylindrical metallic catalyst-impregnated honeycomb that increases heat transfer and resists mechanical breakdown. The Catacel SSR eliminates the periodic replacement that is required for ceramic packed beds and increases the overall performance of the system. Early tests have demonstrated a significant capacity increase through higher heat transfer.



*Catacel's Stackable Structural Reactor (SSR)*

## Technology History

- ◆ Developed by Catacel Corp. in partnership with Hydro-Chem, a subsidiary of the Linde Group, and the University of Toledo.
- ◆ Currently working with Hydro-Chem to perform a pilot plant test at actual field flow conditions to showcase to manufacturers.

## Applications

Can be used to replace the loose ceramic media in steam reforming furnaces.

## Capabilities

- ◆ Offers increased performance and longer life in high-temperature steam reformers.
- ◆ Provides an alternative to loose ceramic media.
- ◆ Eliminates periodic replacement of deteriorated ceramic shapes.

## Benefits

### Cost Savings

Lowers operating costs by enabling increased throughput or lower energy consumption. Also eliminates the periodic replacement of media.

### Performance

Demonstrates higher heat transfer, resulting in increased throughput or reduced energy consumption.

#### Contact Information:

**William Whittenberger**

Email: [waw@catacel.com](mailto:waw@catacel.com)

Phone: (330) 527-0731

**Catacel Corp.**

7998 Gotham Road

Garrettsville, OH 44231

Website: [www.catacel.com](http://www.catacel.com)

# Oil Free Hydrogen Compressor

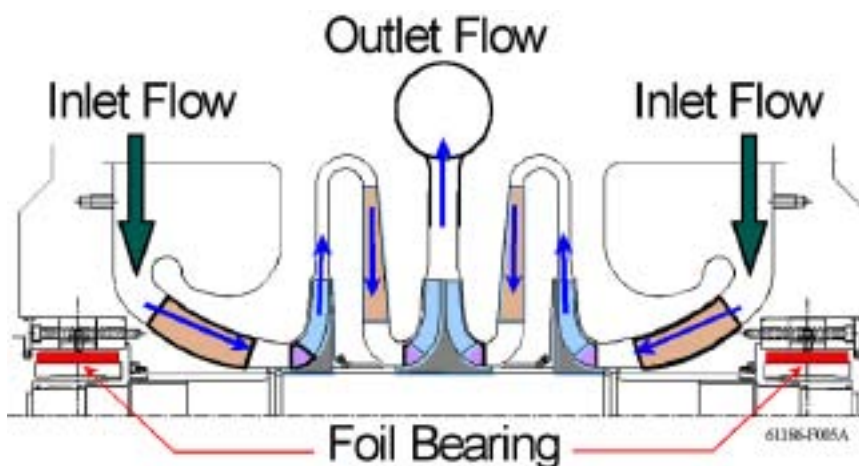
Emerging Technology

## Compressor Being Developed to Reduce the Cost of Hydrogen Transportation and Delivery

Cost-effective compression technology is one of the critical elements needed to effectively deliver hydrogen gas via pipelines for both vehicle transportation and distributed electricity generation with fuel cells. Reciprocating compressors have been widely used in the petrochemical industry for hydrogen gas delivery; however, they are large, noisy units that use oil to lubricate and seal internal parts and are plagued by poor reliability and efficiency as well as in-line contamination of the compressed product gas stream. To ensure availability of the compressed hydrogen gas for refinery processes, two or three reciprocating compressors are often staged at each compressor station, so that one unit can be maintained and repaired without interrupting delivery and service from the station. Centrifugal compressors, which have been commonly used in transporting natural gas because of their simplicity, reliability, durability, and efficiency, have not yet been used to deliver compressed hydrogen gas because of the speed limitations of conventional bearing and seal technologies.

With the focus on hydrogen infrastructure, the advent of high-speed, noncontacting compliant surface foil bearings and seals, and the advances in centrifugal compressor aerodynamics, the potential and need exist to develop technology that substantially improves on the operational characteristics of current technologies and guarantees the delivery of hydrogen that is of the highest achievable purity.

Mohawk Innovative Technology, Inc., with the help of DOE SBIR grants, is developing an oil free, high-speed centrifugal compressor that addresses the limitations of current compression technologies. Using advanced compliant surface foil gas bearings and seals, engineered coatings in conjunction with advanced high-speed drives and centrifugal compressors, this unique approach offers the best solution to overcoming the limitations and risks associated with compressors that use oil for lubrication and sealing. The completely oil free centrifugal compressor technology will have one moving component that will operate without contact between the moving and stationary parts.



*Schematic of the Oil Free Hydrogen Compressor*

## Technology History

- ◆ Developed by Mohawk Innovative Technology, Inc.
- ◆ Establishing partnerships with several large pipeline compressor equipment manufacturers.

## Applications

Can be used in pipeline-sized distribution systems for hydrogen, from production facilities through end use.

## Capabilities

- ◆ Eliminates the need for oil lubrication and sealing in compressors.
- ◆ Provides improved compressor reliability and efficiency.

## Benefits

### Cost Savings

Reduces the acquisition, maintenance, and operations costs for transporting and delivering hydrogen gas from production to local distribution sites.

### Productivity

Eliminates the potential for oil contamination in high-purity hydrogen gas streams.

### Contact Information:

**Jim Walton**

Email: [jwalton@miti.cc](mailto:jwalton@miti.cc)

Phone: (518) 862-4290 ext. 14

**Mohawk Innovative Technology, Inc.**

1037 Watervliet-Shaker Road

Albany, NY 12205

Website: [www.miti.cc](http://www.miti.cc)



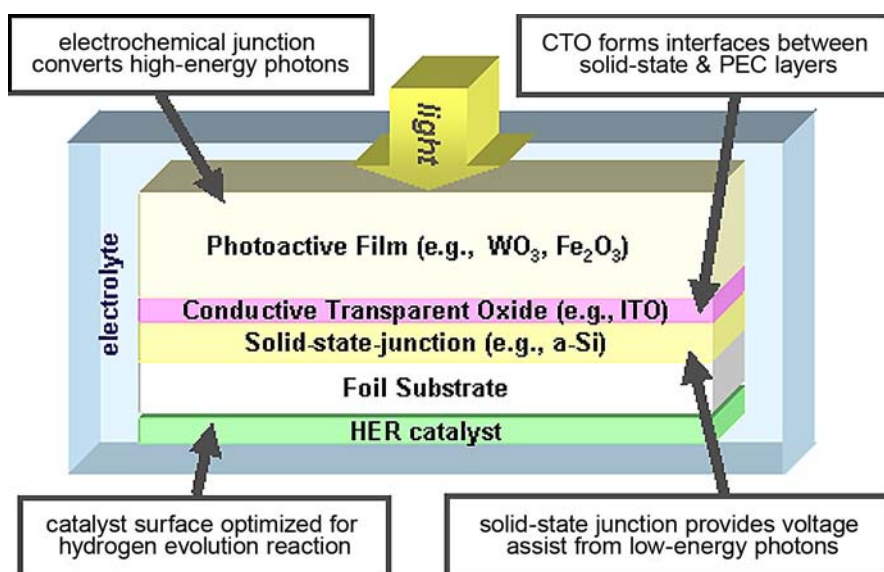
# Photoelectrochemical Hydrogen Production

## New Technology Combines Solar, Chemical, and Electrical Hydrogen Generation

One of the methods of producing hydrogen is through water electrolysis. The electricity for the electrolysis process may be obtained from many sources such as solar, wind, or fossil fuels. To maximize the use of renewable energy, solar energy is one source of electrolysis energy that is being investigated. However, current solar conversion devices are separate from the actual hydrogen generation and losses are incurred when the cells are connected to the electrolysis system. In addition, the efficiency of the solar cells themselves needs to be improved.

A method is needed to increase the system's overall efficiency. If the solar cell were in the water media, connecting wires would not be needed. However, this approach requires researching, developing, and testing materials used for the stable and efficient operation of photoelectrochemical (PEC) hydrogen production systems. Basic material requirements include appropriate light absorption over the solar spectrum, high carrier collection efficiency, stability in suitable electrolyte solutions, and favorable kinetics for the electrode reaction.

The University of Hawaii, with HFCIT funding, is collaborating with numerous partners to identify and develop the most promising material classes to meet current PEC challenges in efficiency, stability, and cost in converting sunlight to hydrogen. Significant effort has focused on developing and determining a comprehensive picture of the properties and their resulting performance for classes of "focus materials" deemed of particular interest for PEC applications. The classes include tungsten-based, zinc-based, iron-based, silicon-based, and copper chalcopyrite-based films. Extensive studies of these materials classes have focused on understanding and improving PEC behavior, specifically by applying theoretical, synthesis, and analytical techniques to identify relevant aspects of structural, optoelectronic, and electrochemical properties.



University of Hawaii's PEC Multi-Junction Hydrogen Production Cell

## Technology History

- ◆ Developed by the University of Hawaii in partnership with MVSystems, Inc., Intematix Corp., Altair Nanotechnologies, Inc., University of California-Santa Barbara, and the National Renewable Energy Laboratory.
- ◆ Continuing work to optimize the performance and durability of PEC materials and to accelerate the interface, device, and system development of the PEC hydrogen production cell.

## Applications

Can be used to produce hydrogen from solar energy.

## Capabilities

- ◆ Offers greater absorption in the visible region of the solar spectrum.
- ◆ Uses control over size and morphology of nanostructures to improve performance.
- ◆ Eliminates extra components for higher solar-to-hydrogen conversion efficiency.

## Benefits

### Cost Savings

Reduces costs by using new materials and controlling the size and morphology of nanostructures.

### Performance

Achieves increased conversion efficiency when converting solar energy to hydrogen.

### Contact Information:

**Dr. Eric Miller**

Email: [ericm@hawaii.edu](mailto:ericm@hawaii.edu)

Phone: (808) 956-5337

**University of Hawaii**

1680 East-West Road, Post 109  
Honolulu, HI 96822

Website: [www.hnei.hawaii.edu](http://www.hnei.hawaii.edu)

## New Technology Integrates Components to Store Renewable Energy as Hydrogen

Renewable energy sources such as photovoltaics, wind, biomass, hydro, and geothermal can provide clean and sustainable electricity for our nation. Several of these options are already cost-competitive and are contributing nearly 10% of the U.S. electricity supply. Limiting greater penetration of these renewable energy sources, however, is their inherent variability and seasonal energy production. The challenge is to convert this variable energy into a form that can be stored for use as needed.

One solution to this problem is to produce hydrogen through water electrolysis and use the hydrogen in a fuel cell or internal combustion engine to produce electricity during times of low power production or peak demand or as a transportation fuel. The National Renewable Energy Laboratory (NREL), with HFCIT funding, and in conjunction with numerous partners, is exploring a strategy to reduce the variability of wind generation, with stored available capacity in the form of hydrogen that can be used in fuel cells or hydrogen generator systems. As part of this effort, NREL is undertaking a project called Wind2H2 in collaboration with Xcel Energy to demonstrate to utilities the benefits of shifting wind energy to hydrogen.

Currently, this approach is limited, in part, by the system cost of the renewable energy storage system. First, capital cost reductions can be realized by designing an optimized renewable-capable electrolyzer system. The reduction of redundant electronics and power conversion steps while accommodating varying power to the stack would help reduce capital cost. Second, improved controls for both the renewable source and electrolyzer system are being combined for smoother operation and improved efficiency. In addition to the ongoing efforts to reduce the cost of renewable technologies and to lower the capital requirements for electrolyzers, NREL is working on optimizing these renewable electrolysis systems and tailoring them to realize the most cost-competitive option for co-generation of electricity and hydrogen production.



### Benefits of the Collaboration:

- Examine benefit to utility by shifting wind production in time
- Research optimal wind/hydrogen through systems engineering
- Characterize and control wind turbine and H2-producing stack
- Evaluate synergies from co-production of electricity and hydrogen
- Compare alkaline and PEM electrolyzer technologies
- Realize efficiency gains through a unique integrated PE

NREL National Renewable Energy Laboratory

## Technology History

- ◆ Developed by NREL in partnership with Xcel Energy, Proton Energy Systems, Teledyne Energy Systems, the University of North Dakota, and the University of Minnesota.
- ◆ Continuing work on baseline and renewable energy source testing for the Wind2H2 project, and accelerating cost and performance modeling/simulation of renewable electrolysis systems.

## Applications

Can be used to generate hydrogen from renewable energy sources.

## Capabilities

- ◆ Stores renewable energy in the form of hydrogen.
- ◆ Uses power electronics to regulate variable outputs from various renewable sources.
- ◆ Eliminates pollution from energy production by using clean renewables.

## Benefits

### Cost Savings

Saves renewable energy that would be wasted if it wasn't needed at the time of generation.

### Performance

Allows the use of efficient fuel cells to produce energy from stored renewable sources in the form of hydrogen.

### Contact Information:

**Kevin Harrison**

Email: Kevin\_Harrison@nrel.gov

Phone: (303) 384-7091

**National Renewable Energy Laboratory**

1617 Cole Blvd.

Golden, CO 80401

**Website:**

[www.nrel.gov/hydrogen/proj\\_wind\\_hydrogen.html](http://www.nrel.gov/hydrogen/proj_wind_hydrogen.html)

# Reversible Liquid Carriers

## New Technology Stores and Releases Hydrogen Safely and Efficiently

Hydrogen can be stored for fuel cells in stationary and mobile applications in several ways. Hydrogen may be stored in its gaseous form in high-pressure tanks but requires storage areas that fit the design of the cylinders. In addition, the cylinders must be protected from impact to prevent a catastrophic release of gas. Liquid hydrogen presents even more problems because it must be kept at an extremely low temperature and requires constant venting to prevent excessive pressure buildup. Chemicals can release hydrogen but require special containers to convert the solid and contain the resulting gas. The byproduct needs specialized regeneration if it is to be recycled because the reaction is not easily reversible. A material is needed that produces hydrogen through an easily reversible reaction and is in a safe, liquid form that could be contained in simple tanks.

Air Products and Chemicals, Inc., with HFCIT funding, is developing a carrier in the form of new liquid-phase hydrogen storage materials that can be reversibly hydrogenated, allowing for hydrogen to be stored in an efficient, safe, and easily transportable form. The liquid carriers can be hydrogenated at large central or regional sites, in locations where inexpensive hydrogen is available, allowing for high overall energy efficiency through material recovery and use of the heat generated by exothermic hydrogenation. Alternatively, autothermal hydrogen carriers could provide both hydrogen and the thermal energy needed to liberate the hydrogen from the carrier, where it would be dispensed to a fuel cell. Several acceptable carrier prototypes have been identified, and the economic and technical aspects of field deployment in both stationary and mobile hydrogen fuel applications are being evaluated. This solution provides liquid carriers that show appropriate storage capacity (5% to 7% hydrogen by weight), have high selectivity for hydrogenation and dehydrogenation reactions at low temperature, and exhibit low volatility, thus improving the safety and storage of hydrogen.

## Technology History

- ◆ Developed by Air Products and Chemicals, Inc., in partnership with United Technologies Research Corporation, Battelle Memorial Institute, and BMW AG.
- ◆ Currently working on the design and construction of a 0.1-kW prototype microchannel dehydrogenation reactor and developing an autothermal process to drive the dehydrogenation reactor.

## Applications

Can be used in both stationary and portable environments that require the stable, efficient, and safe delivery of hydrogen.

## Capabilities

- ◆ Stores in liquid form at 5% to 7% hydrogen by weight.
- ◆ Allows hydrogen to be stored as gas in a stable, hydrogenated liquid.
- ◆ Stores in a simple, nonpressurized tank.

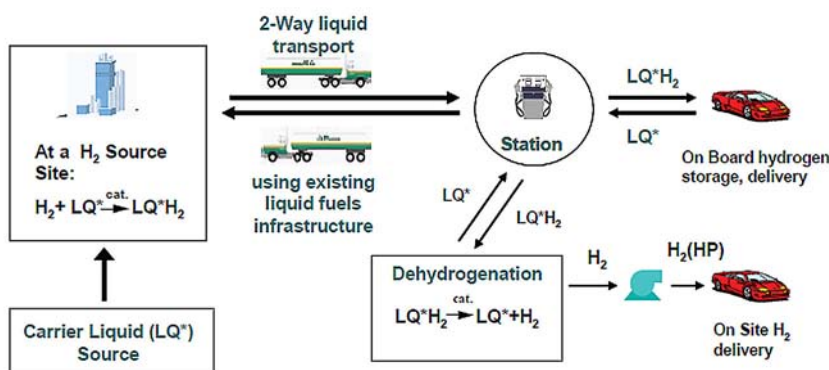
## Benefits

### Performance

Allows for multiple cycles and long life because of the selective, reversible reaction.

### Safety

Enables use of liquid carriers in simplified systems in vehicles and reduces potential exposure to vapors because of its low volatility.



Air Products' Reversible Liquid Carrier System

### Contact Information:

**Alan Cooper**

Email: [cooperac@airproducts.com](mailto:cooperac@airproducts.com)

Phone: (610) 481-2607

**Air Products and Chemicals, Inc.**

7201 Hamilton Boulevard

Allentown, PA 18195

Website: [www.airproducts.com](http://www.airproducts.com)

# Scalable Steam Methane Reformer System for Distributed Hydrogen

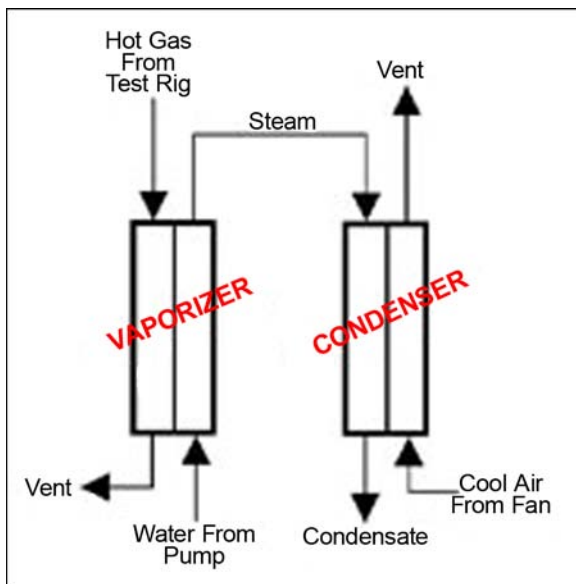
Emerging Technology

## New Technology Delivers Hydrogen for Commercial and Distributed Use Applications

Using hydrogen for transportation and energy presents unique challenges. One of these challenges is the cost-effective creation of hydrogen. Large-scale steam methane reformers increase the efficiency of the process of converting fuels such as methane to hydrogen in large quantities, but they are too large to be used in distributed locations. In addition, the conventional catalysts in these systems are expensive and can be damaged from impurities in the fuel source, requiring additional stages to treat the gas to remove these contaminants.

A system is needed that combines the efficiency of a large-scale steam methane reformer with the flexibility of a smaller system. This system would use a catalyst in a form that operates to remove undesirable contaminants and yet achieves increased efficiency in the conversion process. Ideally, the unit should be modular to serve markets where a small unit is desirable and yet scalable to a size that meets the needs of commercial suppliers.

Catacel Corp., with HFCIT funding through the Edison Materials Technology Center, has developed a scalable steam methane reformer that efficiently addresses these problems. By using catalysts coated on metal foils, Catacel has created a modular system that demonstrates increased efficiency when combined with their new, compact heat exchanger; the reduced size of the components allows the module to be used in multiple, scalable applications. One application is service-station hydrogen production using modules capable of 20 kg/day (10 kW fuel value) hydrogen generation. These modules are scalable to commercial sizes, and one goal of the project is to show that the cost of hydrogen produced from such a system will meet or exceed DOE targets of \$2.50 per gasoline gallon equivalent.



Catacel's Vaporizer/Condenser Heat Exchanger

## Technology History

- ◆ Developed by Catacel Corp. in partnership with NexTech Materials, Ltd., and the University of Toledo.
- ◆ Continuing testing of the scalable steam methane system and evaluating market opportunities.

## Applications

Can be used to generate hydrogen from methane in scalable quantities up to commercial amounts.

## Capabilities

- ◆ Uses a catalyst coated on thin metal foil.
- ◆ Eliminates the problem of scaling down large-scale systems while maintaining efficiency through the use of a modular design.

## Benefits

### Cost Savings

Achieves high solar collection and feedstock conversion efficiencies.

### Performance

Generates hydrogen at 20 kg/day (10 kW fuel value) based on the Catacel heat exchanger platform.

### Contact Information:

**William Whittenberger**

Email: [waw@catacel.com](mailto:waw@catacel.com)

Phone: (330) 527-0731

**Catacel Corp.**

7998 Gotham Road

Garrettsville, OH 44231

Website: [www.catacel.com](http://www.catacel.com)



# Solar-Thermal Production of Hydrogen Using Renewable Feedstock

Emerging Technology

## New Technology Uses Solar Thermal Energy to Produce Hydrogen

World demand for energy and energy products is projected to almost double in the next two decades. With a heavy reliance on fossil fuels to provide a substantial portion of that growth, there are concerns over basic fuel supply and availability, in addition to the well-known environmental impacts associated with processing fossil fuels. The challenge of providing efficient and cost-effective solutions to producing hydrogen and hydrocarbon-based products is being met in part by companies focused on alternative and renewable energy sources.

Sundrop Fuels, Inc., through an exclusive license to technology developed by the University of Colorado with HFCIT funding, has been engineering and developing processes that produce hydrogen and hydrogen-based fuels by directly applying high-temperature solar-thermal energy. The proprietary technology takes advantage of rapid chemical kinetics and favorable thermodynamics to create an integrated and environmentally benign hydrogen production process. Coupling high-efficiency and cost-competitive solar power to the reactor avoids the energy and emissions penalties associated with more conventional sources of heat and power, which are typically based on fossil fuel combustion.

Sundrop Fuels is continuing to research, engineer, and design high-temperature solar-thermal processes, including the continuing development of highly efficient solar reactors, new concepts for protecting materials of construction at ultra-high temperatures, and rapid metal oxide processing for the sustainable production of hydrogen.



*Sundrop Fuel's Solar-Thermal System*

## Technology History

- ◆ Developed by the University of Colorado and licensed to Sundrop Fuels, Inc.
- ◆ Currently working on deploying rapid, high-temperature, solar-thermal reactors and associated processes.

## Applications

Can be used to generate hydrogen from the heat of the sun.

## Capabilities

- ◆ Achieves rapid chemical kinetics and favorable thermodynamic reactions in the integrated conversion process.
- ◆ Uses heat from the sun to generate hydrogen.
- ◆ Eliminates the use of fossil fuels to generate hydrogen.

## Benefits

### Performance

Achieves high solar collection and feedstock conversion efficiencies.

### Product Quality

Facilitates high product selectivity and enables stoichiometric tuning of reaction products because of the robust and flexible design.

### Contact Information:

**Chris Perkins, Ph.D.**

Director, Solar Chemistry

*Email:* [chris.perkins@sundropfuels.com](mailto:chris.perkins@sundropfuels.com)

*Phone:* (720) 890-6507

**Sundrop Fuels, Inc.**

1722 Boxelder St. Suite 101

Louisville, CO 80027

**Website:** [www.sundropfuels.com](http://www.sundropfuels.com)

# Turnkey Hydrogen Fueling Station

Emerging Technology

## New System Creates and Dispenses Hydrogen for Vehicles

The hydrogen economy will introduce fuel cell vehicles that will require sources of hydrogen for operation. Currently, most hydrogen is produced in large commercial plants, and the hydrogen is pressurized and delivered through pipelines or tube trailers, and/or liquefied for delivery in over-the-road cryogenic tankers. Hydrogen gas pipelines may be used to supply hydrogen in concentrated areas having many refineries and chemical plants with large-volume requirements. Liquefied or gaseous over-the-road-delivered hydrogen may be used for those requirements not in proximity to a pipeline, depending on volume and distance from the generation source. Another supply option would be to make the hydrogen in a much smaller plant located right at the demand source, eliminating the requirement for most hydrogen deliveries. The selection of the best hydrogen supply mode should be evaluated based on several factors, including the utilization rate, demand pattern, distance from the large commercial hydrogen plant, and availability of the feedstock to operate a local on-site hydrogen generator. Working with a hydrogen provider who offers all supply modes will typically provide several scenarios for consideration.

Air Products and Chemicals, Inc., with HFCIT funding, has developed the turnkey hydrogen fueling station, which allows for on-site production and dispensing of hydrogen instead of the traditional infrastructure delivery method of pipeline and liquid delivery of hydrogen. This station was developed in three phases. The first phase evaluated the various technologies available in hydrogen generation, compression, storage, and gas dispensing. The second phase involved Air Products designing the components and integrated system chosen from the technologies and installing a prototype fuel station at Penn State University. Phase three involved several months of data collection, full-scale operation, maintenance of the prototype station, and optimization of system reliability and performance. After six months of operation, the station was able to meet the DOE target values for pressure swing absorption efficiency, overall system efficiency, and the price of hydrogen produced per kilogram.



*Air Products and Chemicals' Hydrogen Fueling Station*

## Technology History

- ◆ Developed by Air Products and Chemicals, Inc., in partnership with Harvest Technology, Inc., and Penn State University.
- ◆ Continuing additional research and practical studies of the most appropriate media to supply hydrogen.

## Applications

Can be used to generate and dispense hydrogen on-site for fuel cell vehicles.

## Capabilities

- ◆ Dispenses hydrogen at rates up to 1500 kg/day.
- ◆ Uses natural gas with on-site reformation to produce hydrogen.
- ◆ Eliminates storage and transportation of gas cylinders.

## Benefits

### Performance

Provides an operating station overall efficiency of 65%.

### Product Quality

Provides an aesthetic design with fast-fill technology accurately calculating the dispensing of hydrogen to within 0.2% accuracy.

### Contact Information:

**Edward Kiczek**

*Email:* [kiczekef@airproducts.com](mailto:kiczekef@airproducts.com)

*Phone:* (202) 586-5824

**Air Products and Chemicals, Inc.**

7201 Hamilton Boulevard

Allentown, PA 18195

**Website:** [www.airproducts.com](http://www.airproducts.com)



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# Compressed Hydrogen Gas Integrated Storage System

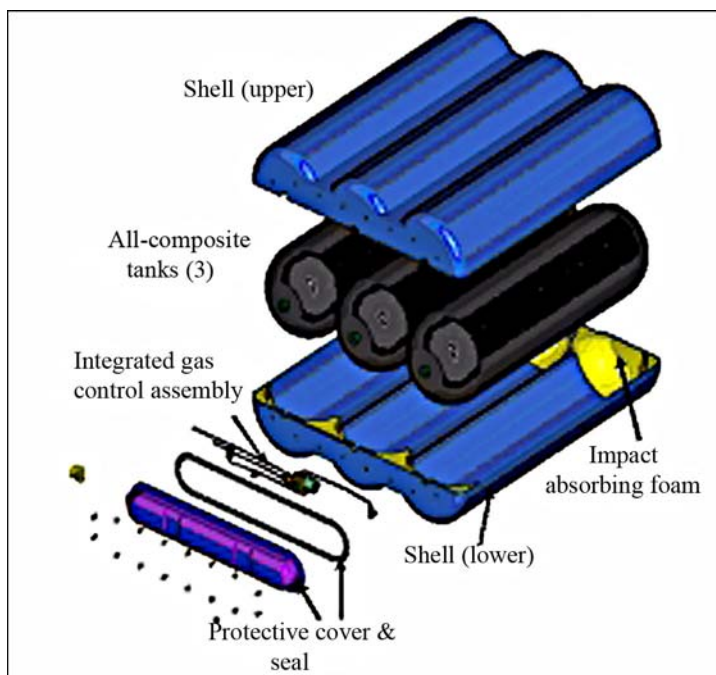
Emerging Technology

## New System Packs Extended Range into Hydrogen Storage

Storing compressed hydrogen gas poses challenges in the areas of relatively low energy density, overall system manufacturing cost, crashworthiness, and vehicle packaging. Separate tanks need to be mounted securely and attached individually to manifolds. Separate protection valves are required for each tank and coordination is needed for flow controls. Crash protection is problematic for individual tanks, and areas of high impact stress need to be addressed. Each additional tank adds to the complexity of the system, raising the cost and failure modes.

A solution to these challenges is offered by the Integrated Storage System (ISS) technology, jointly developed with funding from HFCIT, by Johns Hopkins University Applied Physics Laboratory (JHU/APL), and Lincoln Composites Division of Hexagon Composites Group. The ISS technology supports development of a 5,000 and/or 10,000 psi service pressure semi-conformal gas storage system that provides sufficient fuel storage for an extended driving range without impacting passenger and cargo space or compromising vehicle safety and that can be mass-produced at targeted manufacturing costs.

The ISS technology uses Type IV all-composite tanks constructed with a high-density polyethylene thermoplastic liner structurally overwrapped with carbon fiber and epoxy resin. The tanks are encapsulated within a high-strength outer shell, using the individual cylinders into a single container and providing protection from environmental exposure. Additional physical protection of the tanks is provided by urethane foam surrounding the tank dome region (location of highest stress concentration during impact). A unitized gas control module is incorporated into the ISS package and provides all necessary gas flow control and safety features.



John Hopkins' Integrated Storage System for Hydrogen

## Technology History

- ◆ Developed by JHU/APL and Lincoln Composites Division of Hexagon Composites Group.
- ◆ Using prototype storage systems for further R&D and technology demonstrations.

## Applications

Can be used as a storage mechanism for fuel in hydrogen-powered vehicles.

## Capabilities

- ◆ Improves storage energy density and driving ranges with 5,000 psi storage capability.
- ◆ Withstands impacts similar to those received in a crash.
- ◆ Provides safety measures through unitized gas control module and gas flow control.

## Benefits

### Efficiency

Increases energy density of storage tanks, which reduces space requirements.

### Flexibility

Provides sufficient fuel storage for an extended driving range without impacting space or safety of vehicle.

### Contact Information:

**John Wozniak**

Email: [john.wozniak@jhuapl.edu](mailto:john.wozniak@jhuapl.edu)

Phone: (240) 228-5744

**Johns Hopkins University Applied Physics Laboratory**

11100 John Hopkins Road  
Laurel, Maryland 20723

Website: [www.jhuapl.edu](http://www.jhuapl.edu)

# High-Strength, Low-Cost Microballoons for Hydrogen Storage

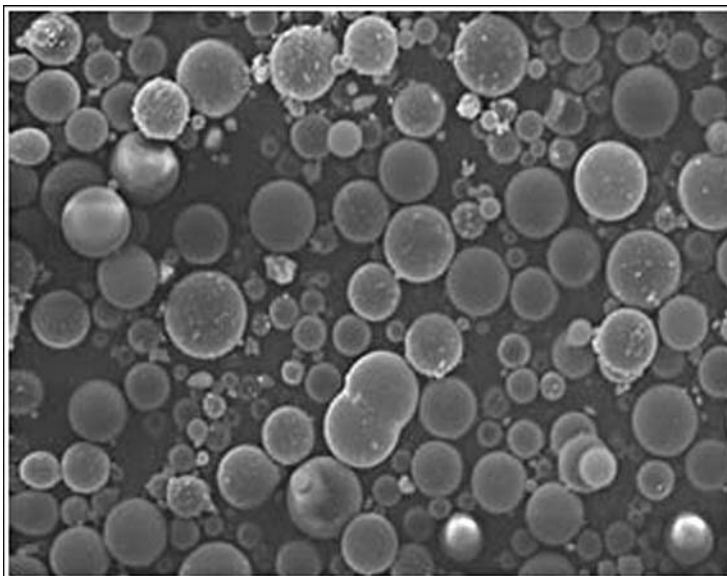
Emerging Technology

## New Material Stores Hydrogen Safely and Cost Effectively

If hydrogen-fueled vehicles are to become widespread, effective and safe containment and transport of hydrogen are needed. Conventional hydrogen storage methods involve cylinders operating at high pressure. The high pressure mandates that the cylinders must be symmetrical and free of stress risers such as sharp corners. High-pressure cylinders also are limited in that they have fixed dimensions and require specialized support and protection from damage. Their fixed dimensions dictate the amount of hydrogen storage available, and the receiving vehicle needs a storage area that matches the cylinders' dimensions and configuration. In addition, if the cylinders are damaged, the spontaneous release of their contents can be catastrophic.

To address these problems, a new method of hydrogen storage needs to be devised. The new method should use a material that conforms to the shape of the storage area available in the vehicle. The material should flow like a liquid so it could be stored in different configurations without concern for stress risers. The material should be designed to prevent catastrophic release of all the hydrogen if the storage container is damaged. Finally, the material remaining after the hydrogen is removed should be harmless to the environment and the personnel who use the device.

Powdermet, Inc., has developed such material with funding from HFCIT, through the Edison Materials Technology Center, in the form of lightweight carbon microballoons, which are used as a scaffold for a high-strength material that can act as a hydrogen-impermeable barrier at room temperature. This structure enables high weight percent storage of hydrogen in safe individual microballoons. The microballoons are easily transported and flow under gravity like a liquid. The waste products after the hydrogen is released (carbon and inert ceramic particles) are harmless to the environment and the personnel who use the device.



*Powdermet Hydrogen Storage Microballoons*

## Technology History

- ◆ Developed by Powdermet, Inc., in collaboration with AF Research Labs, Precision Energy and Technology, and Protonex Technology Corporation.
- ◆ Designing, building, and testing the hydrogen storage and delivery systems for the microballoons.

## Applications

Can be used to safely and effectively store hydrogen gas for use in vehicles or other applications.

## Capabilities

- ◆ Stores over 18 weight percent of hydrogen with a practical limit of about 12 weight percent of hydrogen in 1 mm spheres.
- ◆ Can be used as a storage and delivery system and to create structural foam.

## Benefits

### Environmental

Produces harmless waste products after hydrogen release.

### Flexibility

Flows like water and conforms to any shape container.

### Safety

Uses pressurized microballoons, but the storage container is at atmospheric pressure.

### Contact Information:

**Andrew Sherman**

*Email:* powdermet@earthlink.net

*Phone:* (216) 404-0053

**Powdermet, Inc.**

24112 Rockwell Dr

Euclid, OH 44117

**Website:** [www.powdermetinc.com](http://www.powdermetinc.com)

# Hydrogen Storage in Cryo-Compressed Vessels

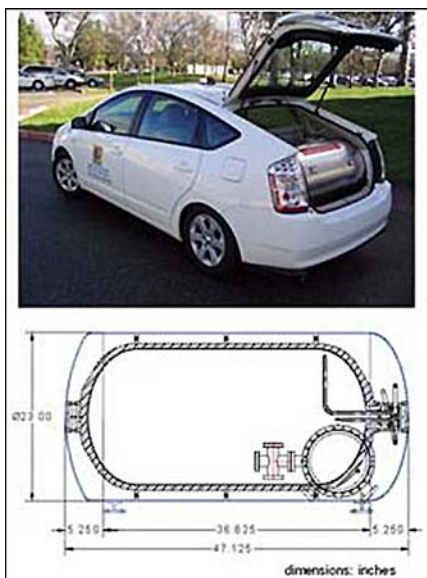
Emerging Technology

## New Hydrogen Tank Demonstrates High Energy Density and Results in Increased Driving Range

Liquid hydrogen is a lightweight and compact form for storing hydrogen, making it an ideal choice for space and weight restrictive environments. However, storing liquid hydrogen onboard automobiles presents a significant problem. Because automobiles are often parked for days at a time, the tank holding the liquid hydrogen starts to build pressure as heat from the environment warms the hydrogen inside. Currently, automotive liquid hydrogen tanks must vent the evaporated hydrogen after being parked for only three to four days, even when using the best thermal insulation available.

Lawrence Livermore National Laboratory (LLNL), with funding from HFCIT, developed cryogenic capable pressure vessels. The cryo-compressed storage tanks present three fundamental advantages over ambient pressure compressed hydrogen tanks, including maintaining the high energy density of liquid hydrogen without evaporative losses, requiring fewer carbon fiber materials of construction yielding long-term cost savings potential, and maintaining fueling flexibility for both liquid and gas fuel sources. The cryogenic pressure vessel can operate at pressures of up to 350 bar, effectively containing the hydrogen even as the pressure increases from heat transfer. The high-pressure capability also improves the vehicle's thermal endurance as the tank is emptied, eventually being able to hold the hydrogen fuel indefinitely.

LLNL's cryogenic pressure vessel was installed in an experimental vehicle, where it demonstrated the longest driving distance on a single hydrogen tank, as well as the longest liquid hydrogen holding time without venting any of the fuel. Continuing research and development are focused on scaling down the existing system while targeting aggressive reductions in the cost, weight, and volume characteristics of the vessel. LLNL is effectively collaborating with industry using the cryogenic pressure vessel as a benchmark for advanced storage system research, such as the 700 bar high pressure storage vessel, ambient temperature systems, and pure liquid hydrogen systems.



LLNL's Cryo-Compressed Hydrogen Storage Vessel

## Technology History

- ◆ Being developed by LLNL in partnership with Structural Composite Industries.
- ◆ Continuing work on designing, manufacturing, and full-cycle testing of a new cryogenic pressure vessel for onboard vehicle hydrogen storage.

## Applications

Can be used to store hydrogen for use in hydrogen-powered vehicles.

## Capabilities

- ◆ Provides high specific energy and high energy density storage.
- ◆ Achieves flexible refueling with either compressed or liquid hydrogen.
- ◆ Can be dormant for extended periods with no measured loss of fuel from the vessel.

## Benefits

### Performance

Exceeds 500 miles per fill for a single liquid hydrogen tank.

### Versatility

Can be used with either compressed or liquid hydrogen.

### Contact Information:

**Salvador M. Aceves**

Email: [saceves@llnl.gov](mailto:saceves@llnl.gov)

Phone: (925) 422-0864

**Lawrence Livermore National Laboratory**

7000 East Avenue, L-644

Livermore, CA 94551

Website: [www.llnl.gov](http://www.llnl.gov)



# Low-Cost Materials, High-Efficiency, High-Pressure Hydrogen Storage

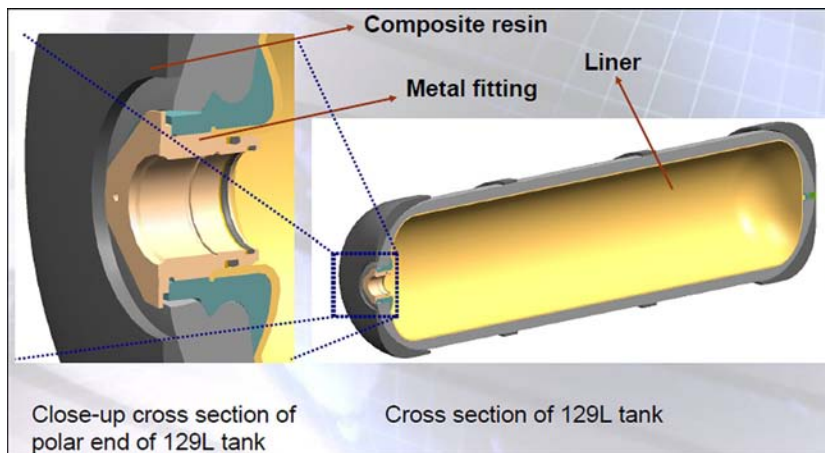
Emerging Technology

## New Storage Container Optimizes Use of Composites for Strength, Cost, and Safety

The automotive industry has a strong demand for cost-effective and efficient high-pressure hydrogen fuel storage systems. Several premier automotive manufacturers that are developing fuel cell vehicles have shown significant interest in hydrogen fuel storage systems. However, current commercially available products use premium-grade materials to support challenging structural requirements for burst pressure. Premium-grade materials are expensive and increase the cost of the storage system. In addition, such materials require special design features and complex manufacturing techniques, which increase both the time of fabrication and the overall expense of the system.

As a result of the storage container issues, the initial offerings of 10,000 psig composite hydrogen fuel tanks using very high-grade construction materials were very expensive to manufacture. In an attempt to lower the cost, subsequent tanks were made with lower-grade materials, but the tanks were still commercially cost prohibitive. To meet commercialization targets, a structurally robust composite tank needs to be developed using lower-grade materials that meet the expected safety and energy storage density of the more expensive units.

To satisfy these requirements, Quantum Technologies, Inc., with funding from HFCIT, is developing an optimized storage tank technology that not only addresses the structural integrity and safety issues but also reduces the overall cost and weight in manufacturing by optimizing the composite structure. Quantum Technologies is achieving this optimization by performing the following tasks: (1) liner material and design development, (2) metal fitting material and design development, and (3) carbon fiber optimization through manufacturing process evaluations and composite fiber translation improvements.



Cross Section of Quantum Technologies' 129L Tank

## Technology History

- ◆ Developed by Quantum Technologies, Inc.
- ◆ Focusing future work on reducing liner thickness and thus composite usage, investigating the metal fitting material and interface with the liner, and performing test trials on the new tanks.

## Applications

Can be used in both stationary and portable environments that require low-cost, high-efficiency, high-pressure hydrogen storage.

## Capabilities

- ◆ Reduces the cycle fatigue associated with refilling the composite tanks.
- ◆ Reduces the cost of manufacturing existing storage systems.
- ◆ Increases the safety and reliability of hydrogen storage systems.

## Benefits

### Cost Effectiveness

Reduces system expense by using cost-competitive materials with high structural integrity.

### Safety

Uses composite tanks that are designed to withstand higher-cycling fatigue.

### Contact Information:

**Elton Rohrer**

Email: [erohrer@qtw.com](mailto:erohrer@qtw.com)

Phone: (949) 399-4500 x586

**Quantum Technologies, Inc.**

17872 Cartwright Road

Irvine, CA. 92653

Website: [www.qtw.com](http://www.qtw.com)

# Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders

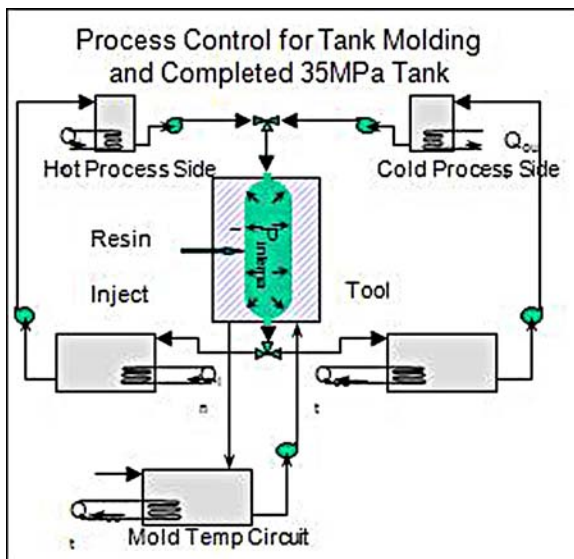
Emerging Technology

## Novel Process and Materials Accelerate the Production of Hydrogen Tanks

Currently, the cost and production rate of high-pressure storage cylinders for onboard hydrogen are limiting vehicle introduction. High-pressure tanks are a key component of fuel systems involving hydrogen, methane, and natural gas and therefore a key factor in fuel cell applications. Filament winding (FW) has been the process used to produce tanks for over 40 years, with incremental improvements being made in materials, application, and manufacturing technologies. FW technology results in a tank being produced every 5 to 8 hours and is well recognized as inconsistent with commercial introduction of hydrogen vehicles, even in specialty and small fleets.

To support the commercial introduction of hydrogen vehicles, a faster and easier method to fabricate tanks is needed. Materials need to be developed that will support a new method of manufacturing that improves the fabrication cycle time yet maintains structural integrity. The goal is to produce tanks at a rate approaching vehicle production. Ideally, the method and materials must be equally applicable to conformal tanks and scalable to larger-size transportation cylinders.

To satisfy these requirements, Profile Composites Inc., with funding from HFCIT through the National Center for Manufacturing Sciences, is developing a manufacturing process for fabricating high-pressure hydrogen storage cylinders in an automotive production environment. The process is compatible with low-volume and specialty vehicle production rates of about 20,000 vehicles per year on a single tooling line. The technology will be used in gas cylinders such as hydrogen, methane, and natural gas. It is equally applicable to conformal tanks and scalable to larger-size transportation cylinders. The process can now produce tanks at rates approaching vehicle production. Although materials costs are not significantly changed, total manufacturing costs are reduced as substantially fewer parallel tooling lines are required.



Profile Composites' Hydrogen Tank Fabrication Process

## Technology History

- ◆ Developed by Profile Composites Inc., in partnership with Toyota Motor Engineering and Manufacturing North America, Inc., MAG Cincinnati Automation & Test, A&P Technology, Inc., and Bayer MaterialScience LLC.
- ◆ Currently implementing tooling with full process control requirements and semi-automated materials for improved robustness. Planning to commercialize a 5,000 psi cylinder in 2009 and begin developing a 10,000 psi cylinder.

## Applications

Can be used in gas cylinders such as hydrogen, methane, and natural gas.

## Capabilities

- ◆ Allows fabrication of high-pressure hydrogen storage tanks in under 20 minutes total cycle time.
- ◆ Produces tanks at rates approaching vehicle production.
- ◆ Reduces the number of parallel tooling lines needed for production.

## Benefits

### Cost Effectiveness

Reduces users' cost through high-volume production of cylinders.

### Safety

Offers benign failure modes compared with filament-wound tanks.

### Contact Information:

**Geoffrey Wood**

Email: [geoff.wood@profilecomposites.com](mailto:geoff.wood@profilecomposites.com)

Phone: (250) 655-7142

**Profile Composites Inc.**

2071B Malaview Avenue West

Sidney, BC Canada V8L 5X6

Website: [www.profilecomposites.com](http://www.profilecomposites.com)



# Safe and Effective Storage and Transmission of Hydrogen

Emerging Technology

## Liquid Magnesium Hydride Slurry Stores Hydrogen Safely and Efficiently

Traditional storage technologies for hydrogen include bottled compressed hydrogen gas and bottled liquid hydrogen. Using such technologies has been limited because of dangers in storing, handling, and transporting the hydrogen. Storing or transporting hydrogen gas and cryogenic liquid has demonstrated instability and high combustibility. In addition, compressed and liquid hydrogen tanks often don't store sufficient volumes and pose safety risks related to both pressure and flammability. The alternative, solid metal hydride tanks, is heavy and time consuming to fill. The solid metal hydride is not easily transferred and is subject to decomposition from moisture in the air.

Ease of transfer of hydrogen "fuel" is a requirement that must be met before hydrogen can be commercially viable as an alternative energy carrier. Ideally, a hydrogen carrier should be safe and easy to pump in a liquid form. It should fit within the existing liquid transfer system and reduce the risk of fire and explosion. It should have a high energy density, exceeding that of liquid hydrogen, and be capable of recycling and regeneration at a reasonable cost.

To meet these requirements, Safe Hydrogen, LLC, with assistance from HFCIT, is developing a chemical hydride technology that offers the required storage efficiency and storage safety. The patented technology provides the cost saving advantage of being able to use the existing fossil fuel infrastructure to deliver and store a pumpable and nonexplosive magnesium hydride mineral oil slurry as the future "hydrogen fuel." At approximately the same volume, one unit of liquid magnesium hydride slurry carries the potential of generating twice as much hydrogen (by volume) as one unit of cryogenically cooled liquid hydrogen without the flammability and pressure hazards.

## Technology History

- ◆ Developed by Safe Hydrogen, LLC.
- ◆ Establishing its application using conventional pumping and transportation mediums and infrastructure.

## Applications

Can be used anywhere consistent delivery of gaseous hydrogen is needed.

## Capabilities

- ◆ Delivers hydrogen with low input of energy.
- ◆ Provides a nonexplosive, noncorrosive hydrogen source.
- ◆ Can be reused by recycling the byproducts into the original hydride.

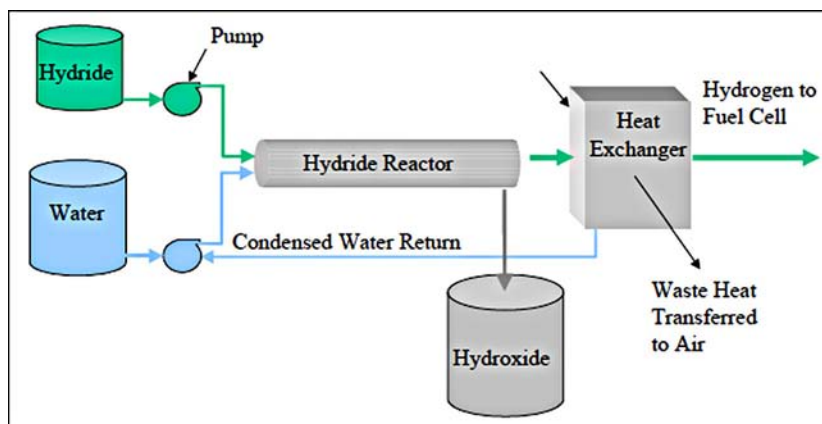
## Benefits

### Efficiency

Displays superior storage density compared with cryogenically cooled liquid hydrogen.

### Safety

Consists of a magnesium hydride slurry, which is a nonexplosive carrier of hydrogen.



Safe Hydrogen's Hydride Slurry System

### Contact Information:

**Andrew W. McClaine**

Email: [awmclaine@rcn.com](mailto:awmclaine@rcn.com)

Phone: (781) 861-7016

**Safe Hydrogen, LLC**

30 York St

Lexington, MA 02420

Website: [www.SafeHydrogen.com](http://www.SafeHydrogen.com)





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