U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FUEL CELL TECHNOLOGIES OFFICE

Pathways to Commercial Success:

Technologies and Products Supported by the Fuel Cell Technologies Office

April 2014

Prepared by Pacific Northwest National Laboratory
for the U.S. Department of Energy Fuel Cell Technologies Office

Notice

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Summary

The purpose of the project described in this report is to identify and document the commercial and emerging (projected to be commercialized within the next 3 to 5 years) hydrogen and fuel cell technologies and products that resulted from Department of Energy support through the Fuel Cell Technologies Office (FCTO) in the Office of Energy Efficiency and Renewable Energy (EERE). Pacific Northwest National Laboratory (PNNL) undertook two efforts simultaneously to accomplish this project. The first effort was a patent search and analysis to identify patents related to hydrogen and fuel cells that are associated with FCTO-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 with current and past FCTO personnel, a review of relevant program annual reports, and an examination of grants made under the Small Business Innovation Research and Small Business Technology Transfer Programs that are related to hydrogen and fuel cells.

The patent analysis identified 455 patents associated with research supported by FCTO dating back to 1977. The 455 FCTO patents include: 230 fuel cell patents, 167 hydrogen production/delivery patents, and 58 hydrogen storage patents. Three types of organizations received the patents: national laboratories (179 patents), private companies (223 patents), and universities (53 patents). Private companies received the greatest number of patent awards in the fuel cell and production/delivery areas, accounting for 56% of the fuel cell patents and 50% of the production/delivery patents. The national laboratories had 60% of the awards in the storage area.

The patent award status by use indicated that 20 patents are currently used in commercial products and 63 are part of research now taking place on emerging technologies. In addition, 245 awarded patents are still being utilized via continuing research and/or active attempts to license the patent. Of all the patents reviewed, 72% are still actively being pursued through use in continuing research, emerging technologies, or commercially available products.

In addition, PNNL identified 41 commercial technologies that have entered the market, of which 39 are still commercially available. From 2000 – 2006, one to three commercial technologies entered the market per year. For 2007 through 2012, an average of five technologies per year entered into the market. In 2013, one technology has entered the market to date. Commercial technologies also supported the creation/retention of 447 direct jobs in FY 2013. This effort also identified 63 emerging technologies that are anticipated to be commercially available in 3 to 5 years. Of the 63 emerging technologies, 51% are in the fuel cell area, 40% are in the production/delivery area, and 9% are in the storage area.

This report documents the methodology and results of this study, including the specific patents as well as commercial and emerging technologies that resulted from FCTO funding.

1.0 Introduction

This report documents the methodology and results of an effort to identify and characterize commercial and emerging[1] technologies and products that resulted from the support of the Fuel Cell Technologies Office[2] (FCTO) within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE). Commercialization of technologies that are cultivated in a government research and development (R&D) program is viewed as one measure of success. PNNL has been conducting similar technology tracking activities for other EERE offices for over two decades.

The results presented in this report represent the findings from 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. The effort is expected to continue, with an updated report produced annually.

This chapter presents a brief overview of the FCTO's research that is leading to commercial technologies and products. The chapter concludes with a summary of the contents of this report.

1.1 Organization of the FCTO

The FCTO 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, technology validation, market transformation, and public awareness. The FCTO 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, and can benefit from leveraging resources and skills, the FCTO encourages public-private partnerships, which include the supply chain industry, 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 FCTO is currently conducting R&D, demonstration, analysis, and other efforts to support development of hydrogen and fuel cell technologies for stationary power (including back-up emergency power and residential electric power generation), transportation (including materials handling equipment, fuel cell vehicles and hydrogen refueling infrastructure), and portable power applications (including consumer electronics such as cellular phones, hand-held computers, radios, and laptop computers). The FCTO subprograms 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 subprograms 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 subprogram that is likely to lead to commercial technologies in the future.

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[1] "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 to 5 years, based on the opinion of the technology developer.
[2] Formerly the Hydrogen, Fuel Cells & Infrastructure Technologies Program, 2002-2009, and the Fuel Cell Technologies Program, 2009-2012.

The current goals of these four subprograms are briefly summarized below.

Hydrogen Production. The goal of the Hydrogen Production subprogram is to develop low-cost, highly efficient hydrogen production technologies from diverse domestic sources, including natural gas and renewable sources. The subprogram 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 subprogram 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 subprogram also coordinates with the Office of Fossil Energy (FE) on coal gasification (with sequestration) and separation processes, and with the Office of Nuclear Energy (NE) on hydrogen production from thermochemical processes.

Hydrogen Delivery. The goal of the Hydrogen Delivery subprogram 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 subprogram is to develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications, as well as early market 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 noteworthy, particularly in developing a fundamental understanding of hydrogen-material interactions.

Fuel Cells. The goal of the Fuel Cells subprogram is to develop and demonstrate fuel cell power system technologies for transportation, stationary, and portable power applications. The subprogram 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. Over the last several years, the subprogram has included small-scale solid oxide fuel cell (SOFC) R&D to complement the Department Office of Fossil Energy's Solid State Energy Conversion Alliance (SECA) Program[3] on megawatt-scale SOFC power systems. The portfolio has been broadened to include other work as well, such as alkaline fuel cells. Work on fundamental catalysis is coordinated with the Office of Science. More recently, coordination with the Advanced Research Projects Agency - Energy (ARPA-E) has been initiated, particularly in innovative areas such as alkaline exchange membranes.

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

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[3] 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 modular and affordable design to allow wide-spread penetration into stationary and utility-scale markets.

The objectives of, and R&D activities funded by, the FCTO and its predecessor programs have changed over the years as the Office 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 FCTO efforts.

1.2 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 FCTO 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. A new area tracked since FY 2011 is an estimate for the number of jobs directly related to FCTO funding. These estimates are based on recipient interviews and may be refined as more information and validation becomes available.

2.0 Approach

Two efforts were undertaken simultaneously by PNNL in August 2007 under FCTO's System Analysis Subprogram, to start the FCTO technology tracking project. The first effort was a patent search and analysis to identify hydrogen- and fuel-cell-related patents that are associated with FCTO-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 FCTO (or funding from EERE predecessor programs) or from grants under programs such as the Small Business Innovation Research and Small Business Technology Transfer. These initial efforts resulted in the August 2009 EERE report entitled: *Pathways to Commercial Success: Technologies and Products Supported by the Hydrogen, Fuel Cells & Infrastructure Technologies Program*. PNNL subsequently updated this report in FY 2010, FY 2011, FY 2012 and FY 2013. The approach taken for these efforts 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[1] and focused exclusively on patents for which DOE had a "Government Interest."[2] 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, NE, and Office of Science, also conduct research on hydrogen and fuel cells, but those patents were not included in this study.)

In addition, PNNL obtained the list of patents that were cited in the Hydrogen and Fuel Cells Program's Annual Progress Reports for 2002 – 2007[3] and included them in the patent list. The list was sent to FCT 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).

The next step was to obtain 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 the FCTO or EERE (or its predecessors) funded the research resulting in the patent. Patents not related to the FCTO 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 nor 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 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 FCTO/EERE funding were sometimes identified and added to the list. Figure 2.1 depicts the initial patent analysis process for the hydrogen and fuel cell technologies.

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[1] 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."

[2] 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."

[3] These reports can be found at http://www.hydrogen.energy.gov/annual_progress.html.

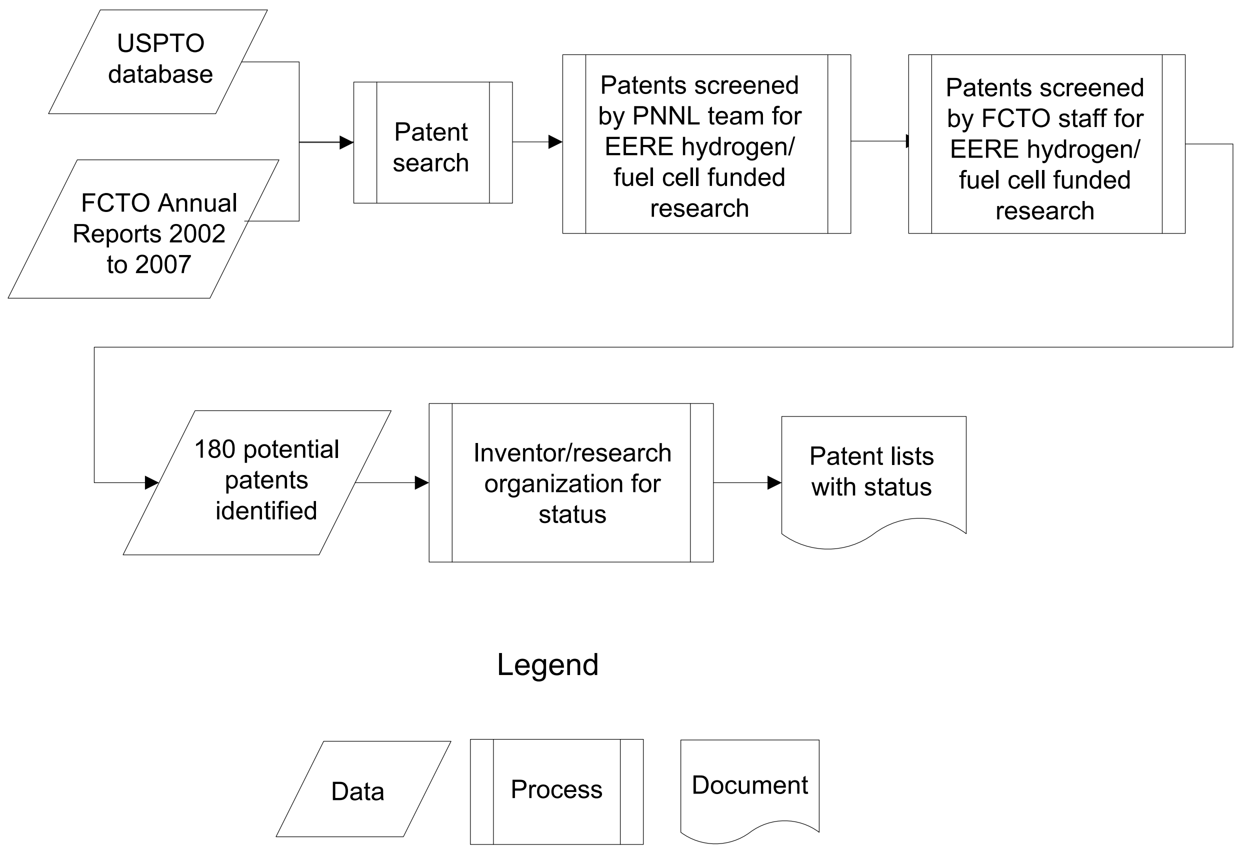


Figure 2.1. Initial Patent Analysis Process for Hydrogen and Fuel Cell Technologies

In FY 2010, PNNL began updating the August 2009 *Pathways to Commercial Success* report. As part of the updating process, the PNNL team conducted a search through FY 2008 and 2009 Hydrogen and Fuel Cells Program Annual Progress Reports to identify any new patents issued during those years. In addition, principal investigators for FCTO-funded emerging technologies and commercial products were asked if they had been awarded any new patents as a result of their research and development work. In June 2010, EERE launched a Technology Commercialization Portal on their website (http://techportal.eere.energy.gov/), which features a portfolio of EERE-funded technologies available for licensing, including patents. Using the EERE Portal, the PNNL team conducted a search for patents which employed similar screening strategies to those used in the original USPTO database searches. The PNNL team contacted patent holders via phone and e-mail to determine whether or not the underlying research associated with a patent was FCTO-funded. If a patent had received such funding, its current status was obtained. In subsequent years, PNNL conducted patent searches using the same methodology as in FY 2010.

The combined results of all the patent searches 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

In 2007, the PNNL team identified FCTO-funded projects that may have led to commercial or emerging technologies. To accomplish this, a series of one-on-one meetings was held with FCTO personnel and former FCTO personnel in which the lists of all FCTO-funded projects, obtained from the Hydrogen and Fuel Cells Program Annual Progress Reports for 2002 – 2007, were reviewed. Also, PNNL reviewed earlier annual reports from FCTO predecessor programs. From these meetings, the PNNL team obtained a preliminary list of projects that the FCTO personnel indicated may have led to commercial or emerging technologies. The government personnel also provided information about points of contact (POCs) 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 categories according to the following research areas: fuel cells, hydrogen production/delivery, and hydrogen storage.

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 to 5 years from commercialization, or no longer being pursued. For technologies identified as commercial or emerging, the POCs/PIs for each technology were contacted to gather data on the technology.

The Hydrogen and Fuel Cells 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 FCTO 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 FCTO 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 FCTO personnel to review. Figure 2.2 depicts the initial technology tracking process. In subsequent years, the PNNL team employed a similar technology tracking process to identify new emerging and commercially available technologies and ascertain the current status of technologies identified in previous years. Beginning in FY 2011, the PNNL team also asked commercial technology POCs to estimate the number of jobs created or retained by the sales of their technologies. The current listing of commercially available and emerging technologies is shown in Appendix A. The results of the technology tracking effort are discussed in Chapter 3.

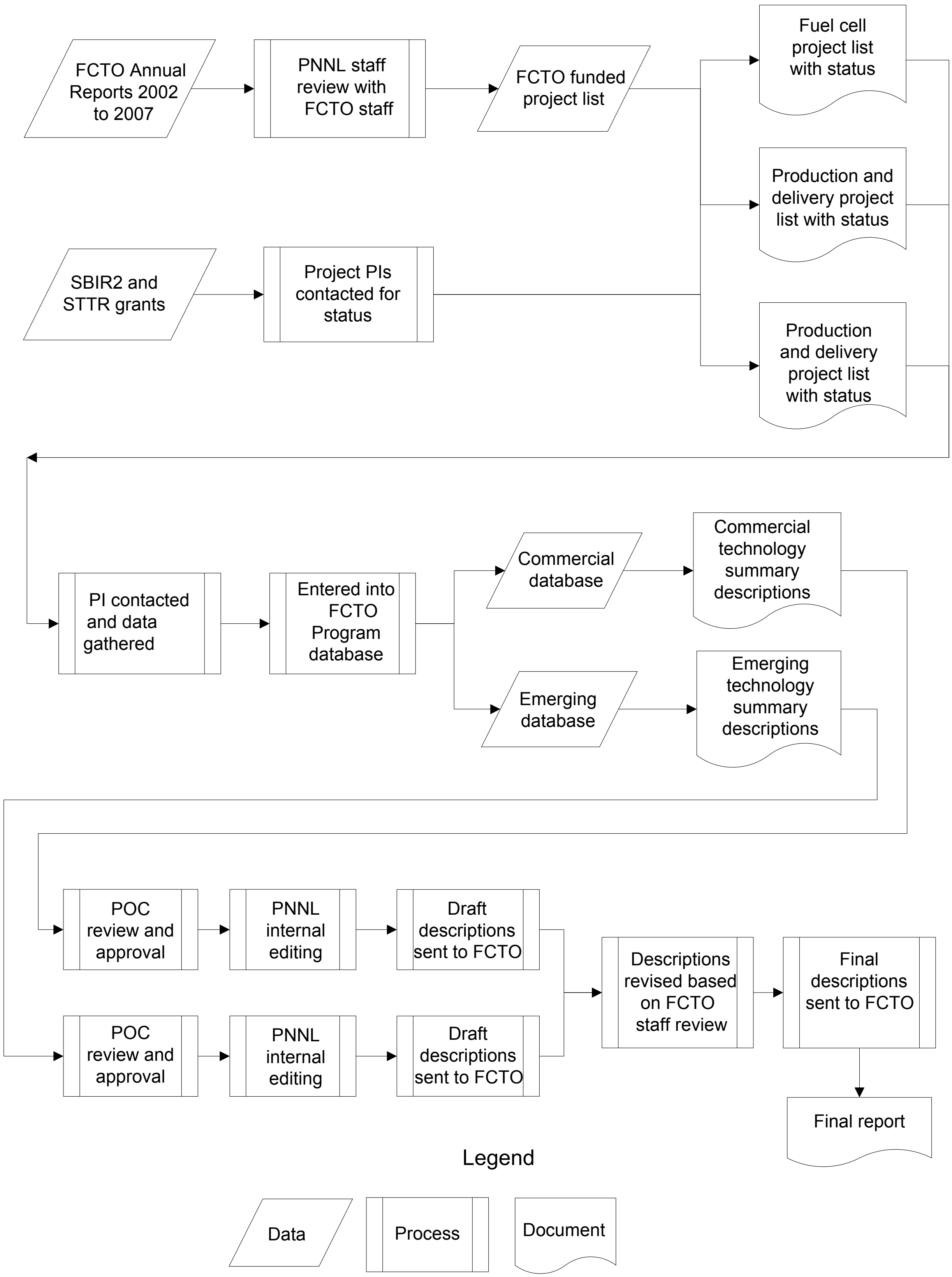


Figure 2.2. Initial Technology Tracking Process for Hydrogen and Fuel

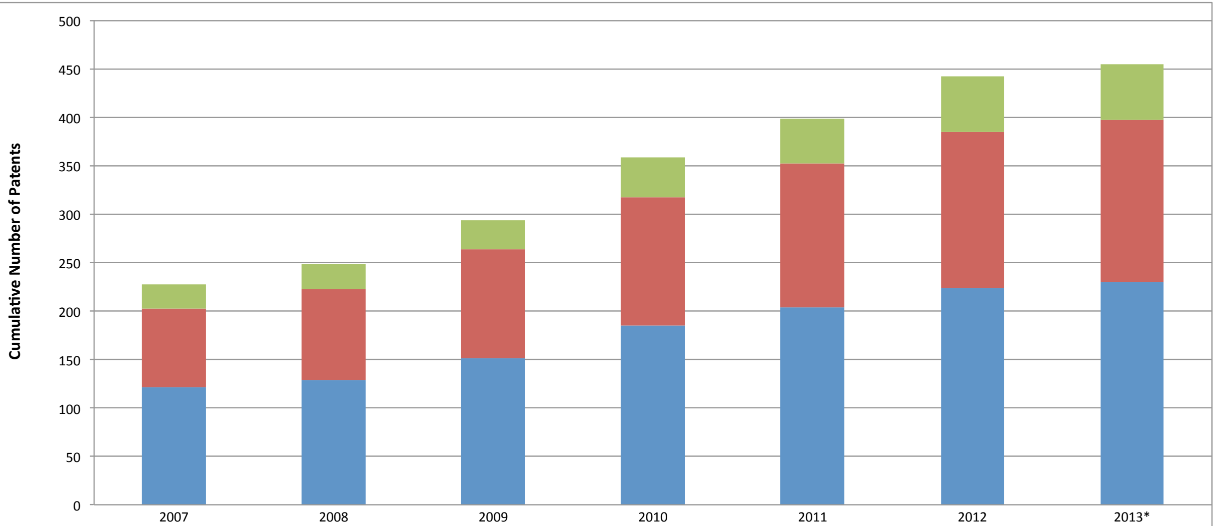
3.0 Results

The results of the efforts undertaken in the FCTO 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 B: the 230 fuel cell patents are listed in Appendix B-1, the 167 hydrogen production/delivery patents are listed in Appendix B-2, and the 58 hydrogen storage patents are listed in Appendix B-3. The patents 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 cumulative number of patents awarded over time, starting with 2007 patent awards through 2013. (At the time of this report, data for 2013 are only partially available.) From 2007 through 2012, an average of 43 patents per year were awarded. During the same time frame, fuel cell, production/delivery, and storage patents were awarded at an average rate of 21, 16, and 6 patents per year, respectively. As the figure shows, the number of patents awarded per year increased significantly in 2009 and 2010. To date, 2010 had the largest number of patents awarded in an individual year, with 34 fuel cell patents, 20 production/delivery patents, and 11 storage patents.

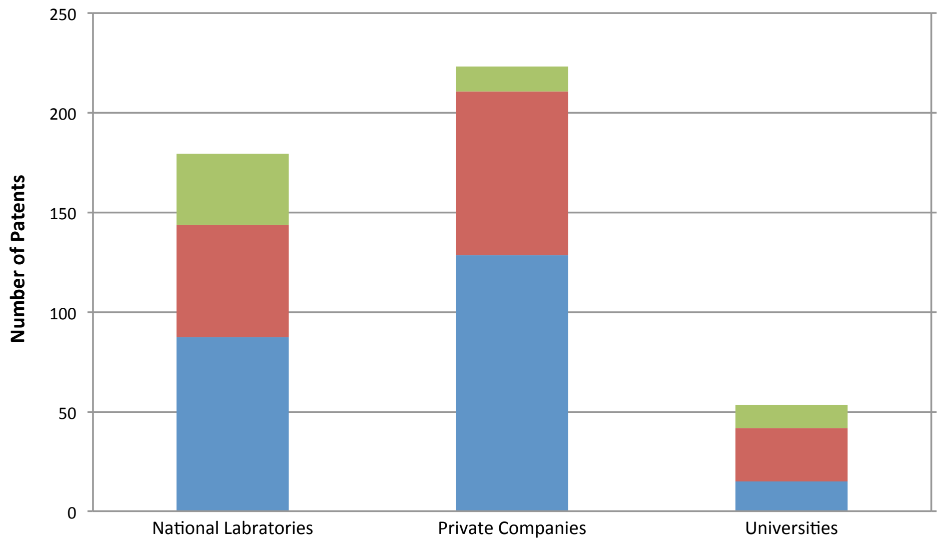


	2007	2008	2009	2010	2011	2012	2013*
Storage	24	26	30	41	47	57	58
Production/Delivery	82	93	112	132	148	161	167
Fuel Cell	121	129	151	185	204	224	230
Total	227	248	293	358	399	442	455

*Partial data for 2013

Figure 3.1. Cumulative 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 (179 patents), private companies (223 patents), and universities (53 patents). National laboratories and private companies account for 93% of all patents awarded for fuel cell technologies, with private companies receiving 56% of the awards. Private companies had more patent awards in the production/delivery area (50%) than national laboratories (34%), while universities had 16% of the production/delivery patents. National laboratories account for 60% of the storage patents, followed by private companies with 21% and universities with 19%.



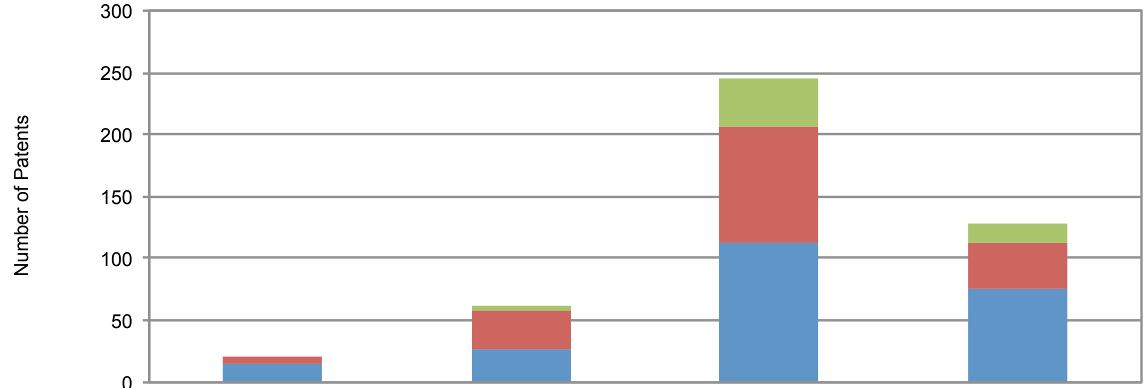
	National Labratories	Private Companies	Universities
Storage	35	12	11
Production/Delivery	57	83	27
Fuel Cell	87	128	15
Total	179	223	53

Figure 3.2. Types of Organization Receiving Patent Awards

Figure 3.3 shows the patent award status by use. As the figure shows, 20 patents are used in commercially available products, including:

- Bipolar plate/diffuser for a proton exchange membrane fuel cell (Patent number 6,171,720, Oak Ridge National Laboratory, 2001)
- Composite bipolar plate for electrochemical cells (Patent number 6,248,467, Los Alamos National Laboratory, 2001)
- Corrosion test cell for bipolar plates (Patent number 6,454,922, Los Alamos National Laboratory, 2002)
- Chemical microreactor and method thereof (Patent number 6,960,235 LLNL, 2005)
- Control method for high-pressure hydrogen vehicle fueling station dispensers (Patent number 7,059,364, Gas Technology Institute, 2006)
- Fuel cell and fuel cell coolant compositions (Patent number 7,138,199, Dynalene, Inc., 2006)
- Gas diffusion electrodes, membrane-electrode assemblies and method for the production thereof (Patent numbers 7,419,546 (2008), 7,601,216 (2009), and 7,785,454 (2010), BASF Corporation)
- Fuel cell electrolyte membrane with acidic polymer (Patent number 7,517,604, 3M Company, 2009)
- Fuel cell membrane electrode assembly (Patent number 7,572,534, 3M Company, 2009)
- System and method for detecting gas (Patent number 7,678,251, Proton Energy Systems, Inc., 2010)
- Gas venting system (Patent number 7,744,733, Proton Energy Systems, Inc., 2010)
- Fuel cell electrolyte membrane with basic polymer (Patent numbers 7,838,138 (2010), and 8,323,809 (2012), 3M Company)
- Cold weather hydrogen generation system and method of operation (Patent number 7,850,838, Proton Energy Systems, Inc., 2010).
- Hybrid adsorptive membrane reactor (Patent number 7,897,122 Media and Process Technology, 2011)
- Proton conducting materials (Patent numbers 8,481,227 (2013), and 8,227,140 (2012), 3M Company)
- Electroplating cell with hydrodynamics facilitating more uniform deposition across a workpiece during plating (Patent number 8,329,006, Faraday Technology, Inc., 2012)

Sixty-one patents are part of research now taking place on emerging technologies identified on the technology tracking list in Appendix A. In addition, 245 awarded patents are still being utilized via continuing research and/or active attempts to license the patent. Of all the patents reviewed, 72% are still actively being pursued through use in continuing research, emerging technologies, or commercially available products.

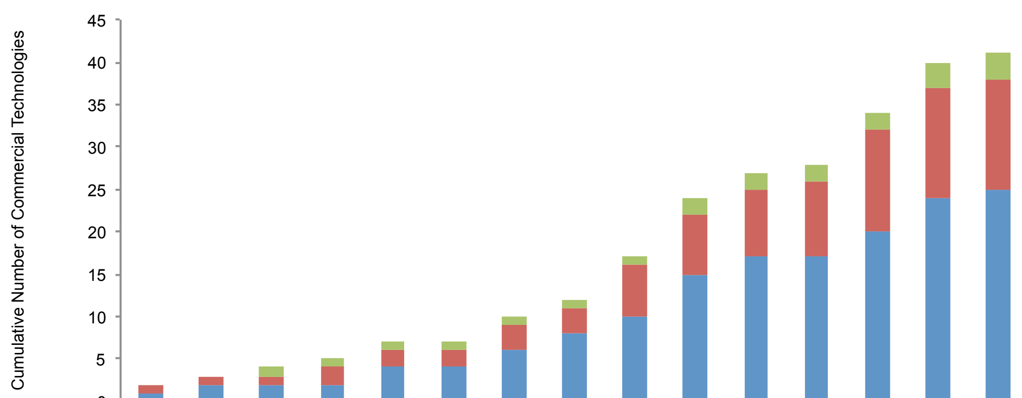


	Used in Commercial Product	Part of Emerging Technology	Still Used in Research and/or Seeking to License	No Longer Being Pursued
Storage	0	4	38	16
Production/Delivery	5	30	94	38
Fuel Cell	15	27	113	75
Total	20	61	245	129

Figure 3.3. Status of Awarded Patents

3.2 Commercial and Emerging Technology Identification and Tracking Results

The FCTO Technology Tracking Database contains 38 commercially available technologies, all of which are described in Appendix C. These descriptions were reviewed and approved by the industry POC for each technology. Figure 3.4 shows the cumulative number of commercial technologies entering the market. Of the 41 technologies that have entered the market two of them are no longer commercially available and one company decided not to continue to participate in the technology tracking effort. From 2000 through 2012, approximately three technologies per year entered the market. The years 2000 through 2006 showed a steady addition of technologies entering the market of one to three per year. For 2007 through 2012, an average of five technologies per year entered the market. In 2013, one technology has entered the market to date.



	Pre 2000	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013*
Storage	0	0	1	1	1	1	1	1	1	2	2	2	2	3	3
Production/Delivery	1	1	1	2	2	2	3	3	6	7	8	9	12	13	13
Fuel Cell	1	2	2	2	4	4	6	8	10	15	17	17	20	24	25
Total	2	3	4	5	7	7	10	12	17	24	27	28	34	40	41

*Partial data for 2013.

Figure 3.4. Cumulative Number of Commercial Technologies Entering the Market

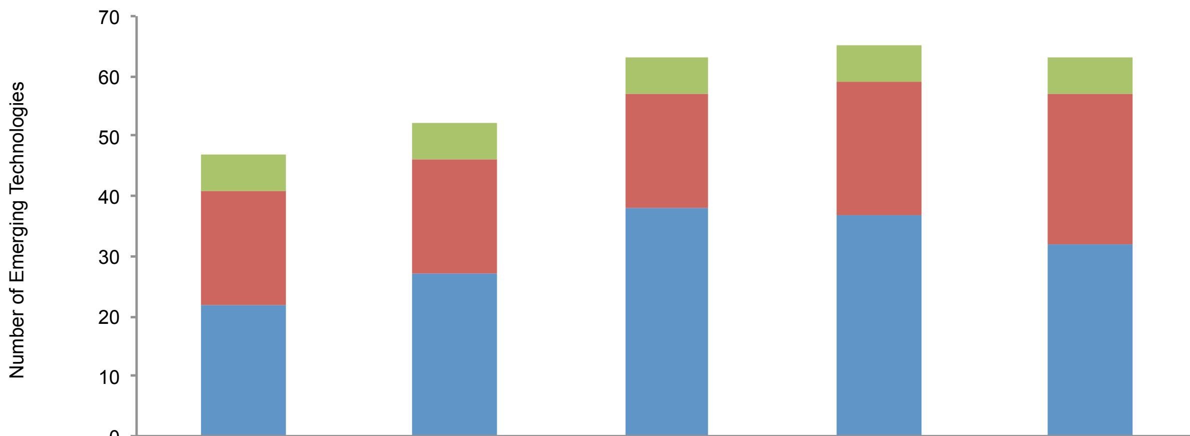
Table 3.1 briefly describes each of the 24 commercially available fuel cell technologies and their benefits. The full descriptions of these technologies are provided in Appendix C-1. These technologies range from an analysis tool to manufacturing processes for fuel cells and their components, to entire fuel cell systems that can be used in vehicles or stationary applications.

Table 3.2 briefly describes each of the 12 commercially available production/delivery technologies and their benefits. The full descriptions of these technologies are provided in Appendix C-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 commercially available storage technologies and their benefits. The full descriptions of these technologies are provided in Appendix C-3. One of the technologies is a composite tank, and the other is a method to store hydrogen in powder form.

FCTO's Multi-Year Research, Development and Demonstration Plan, which was last updated in October 2007 (and is currently in the process of being revised), was examined to see how the commercially available technologies align with FCTO's objectives and goals. The plan lists challenges and approaches for the research areas funded by the FCTO. The fuel cell area listed 19 challenges. The 24 commercially available technologies in Table 3.1 are aligned with 13 of these challenges, as shown in Table 3.4. Similarly, the 12 commercially available production/delivery technologies in Table 3.2 were found to align with 4 of the 13 challenges in that area, as shown in Table 3.5. The 2 commercially available storage technologies in Table 3.3 were found to align with 2 of the 7 storage approaches, as shown in Table 3.6.

The technology tracking database currently contains 63 emerging technologies for which descriptions are provided in Appendix D. These were reviewed and approved by the industry POC for each technology. Figure 3.5 shows the number of emerging technologies in each FCTO research area over the past five years of the technology tracking effort. Since 2009, the number of fuel cell emerging technologies has been about half of the total, with emerging storage technologies making up a very small percentage. Figure 3.6 shows the FY 2013 distribution of the emerging technologies in the three FCTO research areas.



	2009	2010	2011	2012	2013
Storage	6	6	6	6	6
Production/Delivery	19	19	19	22	25
Fuel Cell	22	27	38	37	32
Total	47	52	63	65	63

Figure 3.5. Number of Emerging FCTO Technologies

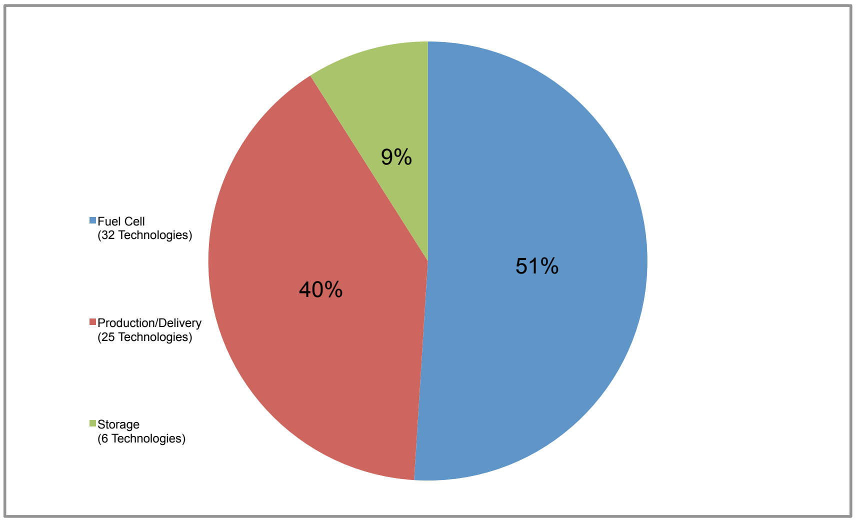


Figure 3.6. Distribution of Emerging FCTO Technologies in FY 2013

Table 3.7 briefly describes each of the 32 emerging fuel cell technologies and their benefits. The full descriptions of these technologies are provided in Appendix D-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 25 emerging production/delivery technologies and their benefits. The full descriptions of these technologies are provided in Appendix D-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 D-3. These technologies include improved tanks or cylinders, as well as new approaches for storing hydrogen.

The 32 emerging fuel cell technologies in Table 3.7 are aligned with 11 of the 19 fuel cell challenges in the FCTO 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 4 emerging fuel cell technologies. Similarly, the 25 emerging production/delivery technologies in Table 3.8 are aligned with 9 of the 13 production and delivery challenges in the plan, as shown in Table 3.11. The 6 emerging storage technologies in Table 3.9 are aligned with 2 of the 7 approaches in the storage area, as shown in Table 3.12.

An alphabetized directory of the organizations that developed the commercial and emerging technologies described in Appendices C and D is provided in Appendix E.

3.3 Jobs Created or Retained as a Result of Commercially Available Technologies

Beginning in FY 2011, the PNNL team asked commercial technology POCs to estimate the number of jobs created or retained by the sales of their technologies. Figure 3.7 shows the number of jobs created or retained in FY 2011, FY 2012 and FY 2013 based on the responses from the POCs.[1] These numbers do not include estimates for indirect jobs. For example, the associated supply chain jobs (e.g., balance-of-plant components, stack materials, etc.) for a fuel cell system are excluded. Figure 3.8 shows the FY 2013 distribution of jobs created or retained in the three FCTO research areas.

[1] Some POCs declined to provide an estimate of the number of jobs created/retained due to business confidentiality.

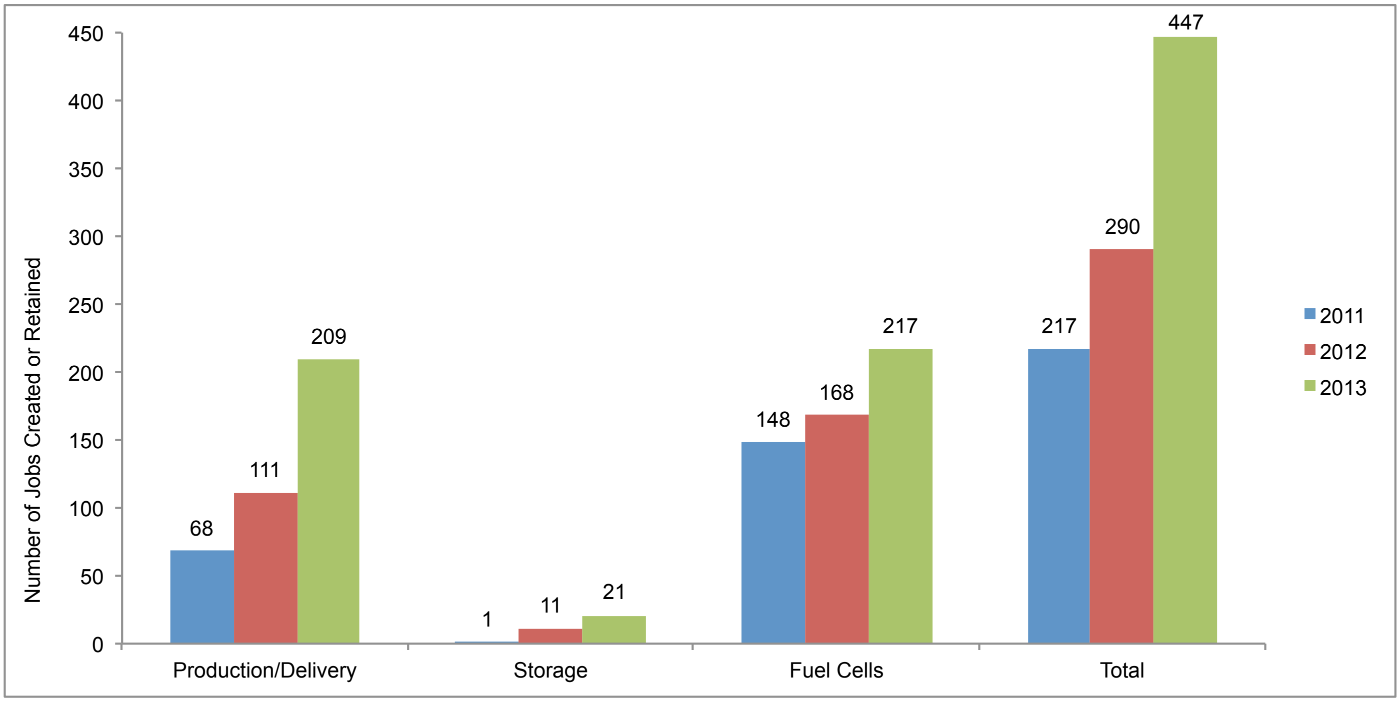


Figure 3.7. Jobs Created or Retained as a Direct Result of Commercially Available Technologies

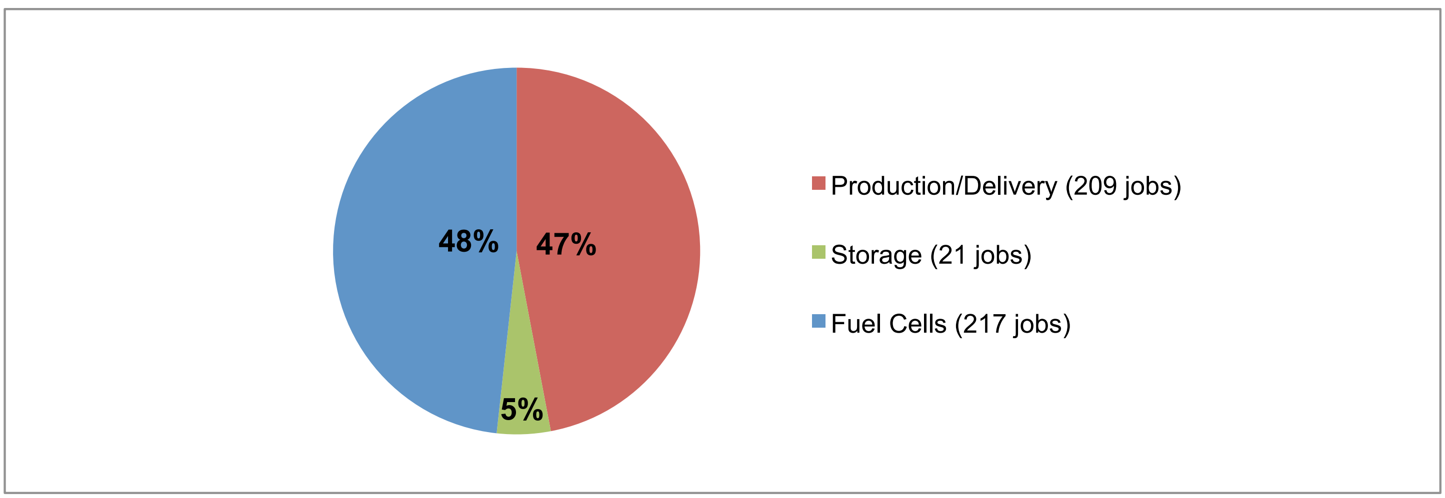


Figure 3.8. Distribution of Jobs Created or Retained in FY 2013

Table 3.1. Commercial Products Summary – Fuel Cells

Technology	Organization	Description	Benefits	Commercial Status
A Silicon-Based Solid Oxide Fuel Cell for Portable Consumer Electronics	Lilliputian Systems, Inc.	A miniature SOFC for the consumer portable power market is fabricated on a silicon chip and is fueled by butane from an on-board cartridge. The device delivers 2.5 watts of power with a run time of more than 30 hours per cartridge and plugs into various portable electronics via a USB cable connection.	The technology can be used as an alternative to conventional wall outlet and battery-based devices for charging portable consumer electronics. It provides on-the-go power and has been approved by the Federal Aviation Administration for passenger use on airplanes.	Commercially available in 2013 through Brookstone.
Bio-Fuled Solid Oxide Fuel Cells (SBIR Project)	TDA Research, Inc.	A novel catalyst and high-capacity sorbent were developed that allows biogas to be used in SOFCs.	This new technology allows SOFCs to operate on biogas as an alternative to natural gas.	Commercialized in 2011.
Cathode Catalysts and Supports for PEM Fuel Cells	3M Company	The 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.
Compact, 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.	Commercialized in 2012 with demonstration units provided to several potential customers.
Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.	The 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 eliminates 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.	Commercialized in 2009.
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.
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.

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

Technology	Organization	Description	Benefits	Commercial Status
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 produces 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.	Commercialized in 2009 and being used to supply hydrogen for material-handling equipment.
FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates (SBIR Project)	Faraday Technology, Inc.	The new manufacturing process, FARADAYIC ElectroEtching, is based on electrochemical through-mask etching and is producing stainless steel bipolar plates with flow channel designs that cannot be manufactured cost-effectively using more conventional machining techniques.	The new manufacturing process reduces the overall manufacturing cost of bipolar plates through use of a high-volume batch process with low capital equipment and tooling costs.	Commercialized in 2012 and a patent awarded in December 2012.
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.	Began licensing in 1999.
GenDrive™ Fuel Cell Power System (ARRA Project)	Plug Power Inc.	A fuel-cell-based power source for electric forklift fleets that increases fleet productivity and improves forklift performance compared with conventional lead-acid batteries.	The system can be refueled with hydrogen in less than 3 minutes (compared with 10 minutes or more for a battery change), allowing operators to spend more time moving product out on the floor. Constant voltage is provided throughout the entire shift, eliminating the performance degradation experienced with batteries.	More than 2,500 units are currently in use.
High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies	BASF Fuel Cell, Inc.	A new fabrication process for gas diffusion electrodes for MEAs allows the use of improved catalyst electrodes and membranes.	The new process is higher speed and lower cost and the new components result in increased durability.	Commercialized in 2012.
Improved Catalyst Coated Membrane (CCM) Manufacturing	IRD Fuel Cells LLC	The spray deposition technology uses 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 line for improved MEAs sold to IRD Fuel Cells, LLC in 2009, 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 seven Arraystats and seven parallel array fuel cell test units have been sold.
Integrated Manufacturing for Membrane Electrode Assemblies	BASF Fuel Cell, Inc.	The MEA fabrication process uses a new gas diffusion 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 temperatures.	Currently marketing the Celtec® -P MEA for high temperature PEM fuel cells.
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.
Low-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.	A low-cost fabrication process produces durable, low-contact resistance metallic bipolar plates for use in PEM fuel cells for automotive, stationary and portable power applications.	The new process reduces costs by using commercially available, stainless steel, low-cost carbon steel or aluminum as substrate materials and by reducing or eliminating the use of more expensive electrically conductive materials.	Commercialized in 2011.
Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership	The seals, used in fuel cell assemblies, use a custom elastomer and carrier material that provide an interfacial design that exhibits improved chemical and mechanical properties compared with conventional silicons.	The seals increase durability, which reduces fuel cell operation and maintenance costs, and eliminates catalyst poisoning concerns in the fuel cell. The system can be mass-produced and leads to shorter fuel cell assembly time.	Commercialized in 2009.
Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions	3M Company	The MEAs use a low equivalent weight, perfluorinated sulfonic acid-based membrane with improved chemical and mechanical stability, and proton conductivity.	The new MEA has improved durability and performance with increased lifetimes while operating under hot (up to 120°C), dry conditions.	Commercialized in 2006 with sales to a wide variety of fuel cell customers for stationary and automotive applications.
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 for military customers are now using it.	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 over 30 M250-CX and M300-CX systems through 2011.

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

Technology	Organization	Description	Benefits	Commercial Status
Portable Reformed Methanol Fuel Cells	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.
PureMotion® Model 120 Fuel Cell Power Plant	ClearEdge Power	The powerplant can be used as a power source for hydrogen-powered vehicles or as a stationery, 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 one older unit still in use on a bus and 16 next generation buses delivered in 2010.
Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC	The new gas diffusion layer (GDL) manufacturing process produces continuous rolls of GDL material and reduces GDL fabrication costs by 60%. Cost-saving measures used in the process include replacing batch processes with continuous ones, implementing on-line control systems, and reducing the number of process steps.	The new process reduces GDL costs through high-volume manufacturing and improves GDL quality and uniformity by using real-time process monitoring.	New process now being used to manufacture GDLs at Ballard.
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 52,000 BPPs since 2003.

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.
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 Performance Palladium-Based Membrane	Pall Corporation	The palladium-based membrane works as a selective barrier to let only H_2 pass through by using sophisticated high-temperature analysis and inorganic membrane development/manufacturing techniques.	The membrane can be economically integrated into the overall H_2 production process and is easily scalable to industrial applications.	Commercialized the AccuSep® Pd membrane module in 2011.
Hydrogen Distributed Production System	Air Liquide Process and Construction, 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 187 units in the U.S. and 228 internationally through 2011. Commercialized the HOGEN H series in 2004, selling 88 units in the U.S. and 90 internationally through 2011. Commercialized the HOFEN C series in 2011, selling 2 units in the U.S. and 3 internationally.
Hydrogen Safety Sensor for 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_4, 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.	Commercialized in 2010.

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

Technology	Organization	Description	Benefits	Commercial Status
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.	Commercialized in 2002.
Membrane Structures for Hydrogen Separation (SBIR Project)	Genesis Fueltech, Inc.	The low-cost membrane to separate hydrogen from other gases in the reforming process is 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.	Commercialized in 2009.
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.
PEM Electrolyzer Incorporating Low-Cost Membrane	Giner Electrochemical Systems, LLC	An electrolysis system that produces 0.5 kg-H_2/hr at 350 psig and uses a dimensionally stable membrane with improved durability under high-pressure conditions.	The electrolyzer stack capital cost has been reduced to <\$500/kW by using low-cost materials, lower catalyst loading, and a reduced part count per cell. The system can make use of renewable electricity sources such as wind and solar.	Commercialized in 2011. GES has delivered 6 stacks and has taken orders for several more.
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.	Commercialized in 2012 with one international sale and one domestic unit being installed
TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Lincoln Composites, Inc.	The large composite tank for storing and transporting compressed hydrogen gas over road, rail, or water has an internal volume of 8,500 liters and contains 150 kg of hydrogen at 3,600 psi. Four of these tanks are mounted in a frame for transport and a system for loading, unloading, and pressure relief has been designed and implemented.	The tank and frame system reduces costs by improving volumetric hydrogen storage capacity compared with conventional tube trailers while meeting strength, environmental, and durability targets.	Commercialized in 2011.

Table 3.3. Commercial Products Summary – Storage

Technology	Organization	Description	Benefits	Commercial Status
Hydrogen Composite Tanks	Quantum Technologies, 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.	Commercialized in 2001.
Sodium Silicide (NaSi) Hydrogen Generation System	SiGNa Chemistry, Inc.	The portable power system uses a stable, room-temperature reaction between sodium silicide and water to generate hydrogen at pressures from 2 to 30 psi. When coupled to a fuel cell generator the system provides 300 watts of continuous power and up to 500 watts of peak power.	The system uses two cartridges filled with NaSi powder and an integrated water reservoir that are hot-swappable, enabling extended runtimes without an interruption of power. Power output is consistent over the entire runtime, without the degradation associated with batteries.	Commercialized in the U.S. in 2012 with sales to a producer of a portable fuel-cell-based charger for electronics.

Table 3.4. Fuel Cell Challenges and Related Commercial Technologies

Challenges*	Technology Title	Organization
Develop membranes that meet all targets	Improved Catalyst Coated Membrane (CCM) Manufacturing	IRD Fuel Cells LLC
	Lifetime Improvements for PEM Fuel Cells	DuPont Fuel Cells
Develop electrodes that meet all targets	High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies	BASF Fuel Cell, Inc.
Develop MEAs that meet all targets	Cathode Catalysts and Supports for PEM Fuel Cells	3M Company
	Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems Inc.
	Integrated Manufacturing for Membrane Electrode Assemblies	BASF Fuel Cell, Inc.
	Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions	3M Company
Develop low-cost, durable GDLs that improve fuel cell performance	Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC
Develop low-cost, durable bipolar plates that meet all targets	A Silicon-Based Solid Oxide Fuel Cell for Portable Consumer Electronics	Lilliputian Systems, Inc.
	Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.
	FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates	Faraday Technology, Inc.
	Low-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.
	Scale-Up of Carbon-Carbon Composite Bipolar Plates	Porvair Advanced Materials, Inc.
Develop efficient, cost-effective thermal/water management systems	Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.
Develop reliable, durable, low-cost seals	Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
Develop cost-effective, efficient, reliable and durable fuel cells for stationary applications that meet all targets	Bio-Fueled Solid Oxide Fuel Cells	TDA Research, Inc.
	Compact, Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.
	Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc.
	PureMotion® Model 120 Fuel Cell Power Plant	ClearEdge Power
Develop cost-effective, reliable, durable fuel cells for portable power applications (e.g., cell phones, computers, etc.) that meet all targets	A Silicon-Based Solid Oxide Fuel Cell for Portable Consumer Electronics	Lilliputian Systems, Inc.
	Portable Reformed Methanol Fuel Cells	UltraCell Corporation
Conduct system and tradeoff analysis	GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory
Develop system to allow PEM fuel cells to operate in off-road applications	GenDrive™ Fuel Cell Power System	Plug Power Inc.
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 FCT Program Multi-Year Plan at 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	H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	GreenField Compression
	Hydrogen Distributed Production System	Air Liquide Process and Construction, Inc.
	ME100 Methanol Reforming Hydrogen Generator	REB Research & Consulting
	Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.
	Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.
Hydrogen production from water via electrolysis	FuelGen® Hydrogen Fueling Systems	Proton Energy Systems, Inc.
	Hydrogen Generation from Electrolysis	Proton Energy Systems, Inc.
	PEM Electrolyzer Incorporating Low-Cost Membrane	Giner Electrochemical Systems, LLC
Separation and purification systems	High Performance Palladium-Based Membrane	Pall Corporation
	Hydrogen Safety Sensor for Energy Applications	NexTech Materials, Ltd.
	Membrane Structures for Hydrogen Separation	Genesis Fueltech, Inc.
Develop carriers that can enable low-cost hydrogen delivery	TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Lincoln Composites, Inc.

* Note: These challenges are described in the FCT Program Multi-Year Plan at http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.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 Technologies, Inc.
Chemical hydrogen storage	Sodium Silicide (NaSi) Hydrogen Generation System	SiGNa Chemistry, Inc.

* Note: The storage approaches are described in the FCT 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
Alternative and Durable High-Performance Cathode Supports for PEM Fuel Cells	Pacific Northwest National Laboratory	A support structure for cathodes used in PEM fuel cells. The technology takes advantage of the stable interface between platinum, a conductive metal oxide, and a honeycombed carbon support.	The support structures increase cathode performance and durability, and are synthesized using a method that can be easily scaled up for high-volume manufacturing.
CIRRUS: Cell Ice Regulation and Removal Upon Start-up	Nuvera Fuel Cells, Inc.	The Orion™ fuel cell exploits higher current density operation to increase the power density of the stack and reduce its thermal mass, enhancing freeze starting ability.	The new fuel cell has improved performance in sub-freezing conditions including increased fuel cell stack power density, improved water purging prior to cold shutdown, and avoidance of significant degradation of stack materials after 200 freeze startup/shutdown cycles.
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 (DMFC) Anode Catalysts	National Renewable Energy Laboratory	An improved anode catalyst for direct methanol fuel cells. The catalyst is manufactured using ion implantation and magnetron sputtering of platinum-ruthenium (PtRu) on high-surface-area carbon support materials.	The new PtRu catalyst materials have shown up to 30% improvement in methanol oxidation reaction activity and increase the durability of membrane electrode assemblies.
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. Received American Recovery and Reinvestment Act (ARRA) funding to facilitate commercialization.	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.
Durable Catalysts for Fuel Cell Protection During Transient Conditions	3M Company	The new catalyst materials alleviate the damaging effects of transient conditions (e.g., startup, shutdown, and fuel starvation) on fuel cells. The materials are being developed by modifying the catalyst's behavior so that oxidation of water instead of carbon corrosion is the preferred reaction during transient conditions.	Fuel cell durability is improved by controlling catalyst reaction behavior during transient conditions. Low platinum-group-metal loading reduces material costs.
Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells	Nanosys, Inc.	A nanowire-supported platinum cobalt (PtCo) catalyst for PEM fuel cells increases catalyst mass activity relative to commercially available platinum carbon (Pt/C) catalysts while using reduced amount of precious metal catalyst.	The new catalyst support structure ensures a high catalyst utilization, enables a higher power density using low catalyst loading, and ensures an improved durability compared with conventional carbon-supported catalysts.

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

Technology	Organization	Description	Benefits
Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes	National Renewable Energy Laboratory	The nanostructured platinum (Pt) catalysts have extended surface areas and show improved specific activity and durability compared with traditional Pt catalysts supported on carbon (Pt/C). The catalysts are synthesized from metal nanowire templates using the spontaneous galvanic displacement process.	The new catalysts achieve increased performance (specific activity) and durability compared with traditional Pt/C catalysts and reduce material costs by using less Pt.
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.
Fuel-Cell-Based Mobile Lighting	Sandia National Laboratories	The fuel cell mobile lighting system uses a 5-kW, hydrogen-fueled PEM fuel cell stack to power high-efficiency plasma lighting. The system is an energy-efficient, environmentally-friendly alternative to the diesel-fueled generators currently used to power most portable lighting equipment.	The system produces zero emissions at the point of use, reduces noise compared with diesel generators, and can be used in indoor or outdoor applications. The use of a fuel cell power source and plasma lighting maximizes the unit's overall energy efficiency.
GenSys® Blue: High-Temperature CHP Fuel Cell System (ARRA Project)	Plug Power Inc.	The GenSys® Blue is a high-temperature PEM fuel cell system that provides up to 5 kW of electricity and 28,000 Btu/hr of usable heat for residential and light commercial applications. The system achieves electrical and CHP efficiencies of 30% and 85%, respectively.	The high-efficiency system reduces residential utility bills and CO_2 emissions. The unit can be easily integrated with existing heating systems because it produces waste heat of a sufficient temperature to meet thermal comfort demands.
High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System	Intelligent Energy Inc.	The CHP system is composed of two main parts: a fuel processor, that uses hydrocarbon feedstock in a steam-methane reforming reaction and water-gas shift reaction to produce hydrogen, and a PEM fuel cell that uses the hydrogen for electricity production. Heat is recovered from the fuel cell and the fuel processor and can be used for a variety of applications.	The system achieves 35% electrical efficiency with greater than 70% combined efficiency possible, depending on the application. The modular and scalable design allows for easy installation and the unit can be configured to provide emergency backup power in the event of a grid failure.
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 an 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.

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

Technology	Organization	Description	Benefits
Low-Cost 3-10 kW Tubular SOFC Power System	Acumentrics Corporation	The system is a natural gas based SOFC which is being developed for use as a micro CHP unit to provide electricity and hot water in residential applications. The system has demonstrated an electrical efficiency of 35%-40% and a CHP energy efficiency of 85%.	The system handles readily available fuels such as natural gas and propane, without requiring an external reformer to produce hydrogen. On-site simultaneous generation of heat and power will increase efficiency and lower energy costs to consumers.
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 Electrocatalysts	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.
Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies	W.L. Gore and Associates, Inc.	A high-volume manufacturing process for producing low-cost, durable, high-power-density, three-layer MEAs that require minimal conditioning. The process is scalable to industry MEA volume targets of 500,000 systems per year.	MEAs produced using the new manufacturing process have withstood 9,000 hours of durability testing in an 80°C automotive duty cycle, exceeding DOE's 2015 target by 5,000 hours. The MEAs also have improved power density and conditioning times of less than 4 hours. The use of high-volume manufacturing reduces fuel cell costs.
Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers	W.L. Gore and Associates, Inc.	A system that uses the product water from a hydrogen fuel cell's reaction to humidify the incoming reactant gases on the cell's anode and cathode sides. The system contains an inexpensive and durable composite membrane consisting of an ionomer layer sandwiched between micro porous polymer layers. The membrane is capable of high water transport rates and prevents gas crossover from occurring.	The system improves the performance and longevity of fuel cell electrolyte membranes by controlling reactant gas humidity, which is essential for maintaining proper membrane hydration.
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.

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.
Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports	Brookhaven National Laboratory	The high-surface-area electrocatalysts have a platinum (Pt) monolayer that is deposited on top of transition metal nanostructures. These catalysts, which are used in the fuel cell’s oxygen reduction reaction, have a higher activity per mass of Pt than pure Pt nanoparticles.	The new catalysts achieve high activity for the oxygen reduction reaction, resist Pt dissolution under cycling conditions, and reduce costs by reducing Pt loading.
PowerEdge™ Fuel Cell System (ARRA Project)	Nuvera Fuel Cells, Inc.	A fuel-cell-based power source for electric forklift fleets that increases fleet productivity and improves forklift performance compared with conventional lead-acid batteries.	The system can be refueled with hydrogen in less than 2 minutes (compared with 10 minutes or more for a battery change), allowing operators to spend more time moving product out on the floor. Constant voltage is provided throughout the entire shift, eliminating the performance degradation experienced with batteries.
Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd.	The bipolar plate uses expanded graphite in conjunction with a 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_2S sensor operates by a reversible change in resistance caused by adsorption and desorption of H_2S in a film of H_2S-sensitive material. It can detect H_2S from 25 ppb to 10 ppm, with response times of less than one minute.	The sensor will detect H_2S 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.
Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.	The solid acid fuel cell stack generates electricity using hydrogen from a variety of commercial fuel reformate sources, including diesel fuels commonly used in the trucking industry. The technology offers near silent operation, quick start-up time, and the ability to handle start-stop cycling.	The technology can operate reliably on a variety of gas and liquid fuel reformate and reduces emissions by providing a more fuel-efficient alternative to auxiliary power generated from combustion engines. The stacks can be manufactured by low-cost, high-volume methods because of the solid nature of the electrolyte and the use of metal and polymer components.

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

Technology	Organization	Description	Benefits
Solid Oxide Fuel Cell Auxiliary Power Unit	Delphi Corporation	The SOFC power unit will provide up to 3 kW of auxiliary electrical power for a variety of mobile applications operating with a wide range of commercially available fuels such as natural gas, diesel, and propane. Received ARRA funding to test the power unit.	The power unit operates at a higher efficiency than internal combustion engines because of the electrochemical conversion of fuel and reduces the noise and pollutants associated with these engines.
Ultra-Low Platinum Alloy Cathode Catalysts for PEM Fuel Cells	University of South Carolina	A new catalyst synthesis process reduces the precious metal content in the cathode of PEM fuel cells while maintaining or exceeding current fuel cell durability and performance specifications.	The new catalyst process reduces fuel system costs by reducing precious metal content and is scalable from the laboratory to high-volume production.
Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture	Rensselaer Polytechnic Institute	To aid in cost-effective, high-volume manufacturing of PEM fuel cell MEAs, diagnostic methods and ultrasonic bonding processes are being developed.	The new methods and processes will reduce manufacturing costs by reducing cycle time and energy consumption and improving product yield.

Table 3.8. Emerging Products Summary – Production/Delivery

Technology	Organization	Description	Benefits
Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC	A new, high-efficiency hydrogen liquefier that uses active magnetic regenerative liquefaction (AMRL) to produce ~25 kg of liquid hydrogen per day with a thermodynamic cycle efficiency (figure of merit) of ~0.5.	The technology improves the efficiency and reduces the cost of hydrogen liquefaction.
Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC	A centrifugal compressor system for pipeline transport of hydrogen gas achieves higher compression efficiency than conventional reciprocating compression equipment and delivers hydrogen at a rate of 240,000 kg/day at a discharge pressure of 1285 psig.	The compressor system can be used to support existing hydrogen pipeline infrastructure in the industrial sector and for future pipeline transport of high-pressure hydrogen gas from production sites to vehicle fueling stations at reduced capital costs.
Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas (ITM Syngas)	Air Products and Chemicals, Inc.	The ion transport membrane (ITM) system uses ceramic membranes to generate syngas and hydrogen in a more compact, lower-cost, and higher-efficiency process than competing technologies. ITM syngas membranes combine air separation and methane partial oxidation into a single unit operation.	The system has very high flux and selectivity that help reduce both capital and operating costs. The ITM syngas process is also readily configured for carbon capture from the high-pressure syngas product.
Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory	Extensive testing of fiber-reinforced polymer pipelines are underway to determine their use for safe delivery of hydrogen over long distances.	Composite pipelines can reduce the cost of installation and increase the corrosion resistance of the pipes
Efficient, Low-Cost Hydrogen Generation from Renewable Energy	Proton Energy Systems, Inc.	New fuel cell materials, components, and manufacturing methods to reduce the cost and improve electrical efficiency for fuel cells integrated with renewable energy sources.	The new system is compatible with high volume manufacturing by consolidating fuel components and simplifying assembly.
Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.	The new compressor is more efficient than existing mechanical compressors, contains no moving parts, and has a modular architecture which allows the capacity to be increased by simply adding more fuel cells.	The compressor can produce up to 4 lbs of hydrogen per day at pressures up to 12,000 psi at a hydrogen recovery efficiency of 95%.
HRS-100™ Hydrogen Recycling System (SBIR Project)	H2Pump, LLC	An electrochemical hydrogen recovery system that separates hydrogen from a mixed gas stream (e.g., furnace exhaust), purifies it, and pumps it back into the feed stream of an industrial process. The system can recycle up to 100 kg-H_2/day (1,600scfh) and recovers up to 90% of the hydrogen present in the exhaust stream.	The system reduces hydrogen feedstock costs for industrial processes by recovering previously wasted hydrogen at a lower cost than would be required for a new supply.
Hydrogen by Wire — Home Fueling System (SBIR Project)	Proton Energy Systems, Inc.	A new PEM electrolysis system produces 2 Kg/day of hydrogen at 350 bar for refueling hydrogen-powered vehicles or for stationary/portable power devices.	The new on-site system enables widespread adoption of hydrogen-powered transportation without a well-developed hydrogen supply infrastructure.
Hydrogen Gas Sensing System	Intelligent Optical Systems, Inc.	The quick-response sensor system accurately detects hydrogen leaks in a broad range of operating environments including fuel cell vehicle garages, production facilities, and refueling stations. The sensor detects hydrogen at concentrations from 100 ppm to 10% hydrogen-in-air with a response time of less than 5 seconds.	The system operates over a wide range of conditions, including temperatures of 10-55°C and 0-90% relative humidity. The system identifies the points at which hydrogen is leaking thus alerting users before safety is compromised.

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

Technology	Organization	Description	Benefits
Hydrogen Production for Refineries (SBIR Project)	TDA Research, Inc.	The hydrogen generation process uses a fluidized bed reactor to produce hydrogen from heavy feedstocks at refineries.	The process saves energy and costs by operating at lower temperatures compared with conventional methods (methane steam reforming or petcoke gasifiers).
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_2, H_2S, 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.
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 applicable to small, on-site hydrogen generators, such those located at fueling stations.
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.
Leak Detection and Hydrogen Sensor Development	Los Alamos National Laboratory	A robust zirconia-based, electrochemical sensor for vehicular and stationary applications. The low-cost sensor measures hydrogen in air from 0.04-4% with an accuracy of ± 1%	The safety sensor is low-cost and durable with good response time, stability, and resistance to aging and degradation from thermal cycling.
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage (SBIR Project)	Proton Energy Systems, Inc.	A new electrolysis system using improved catalyst and membrane materials to reduce efficiency losses arising from oxygen evolution over-potential and membrane ionic resistance.	The new catalysts and membranes reduce MEA cost by using less expensive materials while improving long-term stability and scale up.
Materials Solutions for Hydrogen Delivery in Pipelines	Secat, Inc.	Methods are being developed to identify steel compositions and associated welding filler wires and processes that would enable safe transmission of hydrogen at high pressures (800-3000 psi).	The methods would reduce pipeline infrastructure costs by identifying suitable existing pipelines thus avoiding replacement costs while ensuring safety.
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.
MEMS Hydrogen Sensor for Leak Detection	Oak Ridge National Laboratory	Microelectromechanical system (MEMS) hydrogen sensor uses a nanostructured palladium/argon alloy to improve sensitivity and response. The sensor can be used for hazardous condition detection in hydrogen fuel-powered applications.	The sensor has sufficient response, sensitivity, and accuracy for safety applications at low-cost.

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

Technology	Organization	Description	Benefits
Nanotube Array Photocatalysts (SBIR Project)	Synkera Technologies, Inc.	The photoelectrochemical hydrogen production system uses high-density arrays of nanotubes with coaxial architecture to enhance light harvesting through a large absorption cross-section and a high surface area to promote catalytic chemistry.	The photocatalysts increases efficiency through broadband light absorption and a vertically graded bandgap. The system is scalable to large size and high volumes and lowers costs compared with traditional technologies.
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 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.
Oil Free Hydrogen Compressor (SBIR Project)	Mohawk Innovative Technology, Inc.	The oil-free, high-speed centrifugal compressor uses compliant surface foil gas bearings and seals, engineered coatings in conjunction with 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	MVSystems, Inc.	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.	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.
Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi	Giner, Inc.	The technology is a 5,000 psi PEM-based water electrolyzer system that produces hydrogen for residential refueling of hydrogen vehicles.	The refueling system reduces overall cost by eliminating the need for hydrogen storage and compression at the user end site.

Table 3.9. Emerging Products Summary – Storage

Technology	Organization	Description	Benefits
Electrochemical Reversible Formation of Alane	Savannah River National Laboratory	The process uses direct hydrogeneration and electrochemical synthesis to produce alane, a low-cost rechargeable hydrogen storage material for portable or stationary fuel cell applications.	The process increases alane production by using more efficient, less costly electrochemical reactions and avoids hazardous material handling problems by surface passivation.
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, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers, LLC	A metal hydride solid-state-based hydrogen fuel system to power PEM fuel cell forklifts has the advantage of reduced charging/fueling time, consistent power delivery, longer lift span, added ballast, and the ability to be used with renewable energy source.	The new system offers safer operation, increased tank storage capacity, lower capital cost, reduced fleet size, and the capability to fill directly from an electrolyzer or other low-pressure source.
Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Oak Ridge National Laboratory	This lower cost carbon fiber precursor, polyacrylonitrile with methyl acrylate (PAN-MA), will be used to improve the strength-to-weight ratio of carbon fiber composite materials for hydrogen storage tanks.	The carbon fiber can be manufactured using existing high textile production processes rather than highly specialized processes and materials thus reducing fiber costs by 25%.
Manufacturing Technologies for Low-Cost Hydrogen Storage Vessels	Quantum Fuel System Technologies Worldwide, Inc.	A new process for manufacturing composite pressure vessels used for storing compressed hydrogen. The process combines two techniques for the placement of carbon fibers (filament winding and fiber placement) to reduce the cost and weight of the vessel.	The process reduces the weight and cost of composite hydrogen storage vessels without compromising the structural integrity of the vessels.
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 reduce production time, lower costs, improve fabrication reliability and volumes, and provide safer failure modes compared with filament winding tanks.

Table 3.10. Fuel Cell Challenges and Related Emerging Technologies

Challenges*	Technology Title	Organization
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.
Develop electrodes that meet all targets	Alternative and Durable High-Performance Cathode Supports for PEM Fuel Cells	Pacific Northwest National Laboratory
	Direct Methanol Fuel Cell (DMFC) Anode Catalysts	National Renewable Energy Laboratory
	Durable Catalysts for Fuel Cell Protection During Transient Conditions	3M Company
	Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes	National Renewable Energy Laboratory
	High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders
	Low Platinum Loading Fuel Cell Electrocatalysts	Brookhaven National Laboratory
	Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports	Brookhaven National Laboratory
	Ultra-Low Platinum Alloy Cathode Catalysts for PEM Fuel Cells	University of South Carolina
Develop MEAs that meet all targets	Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells	Nanosys, Inc.
	Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies	W.L. Gore and Associates, Inc.
	Platinum and Fluoropolymer Recovery from PEM 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 efficient, cost-effective thermal/water management systems	CIRRUS: Cell Ice Regulation and Removal Upon Start-up	Nuvera Fuel Cells, Inc.
	Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers	W.L. Gore and Associates, 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	Low-Cost 3-10 kW Tubular SOFC Power System	Acumentrics Corporation
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.
	Fuel-Cell-Based Mobile Lighting	Sandia National Laboratories

Table 3.10. Fuel Cell Challenges and Related Emerging Technologies (Cont'd)

Challenges*	Technology Title	Organization
Develop auxiliary power unit (APU) system for heavy truck applications to reduce idling of the main engine that meet all targets	Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.
	Solid Oxide Fuel Cell Auxiliary Power Unit	Delphi Corporation
Develop system to allow PEM Fuel Cells to operate in off-road applications	PowerEdge™ Fuel Cell System	Nuvera Fuel Cells, Inc.
Stationary fuel cell demonstrations	GenSys® Blue: High-Temperature CHP Fuel Cell System	Plug Power Inc.
	High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System	Intelligent Energy Inc.
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.
	Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture	Rensselaer Polytechnic Institute
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 FCT Program Multi-Year Plan for fuel cells at 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

Challenges*	Technology Title	Organization
Cost reduction of distributed hydrogen production from natural gas and bio-derived liquids	Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas (ITM Syngas)	Air Products and Chemicals, Inc.
	Efficient, Low-Cost Hydrogen Generation from Renewable Energy	Proton Energy Systems, Inc.
	Hydrogen by Wire — Home Fueling System	Proton Energy Systems, Inc.
	Hydrogen Production for Refineries	TDA Research, Inc.
	Integrated Short Contact Time Hydrogen Generator	GE Global Research Center
	Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage	Proton Energy Systems, Inc.
	Novel Catalytic Fuel Reforming	InnovaTek, Inc.
Hydrogen production from water via electrolysis	Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory
	Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi	Giner, Inc.
Photoelectrochemical hydrogen production from water (direct water splitting)	Nanotube Array Photocatalysts	Synkera Technologies, Inc.
	Photoelectrochemical Hydrogen Production	MVSystems, Inc.
Biological production of hydrogen	Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	UC Berkeley
Separation and purification systems	HRS-100™ Hydrogen Recycling System	H2Pump, LLC
	Hydrogen Gas Sensing System	Intelligent Optical Systems, Inc.
	Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.
	Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.
	Leak Detection and Hydrogen Sensor Development	Los Alamos National Laboratory
	MEMS Hydrogen Sensor for Leak Detection	Oak Ridge National Laboratory
Reduce capital costs and ensure safety, reliability, and durability of pipelines.	Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory
	Materials Solutions for Hydrogen Delivery in Pipelines	Secat, 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	Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC
	Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.
	Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.
Reduce the cost and improve the energy efficiency of hydrogen liquefaction	Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC

* Note: The challenges are described in the FCT 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

Challenges*	Technology Title	Organization
Compressed, cryo-compressed and conformal hydrogen tanks	Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory
	Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Oak Ridge National Laboratory
	Manufacturing Technologies for Low-Cost Hydrogen Storage Vessels	Quantum Fuel System Technologies Worldwide, Inc.
	Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.
Advanced metal hydrides	Electrochemical Reversible Formation of Alane	Savannah River National Laboratory
	Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers, LLC

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

Appendix A:
Technology Tracking List

Fuel Cell Technologies

Technology Title	Company
A Silicon-Based Solid Oxide Fuel Cell for Portable Consumer Electronics: nectar™	Lilliputian Systems, Inc.
Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells	PNNL
Bio-Fueled Solid Oxide Fuel Cells	TDA Research
Cathode Catalysts and Supports for PEM Fuel Cells	3M Company
CIRRUS: Cell Ice Regulation and Removal Upon Start-up	Nuvera Fuel Cells, Inc.
Compact, Multi-Fuel Solid Oxide Fuel Cell (SOFC) System	Technology Management, Inc.
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 (DMFC) Anode Catalysts	NREL
Direct Methanol Fuel Cell for Handheld Electronics Applications	MTI Micro Fuel Cells, Inc.
Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors	InnoSense, LLC
Durable Catalysts for Fuel Cell Protection During Transient Conditions	3M Company
Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells	Nanosys, Inc.
Extended Continuous Pt Nanostructures in Thick, Dispersed Electrodes	NREL
FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates	Faraday Technology, Inc.
Fuel Cell Membrane Measurement System for Manufacturing	Scribner Associates, Inc.
Fuel-Cell-Based Mobile Lighting	SNL
GCtool: Fuel Cell Systems Analysis Software Model	ANL
GenDrive™ Fuel Cell Power System	Plug Power Inc.
GenSys® Blue: High-Temperature CHP Fuel Cell System	Plug Power Inc.
High-Efficiency PEM Fuel Cell Combined Heat and Power System	Intelligent Energy Inc.
High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders
High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies	BASF Fuel Cell, Inc.
High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.
Improved Catalyst Coated Membrane (CCM) Manufacturing	IRD Fuel Cells LLC
Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems Inc.
Integrated Manufacturing for Membrane Electrode Assemblies	BASF Fuel Cell, Inc.
Lifetime Improvements for PEM Fuel Cells	DuPont Fuel Cells
Low-Cost 3-10 kW Tubular SOFC Power System	Acumentrics Corporation
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-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.
Low Platinum Loading Fuel Cell Electrocatalysts	BNL
Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
Manufacturing of Low-Cost, Durable MEAs	W.L. Gore and Associates, Inc.
Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers	W.L. Gore and Associates, Inc.
Membranes and MEAs for Dry, Hot Operating Conditions	3M Company
Nitrided Metallic Bipolar Plates for PEM Fuel Cells	ORNL
Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation
Platinum and Fluoropolymer Recovery from PEM Fuel Cells	Ion Power, Inc.

Technologies highlighted in red are commercial and blue are emerging.

Fuel Cell Technologies (Cont'd)

Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC
Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports	BNL
Portable Reformed Methanol Fuel Cells	UltraCell Corporation
PowerEdge™ Fuel Cell System	Nuvera Fuel Cells, Inc.
PureMotion® Model 120 Fuel Cell Power Plant	ClearEdge Power
Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC
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.
Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.
Solid Oxide Fuel Cell Auxiliary Power Unit	Delphi Corporation
Ultra-Low Platinum Alloy Cathode Catalysts for PEM Fuel Cells	University of South Carolina
Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture	Rensselaer Polytechnic Institute

Technologies highlighted in red are commercial and blue are emerging.

Production/Delivery Technologies

Technology Title	Company
Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC
Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC
Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas (ITM Syngas)	Air Products and Chemicals, Inc.
Composite Pipeline Technology for Hydrogen Delivery	ORNL
Efficient, Low-Cost Hydrogen Generation from Renewable Energy	Proton Energy Systems, Inc.
Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.
FuelGen® Hydrogen Fueling Systems	Proton Energy Systems, Inc.
H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	GreenField Compression
High Performance Palladium-Based Membrane	Pall Corporation
HRS-100™ Hydrogen Recycling System	H2Pump, LLC
Hydrogen By Wire — Home Fueling System	Proton Energy Systems, Inc.
Hydrogen Distributed Production System	Air Liquide Process and Construction, Inc.
Hydrogen Gas Sensing System	Intelligent Optical Systems, Inc.
Hydrogen Generation from Electrolysis	Proton Energy Systems, Inc.
Hydrogen Production for Refineries	TDA Research
Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.
Hydrogen Safety Sensor for Energy Applications	NexTech Materials, Ltd.
Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.
Integrated Short Contact Time Hydrogen Generator	GE Global Research Center
Leak Detection and Hydrogen Sensor Development	LANL
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage	Proton Energy Systems, Inc.
Materials Solutions for Hydrogen Delivery in Pipelines	Secat, Inc.
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.
MEMS Hydrogen Sensor for Leak Detection	ORNL
Nanoscale Water Gas Shift Catalysts	NexTech Materials, Ltd.
Nanotube Array Photocatalysts	Synkera Technologies, Inc.
Novel Catalytic Fuel Reforming	InnovaTek, Inc.
Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.
PEM Electrolyzer Incorporating Low-Cost Membrane	Giner Electrochemical Systems, LLC
Photoelectrochemical Hydrogen Production	MVSystems, Inc.
Renewable Electrolysis Integrated System Development and Testing	NREL
Reversible Liquid Carriers	Air Products and Chemicals, Inc.
Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corporation
TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Lincoln Composites, Inc.
Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi	Giner Electrochemical Systems, LLC

Technologies highlighted in red are commercial and blue are emerging.

Storage Technologies

Technology Title	Company
Electrochemical Reversible Formation of Alane	SRNL
Hydrogen Composite Tanks	Quantum Technologies, Inc.
Hydrogen Storage in Cryo-Compressed Vessels	LLNL
Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers LLC
Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	ORNL
Manufacturing Technologies for Low-Cost Hydrogen Storage Vessels	Quantum Fuel System Technologies Worldwide, Inc.
Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites Inc.
Sodium Silicide (NaSi) Hydrogen Generation System	SiGNa Chemistry, Inc.

Technologies highlighted in red are commercial and blue are emerging.

Appendix B:
Patent Status Lists

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,481,227	07/09/13	3M Company	Proton conducting materials	Fuel cell membrane materials with an increased number of strong acid groups created in some embodiments by reaction of these acid-containing molecules with acid-containing organic molecules, metal oxide or phosphate particles, metal salts, heteropolyacids, and the like.	Still being used in ongoing research efforts. Part of a commercial fuel cell technology project.
8,465,858	06/18/13	University of South Carolina	Development of a novel method for preparation of PEMFC electrodes	A method for preparation of membrane electrode assemblies that is based on pulse electrodeposition.	Research complete - licensed/ seeking to license. Part of an emerging fuel cell technology project.
8,420,271	04/16/13	General Motors Corporation	Method to improve reliability of a fuel cell system using low performance cell detection at low power operation	A system and method for detecting a low performing cell in a fuel cell stack using measured cell voltages. The method includes determining that the fuel cell stack is running, the stack coolant temperature is above a certain temperature and the stack current density is within a relatively low power range.	Licensed to Honda.
8,415,070	04/09/13	E.I. du Pont de Nemours and Company	Partially Fluorinated Cyclic Ionic Polymers and Membranes	Ionic polymers are made from selected partially fluorinated dienes, in which the repeat units are cycloaliphatic. The polymers are formed into membranes.	Still being used in ongoing research efforts.
8,394,352	03/12/13	University of South Carolina	Porous metal oxide particles and their methods of synthesis	Methods for the formation of metal oxide nanoparticles that can be used in solid oxide fuel cells.	Research complete - licensed/ seeking to license.
8,394,298	03/12/13	LANL	Non-aqueous liquid compositions comprising ion exchange polymers	Compositions useful for formation of uniformly-dispersed electrodes, which in turn are useful as a component of membrane-electrode assemblies for, e.g., fuel cells, sensors and capacitors.	Still being used in ongoing research efforts.
8,329,006	12/11/12	Faraday Technology, Inc.	Electroplating cell with hydrodynamics facilitating more uniform deposition across a workpiece during plating	An apparatus for establishing more uniform deposition across one or more faces of a workpiece in an electroplating process. The apparatus employs eductors in conjunction with a flow dampener member and other measures to provide a more uniform current distribution and a more uniform metal deposit distribution as reflected in a coefficient of variability that is lower than conventional processes.	Being used in ongoing research. Part of a commercial fuel cell technology project.
8,326,477	12/04/12	General Motors Corporation	Heel and toe driving on fuel cell vehicle	A system and method for providing nearly instantaneous power in a fuel cell vehicle.	Licensed to Honda.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,323,809	12/04/12	3M Company	Fuel cell electrolyte membrane with basic polymer	An electrolyte membrane comprising an acid and a basic polymer, where the acid is a low-volatile acid that is fluorinated and is either oligomeric or non-polymeric, and where the basic polymer is protonated by the acid and is stable to hydrolysis.	Still being used in ongoing research efforts. Part of a commercial fuel cell technology project.
8,308,989	11/13/12	BNL	Electrocatalyst for oxygen reduction with reduced platinum oxidation and dissolution rates	Methods for preventing the oxidation of the platinum electrocatalyst in the cathodes of fuel cells by use of platinum-metal oxide composite particles.	Still being used in research and seeking to license. Part of an emerging fuel cell technology project.
8,304,122	11/06/12	Protonex Technology Corporation	Solid oxide fuel cell systems with hot zones having improved reactant distribution	A solid oxide fuel cell system having a hot zone with a center cathode air feed tube for improved reactant distribution, a catalytic partial oxidation reactor attached at the anode feed end of the hot zone with a tail gas combustor at the opposing end for more uniform heat distribution, and a counter-flow heat exchanger for efficient heat retention.	Being used in ongoing research.
8,278,011	10/02/12	Nanosys, Inc.	Nanostructured catalyst supports	Silicon carbide nanostructures that can be used as catalyst supports in membrane electrode assemblies and in fuel cells.	Being used in ongoing research. Part of an emerging fuel cell technology project.
8,236,207	08/07/12	LANL	Non-aqueous liquid compositions comprising ion exchange polymers reference to related application	Compositions useful for formation of uniformly-dispersed electrodes, which in turn are useful as a component of membrane-electrode assemblies for, e.g., fuel cells, sensors and capacitors.	Still being used in ongoing research efforts.
8,227,147	07/24/12	LANL	Advanced membrane electrode assemblies for fuel cells	Method for producing polymer electrolyte membranes with improved performance and durability for fuel cell use.	Still being used in ongoing research efforts.
8,227,140	07/24/12	3M Company	Proton conducting materials	Fuel cell membrane materials with an increased number of strong acid groups created in some embodiments by reaction of these acid-containing molecules with acid-containing organic molecules, metal oxide or phosphate particles, metal salts, heteropolyacids, and the like.	Still being used in ongoing research efforts. Part of a commercial fuel cell technology project.
8,206,682	06/26/12	BASF Corporation	Method for recovering catalytic elements from fuel cell membrane electrode assemblies	A method for recovering catalytic elements from a fuel cell membrane electrode assemblies. Recovery of the membrane electrode assembly materials is achieved by converting the membranes into particulate, forming a slurry and then dissolving catalytic elements into a soluble catalytic element salt.	Research complete - company holding IP. Part of an emerging fuel cell technology project.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,197,955	06/12/12	General Electric Company	Electrolyte membrane, methods of manufacture thereof and articles comprising the same	Method to form an electrolyte membrane comprising of polyhydroxy, aromatic polyhalide and alkali metal hydroxide compounds. The process forms a porous substrate; and a crosslinked proton conductor deposited onto the porous substrate.	Still being used in ongoing research.
8,178,463	05/15/12	ANL	Highly durable nanoscale electrocatalyst based on core shell particles	A multimetallic nanoscale catalyst having a core portion enveloped by a shell portion and exhibiting high catalytic activity and improved catalytic durability	Still being used in ongoing research efforts.
8,153,324	04/10/12	Nanotek Instruments, Inc.	Controlled-release vapor fuel cell	A controlled-release fuel cell that is useful for powering small vehicles and portable electronic devices.	Being used in ongoing research.
8,137,858	03/20/12	ANL	Method of fabricating electrode catalyst layers with directionally oriented carbon support for proton exchange membrane fuel cell	A new method of preparing a membrane electrode assembly (MEA) for a PEMFC that reduces precious metal usage, eliminates the need for GDE and simplifies the design and fabrication of bipolar plates.	Still being used in ongoing research efforts.
8,129,306	03/06/12	ANL	Non-platinum bimetallic polymer electrolyte fuel cell catalysts	A polymetallic nanoparticle alloy having enhanced catalytic properties including at least one noble metal and at least one base metal, where the noble metal is preferentially dispersed near the surface of the nanoparticle and the base metal modifies the electronic properties of the surface disposed noble metal.	Research complete; seeking to license.
8,124,261	02/28/12	BASF Corporation	Process for recycling components of a PEM fuel cell membrane electrode assembly	Process for recycling components of a PEM fuel cell membrane electrode assembly. The membrane electrode assembly (MEA) of a PEM fuel cell can be recycled by dissolving the MEA with a lower alkyl alcohol solvent which separates the membrane from the anode and cathode layers of the assembly. The solution contains both the polymer membrane and noble metal catalysts which can be heated to form particulates which can then be separated by filtration.	Research complete - company holding IP. Part of an emerging fuel cell technology project.
8,114,547	02/14/12	Ford Motor Company	Fuel cell stack flow diversion	A control valve to affect the flow of compressed gas in a fuel cell system.	Being used in ongoing research.
8,101,317	01/24/12	3M Company	Durable fuel cell having polymer electrolyte membrane comprising manganese oxide	Fuel cell membrane electrode assemblies and fuel cell polymer electrolyte membranes are provided comprising manganese oxides which demonstrate increased durability.	Still being used in ongoing research efforts.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,092,954	01/10/12	3M Company	Method of making a fuel cell polymer electrolyte membrane comprising manganese oxide	Fuel cell membrane electrode assemblies and fuel cell polymer electrolyte membranes are provided comprising manganese oxides which demonstrate increased durability. Methods of making the same are provided.	Still being used in ongoing research efforts.
8,088,526	01/03/12	General Motors Corporation	Anode reactive bleed and injector shift control strategy	A system and method for correcting a large fuel cell voltage spread for a split sub-stack fuel cell system.	Licensed to Honda.
8,062,552	11/22/11	BNL	Electrocatalyst for oxygen reduction with reduced platinum oxidation and dissolution rates	Method for using platinum-metal oxide composite particles as electrocatalysts in oxygen-reducing cathodes in fuel cells. The method prevents oxidation of platinum electrocatalyst at the cathodes.	Still being used in research and seeking to license. Part of an emerging fuel cell technology project.
8,058,383	11/15/11	E.I. du Pont de Nemours and Company	Arylene-fluorinated-sulfonimide ionomers and membranes for fuel cells	Method for preparation of aromatic sulfonimide polymers for membranes in electrochemical cells. The resulting polymers are useful as cation-exchange resins which can be used for producing proton-exchange membranes for fuel cells and can be used in any application wherein cation-exchange capacity is desired. The resins may also be used as electrolytes, electrode binders, in lithium batteries in lithium salt form, and in any application requiring charge-transfer phenomena, such as components of light-emitting displays. The polymers described herein can be either homopolymers or copolymers.	Research complete - company holding IP.
8,057,949	11/15/11	Ford Motor Company	Fuel cell stack flow diversion	A control valve to affect the flow of compressed gas in a fuel cell system.	Being used in ongoing research.
8,048,548	01/11/11	BNL	Electrocatalyst for alcohol oxidation at fuel cell anodes	An electrocatalyst is used in an anode for oxidizing alcohol in a fuel cell. The electrocatalyst consists of a noble metal particle with surface clusters of SnO_2 and Rh. The noble metal particles include platinum, palladium, ruthenium, iridium, gold, and combinations thereof. In some embodiments the electrocatalyst particle cores are nanoparticles.	Still being used in research and seeking to license. Part of an emerging fuel cell technology project.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,039,160	10/18/11	Arkema Inc.	Multi-layer polyelectrolyte membrane	Method to produce multi-layer polyelectrolyte membranes containing polymeric resins, specifically fluoropolymer and non-perfluorinated polymeric resins containing ionic and/or ionizable groups (also referred to as a "polyelectrolytes"). These are useful in a variety of products such as fuel cells.	Still being used in ongoing research efforts.
8,028,842	10/04/11	Virginia Polytechnic Institute	Chlorine resistant desalination membranes based on directly sulfonated poly(arylene ether sulfone) copolymers	A method of making a hydrophilic-hydrophobic random copolymer membrane that can be used in fuel cells.	Research complete; seeking to license.
8,011,598	09/06/11	Delphi Technologies, Inc.	SOFC power system with A/C system and heat pump for stationary and transportation applications	A combined heat and power system wherein the compressor motor of a heat pump is powered by a portion of the electricity generated by a solid oxide fuel cell (SOFC), and wherein the thermal output of the heat pump is increased by abstraction of heat from the SOFC exhaust.	Still being used in ongoing research efforts. Part of an emerging fuel cell technology project.
7,981,319	07/19/11	LANL	Non-aqueous liquid compositions comprising ion exchange polymers	Compositions useful for formation of uniformly-dispersed electrodes, which in turn are useful as a component of membrane-electrode assemblies for, e.g., fuel cells, sensors and capacitors.	Still being used in ongoing research efforts.
7,955,759	06/07/11	ORNL	Metallization of bacterial cellulose for electrical and electronic device manufacture	Method for deposition of metals in bacterial cellulose and the utilization of the metallized bacterial cellulose in the construction of fuel cells and other electronic devices.	Still being used in ongoing research efforts.
7,943,266	05/17/11	General Electric Company	SOFC seal and cell thermal management	A solid oxide fuel cell module in which the cell and its peripheral gas-flow-directing components (e.g., manifold and seals) are cooled to reduce stress-inducing thermal gradients and prevent cell cracking.	Being used in continuing research at the company.
7,927,748	04/19/11	ANL	Catalytic membranes for fuel cells	A fuel cell of the present invention comprises a cathode and an anode, one or both of the anode and the cathode including a catalyst comprising a bundle of longitudinally aligned graphitic carbon nanotubes including a catalytically active transition metal incorporated longitudinally and atomically distributed throughout the graphitic carbon walls of said nanotubes.	Still being used in ongoing research efforts.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,910,653	03/22/11	E.I. du Pont de Nemours and Company	Process for the preparation of arylene fluorinated sulfonimide polymers and membranes	Polymer electrolyte membrane fuel cells (PEMFC) are expected to provide higher efficiencies, fewer environmental pollutants, and reduced operating and maintenance costs than traditional power sources. An important component of a PEMFC is a polymer electrolyte membrane (PEM). The range of potential candidates for use as membrane materials in PEMFCs is limited by a number of requirements, including chemical, thermal, and mechanical stability, high ionic conductivity, and low reactant permeability. Developments have been made in the use of sulfonic acid functionalized polymers, including membranes such as Nafion.RTM. perfluorosulfonic acid membranes.	No longer being used.
7,906,251	03/15/11	3M Company	Oxygen-reducing catalyst layer	Process for thin film deposition of oxygen-reducing catalysts on a substrate using vapor deposition and thermal treatment. The catalytic material film includes a transition metal that is substantially free of platinum.	Still being used in ongoing research.
7,902,299	03/08/11	LBNL	Single ion conductor cross-linked polymeric networks	The invention relates to the synthesis, characterization, and electrochemical response of a new type of single-ion comb-branch polymer electrolyte that can be used as a proton exchange membrane in fuel cells.	Being used in research at LBNL and seeking to license.
7,901,940	03/08/11	BASF Corporation	Method for measuring recovery of catalytic elements from fuel cells	A method for measuring the concentration of a catalytic element in a fuel cell powder. The method includes depositing a powder mixture consisting of the fuel cell powder and an internal standard material on a porous substrate, ablating a sample of the powder mixture using a laser, and vaporizing the sample using an inductively coupled plasma.	No longer being used.
7,887,927	02/15/11	Nanotek Instruments, Inc.	Highly conductive, multi-layer composite precursor composition to fuel cell flow field plate or bipolar plate	A roll-to-roll method of producing a flexible graphite-based, highly electrically conductive sheet molding compound (SMC) and SMC-based flow field or bipolar plates for use in a proton exchange membrane fuel cell.	Part of an emerging fuel cell technology project.
7,871,738	01/18/11	ANL	Nanosegregated surfaces as catalysts for fuel cells	A method of preparing a nanosegregated Pt alloy having enhanced catalytic properties. The method includes providing a sample of Pt and one or more of a transition metal in a substantially inert environment, and annealing the sample in such an environment for a period of time and at a temperature profile to form a nanosegregated Pt alloy having a Pt-skin on a surface.	Still being used in ongoing research efforts.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,868,086	01/11/11	E.I. du Pont de Nemours and Company	Arylene fluorinated sulfonimide polymers and membranes	Aromatic sulfonimide polymers that are useful in making proton exchange membranes for fuel cells.	Being used in continuing research at the company.
7,867,669	01/11/11	Giner Electrochemical Systems, LLC	Solid polymer electrolyte composite membrane comprising laser micromachined porous support	A solid polymer electrolyte composite membrane and methods of manufacturing the same.	Part of an emerging fuel cell technology project.
7,855,021	12/21/10	BNL	Electrocatalysts having platinum monolayers on palladium, palladium alloy, and gold alloy core-shell nanoparticles, and uses thereof	The invention relates to platinum-coated particles useful as fuel cell electrocatalysts. The particles are composed of a noble metal or metal alloy core at least partially encapsulated by an atomically thin surface layer of platinum atoms. The invention particularly relates to such particles having a palladium, palladium alloy, gold alloy, or rhenium alloy core encapsulated by an atomic monolayer of platinum.	Part of an emerging fuel cell technology project.
7,851,399	12/14/10	LANL	Method of making chalcogen catalysts for polymer electrolyte fuel cells	A method of making a catalyst material for use in fuel cell cathodes. The catalyst material includes a support comprising at least one transition metal and at least one chalcogen disposed on a surface of the transition metal.	Being used in continuing research at LANL.
7,838,612	11/23/10	E.I. du Pont de Nemours and Company	Arylene fluorinated sulfonimide compositions	Aromatic sulfonimide compositions that can be used to prepare polymers useful as membranes in electrochemical cells.	Still being used in ongoing research efforts.
7,838,138	11/23/10	3M Company	Fuel cell electrolyte membrane with basic polymer	A fuel cell electrolyte membrane that includes an acid and a basic polymer. The acid is a low-volatility acid that is fluorinated and is either oligomeric or non-polymeric. The basic polymer is protonated by the acid and is stable to hydrolysis. As a result, the electrolyte membrane may be used at high operating temperatures while preserving proton conductivity.	Part of a commercial fuel cell technology project.
7,829,603	11/09/10	E.I. du Pont de Nemours and Company	Stable trifluorostyrene containing compounds grafted to base polymers, and their use as polymer electrolyte membranes	Ion exchange polymers that are useful in preparing catalyst coated membranes and membrane electrode assemblies used in fuel cells.	No longer being used.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,829,194	11/09/10	ORNL	Iron-based alloy and nitridation treatment for PEM fuel cell bipolar plates	A corrosion resistant electrically conductive component that can be used as a bipolar plate in a PEM fuel cell. The plates are composed of an alloy substrate (Fe base metal with 10-30 wt. % Cr and 0.5-7 wt. % V) and a continuous surface layer of chromium nitride and vanadium nitride.	Part of an emerging fuel cell technology project.
7,824,651	11/02/10	Nanotek Instruments, Inc.	Method of producing exfoliated graphite, flexible graphite, and nano-scaled graphene platelets	A method of exfoliating a layered material (e.g., graphite and graphite oxide) to produce nano-scaled platelets having a thickness smaller than 100 nm and typically smaller than 10 nm. The invention can be used in the manufacturing of fuel cell bipolar plates.	Part of an emerging fuel cell technology project.
7,815,986	10/19/10	Arkema Inc.	Blend of ionic (co)polymer resins and matrix (co) polymers	A novel polymeric resin blend useful for forming durable and chemical-resistant films for fuel cell membranes.	No longer being used.
7,807,063	10/05/10	Giner Electrochemical Systems, LLC	Solid polymer electrolyte composite membrane comprising plasma etched porous support	A solid polymer electrolyte composite membrane and methods of manufacturing the same.	Part of an emerging fuel cell technology project.
7,803,891	09/28/10	Arkema Inc.	Blend of ionic (co)polymer resins and matrix (co)polymers	A novel polymeric resin blend useful for forming durable and chemical-resistant films for fuel cell membranes.	No longer being used.
7,803,493	09/28/10	General Electric Company	Fuel cell system with separating structure bonded to electrolyte	The invention relates to a fuel cell assembly that is sealed in an efficient way to keep the fuel and oxidant paths separated at high operating temperatures.	Being used in continuing research at the company.
7,803,477	09/28/10	ORNL	Metallization of bacterial cellulose for electrical and electronic device manufacture	A method for the deposition of metals in bacterial cellulose and for the employment of the metallized bacterial cellulose in the construction of fuel cells and other electronic devices.	Being used in continuing research at ORNL.
7,794,170	09/14/10	PNNL	Joint with application in electrochemical devices	A hermetic seal forming flexible joint for use in electrochemical devices, such as solid oxide fuel cells (SOFCs), oxygen separators, and hydrogen separators, at operating temperatures of greater than 600°C and other extreme operating conditions. The joint is comprised of metal and ceramic pats and a flexible gasket. The flexible gasket is metal, but is thinner and more flexible than the metal part.	Research Complete; Seeking to License

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,790,837	09/07/10	Virginia Polytechnic Institute	Ion-conducting sulfonated polymeric materials	Sulfonated polymers that can be formed into membranes that may be used in proton exchange membrane fuel cells.	Licensed to Battelle Memorial Institute.
7,790,314	09/07/10	Virginia Polytechnic Institute	Sulfonated polymer composition for forming fuel cell electrodes	Materials for a fuel cell membrane electrode assembly that are formed from sulfonated polymers.	Licensed to Battelle Memorial Institute.
7,785,454	08/31/10	BASF Corporation	Gas diffusion electrodes, membrane-electrode assemblies and method for the production thereof	The invention relates to the production of an improved gas diffusion electrode for fuel cells. The electrode consists of an electrically conductive web, a non-catalyzed gas diffusion layer, and a noble metal coating.	Part of a commercial fuel cell technology project.
7,781,529	08/24/10	Arkema Inc.	Blend of ionic (co)polymer resins and matrix (co) polymers	A novel polymeric resin blend useful for forming durable and chemical-resistant films for fuel cell membranes.	No longer being used.
7,781,364	08/24/10	LANL	Chalcogen catalysts for polymer electrolyte fuel cell	A cathode catalyst comprising a metal support that includes at least one transition metal and at least one chalcogen, both in elemental form. The catalyst is intended for use in polymer electrolyte membrane fuel cells and direct methanol fuel cells.	Being used in continuing research at LANL.
7,767,616	08/03/10	ANL	Aligned carbon nanotube with electro-catalytic activity for oxygen reduction reaction	A catalyst for an electro-chemical oxygen reduction reaction (ORR) of a bundle of longitudinally aligned carbon nanotubes having a catalytically active transition metal incorporated longitudinally in said nanotubes.	No longer being used in research/ no longer being pursued.
7,767,610	08/03/10	SNL	Metal nanoparticles as a conductive catalyst	A metal nanocluster composite material for use as a conductive catalyst in fuel cell electrodes. The material has noble metal nanoclusters on a carbon substrate formed within a porous zeolitic material.	Being used in continuing research at SNL.
7,763,217	07/27/10	PNNL	Rapid start fuel reforming systems and techniques	An on-board fuel processor includes a microchannel steam reforming reactor and a water vaporizer heated in series with a combustion gas. A rapid cold start can be achieved in under 30 seconds with a manageable amount of electric power consumption, making the device advantageous for use in automotive fuel cell applications.	Research complete; seeking to license.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,758,921	07/20/10	ANL	Method of fabricating electrode catalyst layers with directionally oriented carbon support for proton exchange membrane fuel cell	A method of making a membrane electrode assembly (MEA) having an anode and a cathode and a proton conductive membrane there between. A bundle of longitudinally aligned carbon nanotubes with a catalytically active transition metal incorporated in the nanotubes forms at least one portion of the MEA and is in contact with the membrane.	No longer being used in research/ no longer being pursued.
7,758,783	07/20/10	Nanotek Instruments, Inc.	Continious production of exfoliated graphite composite compositions and flow field plates	A process for continuously producing a composite composition that can be used to make fuel cell bipolar plates or flow field plates. The flow field plates have a high electrical conductivity in the plate thickness direction.	Part of an emerging fuel cell technology project.
7,737,190	06/15/10	E.I. du Pont de Nemours and Company	Process to prepare stable trifluorostyrene containing compounds grafted to base polymers using a solvent/ water mixture	A process for preparing a fluorinated ion exchange polymer that involves grafting at least one monomer derived from trifluorostyrene onto at least one base polymer in an organic solvent/water mixture. These ion exchange polymers are useful in preparing catalyst coated membranes and membrane electrode assemblies used in fuel cells.	No longer being used.
7,732,084	06/08/10	General Electric Company	Solid oxide fuel cell with internal reforming, catalyzed interconnect for use therewith, and methods	A catalyzed interconnect for placement between an anode and a current collector in a fuel cell. This interconnect improves the efficiency of internal reforming of hydrocarbon fuels in solid oxide fuel cells.	Being used in continuing research at the company.
7,709,135	05/04/10	BASF Corporation	Efficient process for precious metal recovery from cell membrane electrode assemblies	A method is provided for recovering a catalytic element from a fuel cell membrane electrode assembly. The method includes grinding the membrane electrode assembly into a powder, extracting the catalytic element by forming a slurry comprising the powder and an acid leachate adapted to dissolve the catalytic element into a soluble salt, and separating the slurry into a depleted powder and a supernatant containing the catalytic element salt.	Part of an emerging fuel cell technology project.
7,704,919	04/27/10	BNL	Elecrocatalysts having gold monolayers on platinum nanoparticle cores, and uses thereof	Gold-coated particles useful as fuel cell electrocatalysts. The particles are composed of a platinum or platinum alloy core at least partially encapsulated by an outer shell of gold or gold alloy.	Being used in continuing research at BNL and seeking to license.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,704,918	04/27/10	BNL	Synthesis of metal-metal oxide catalysts and electrocatalysts using a metal cation adsorption/ reduction and adatom replacement by more noble ones	Platinum-metal oxide composite particles and their use as electrocatalysts in oxygen-reducing cathodes and fuel cells. The invention also relates to methods of making the metal-metal oxide composites.	Being used in continuing research at BNL and seeking to license.
7,699,916	04/20/10	ANL	Corrosion-resistant, electrically-conductive plate for use in a fuel cell stack	A corrosion resistant, electrically-conductive, durable plate at least partially coated with an anchor coating and a corrosion resistant coating. Preferably, the plate is used as a bipolar plate in a proton exchange membrane (PEMFC) fuel cell stack.	Being used in continuing research efforts at ANL.
7,691,780	04/06/10	BNL	Platinum- and platinum alloy-coated palladium and palladium alloy particles and uses thereof	The invention relates to particle and nanoparticle composites useful as oxygen-reduction electrocatalysts. The particle composites are composed of a palladium or palladium-alloy particle or nanoparticle substrate coated with an atomic submonolayer, monolayer, bilayer, or trilayer of zerovalent platinum atoms.	Part of an emerging fuel cell technology project. Non-exclusive license to N.E. Chemcat Corporation.
7,691,770	04/06/10	General Electric Company	Electrode structure and methods of making same	The invention relates to a new electrode structure that improves the performance of solid oxide fuel cells.	Being used in continuing research at the company.
7,659,026	02/09/10	E.I. du Pont de Nemours and Company	Fluorinated Sulfonamide Compounds and Polymer Electrolyte Membranes Prepared Therefrom For Use In Electrochemical Cells	A fluorinated sulfonamide small molecule with an aromatic heterocyclic group, carbon atoms substituted by fluorinated sulfonamide groups and linear or branched perfluoroalkylene groups, optionally containing oxygen, chlorine, bromine, or iodine atoms. These polymers and small molecules are useful in making polymer electrode membranes, membrane electrode assemblies, and electrochemical cells, such as fuel cells.	No longer being used.
7,652,479	01/26/10	Scribner Associates, Inc.	Electrolyte measurement device and measurement procedure	A novel electrode design and measurement system that allows rapid assessment of the through-thickness resistance of bare, non-catalyzed thin electrolytes such as those used in PEM fuel cells.	Part of an emerging fuel cell technology project.

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Patent Number	Award Date	Organization	Title	Description	Status
7,648,784	01/19/10	Delphi Technologies, Inc.	Method and apparatus for controlling a fuel cell system having a variable number of parallel-connected modules	A fuel cell APU system comprising a plurality of fuel cell modules connected in parallel. Each module includes a local controller connected to a master controller that coordinates the modules to achieve a desired power output at any given time. Each module is operated within an output range to maximize efficiency of the system.	Still being used in ongoing research efforts. Part of an emerging fuel cell technology project.
7,635,534	12/22/09	BASF Corporation	Simplified process for leaching precious metals from fuel cell membrane electrode assemblies	An improved process for recovering precious metal catalysts from recycled fuel cell membrane electrode assemblies.	Part of an emerging fuel cell technology project.
7,633,267	12/15/09	Farasis Energy, Inc.	Apparatus for combinatorial screening of electrochemical materials	A high throughput combinatorial screening method and apparatus for the evaluation of electrochemical materials using a single voltage source.	No longer being used.
7,632,601	12/15/09	BNL	Palladium-cobalt particles as oxygen-reduction electrocatalysts	An electrocatalyst is provided for oxygen-reducing cathodes and fuel cells containing palladium-cobalt particles.	Part of an emerging fuel cell technology project.
7,632,595	12/15/09	General Electric Company	Compliant fuel cell system	A fuel cell assembly comprising at least one metallic component, at least one ceramic component, and a structure disposed between the metallic component and the ceramic component. The assembly is designed to withstand strain during thermal cycles.	Being used in continuing research at the company.
7,632,593	12/15/09	ANL	Bipolar plate supported solid oxide fuel cell with a sealed anode compartment	A bipolar plate supported solid oxide fuel cell with a sealed anode compartment. An improved method of sealing is provided by extending the metal seal around the entire perimeter of the cell between an electrolyte and the bipolar plate to form the anode compartment.	No longer being used in research/ no longer being pursued.
7,629,426	12/08/09	Arkema Inc.	Blend of ionic (co)polymer resins and matrix (co) polymers	A novel polymeric resin blend useful for forming durable and chemical-resistant films for fuel cell membranes.	No longer being used.
7,629,285	12/08/09	University of South Carolina	Carbon-based composite electrocatalysts for low temperature fuel cells	A process for synthesis of a low-cost, easily manufactured carbon-based composite catalyst for use in proton exchange membrane (PEM) fuel cells is provided.	Research complete - licensed/ seeking to license.
7,618,915	11/17/09	University of South Carolina	Composite catalysts supported on modified carbon substrates and methods of making the same	A method of producing a low-cost, easily manufactured carbon-based composite catalyst for use in proton exchange membrane (PEM) fuel cells is disclosed.	Research complete - licensed/ seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
7,601,216	10/13/09	BASF Corporation	Gas diffusion electrodes, membrane-electrode assemblies and method for the production thereof	The invention relates to the production of an improved gas diffusion electrode for fuel cells. A method for forming a patterned noble metal coating on a gas diffusion medium is provided.	Part of a commercial fuel cell technology project.
7,589,047	09/15/09	LANL	Composite materials and method of making	A method of depositing noble metals on a metal hexaboride support. The method permits the deposition of metallic films of controlled thickness and particle size at room temperature without using separate reducing agents. Composite materials comprising noble metal films deposited on such metal hexaborides may be used as catalysts and electrodes in fuel cells.	Being used in continuing research at LANL.
7,588,857	09/15/09	LANL	Chalcogen catalysts for polymer electolyte fuel cell	A methanol-tolerant cathode catalyst and a membrane electrode assembly for fuel cells that includes such a cathode catalyst. The cathode catalyst includes a support having at least one transition metal in elemental form and a chalcogen disposed on the support. Methods of making the cathode catalyst and membrane electrode assembly are also described.	Research complete; seeking to license.
7,588,849	09/15/09	Delphi Technologies, Inc.	Solid-oxide fuel cell system having tempering of fuel cell stacks by exhaust gas	A fuel cell system which enhances stack performance via heat exchange with exhaust gas and use of a tempering jacket space surrounding the stack.	Part of an emerging fuel cell technology project.
7,575,824	08/18/09	LANL	Method of improving fuel cell performance by removing at least one metal oxide contaminant from a fuel cell electrode	A method of removing contaminants from a fuel cell electrode. The method includes providing a getter electrode and a fuel cell catalyst electrode having at least one contaminant to a bath and applying a voltage sufficient to drive the contaminant from the fuel cell catalyst electrode to the getter electrode.	Being used in continuing research at LANL and seeking to license.
7,572,534	08/11/09	3M Company	Fuel cell membrane electrode assembly	A highly durable fuel cell membrane electrode assembly and methods of manufacturing are provided.	Part of a commercial fuel cell technology project.
7,563,532	07/21/09	E.I. du Pont de Nemours and Company	Trifluorostyrene containing compounds, and their use in polymer electrolyte membranes	A method for preparing a fluorinated ion exchange polymer by grafting a monomer onto a base polymer. These ion exchange polymers are useful in preparing catalyst coated membranes and membrane electrode assemblies for fuel cells.	No longer being used.

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Patent Number	Award Date	Organization	Title	Description	Status
7,562,588	07/21/09	Delphi Technologies, Inc.	Method and apparatus for controlling mass flow rate of recycled anode tail gas in solid oxide fuel cell system	A system for controlling the mass flow rate of anode tail gas being recycled in a solid oxide fuel cell system.	Still being used in ongoing research efforts.
7,550,223	06/23/09	LANL	Method of making metal-polymer composite catalysts	A metal-polymer-carbon composite catalyst for use as a cathode electrocatalyst in fuel cells. The catalyst includes a heteroatomic polymer, a transition metal linked to the heteroatomic polymer by one of nitrogen, sulfur, and phosphorus, and a recast ionomer dispersed throughout the heteroatomic polymer-carbon composite.	Being used in continuing research at LANL.
7,544,764	06/09/09	Virginia Polytechnic Institute	Sulfonated polymer composition for forming fuel cell electrodes	Materials for a fuel cell membrane electrode assembly that are formed from sulfonated polymers.	Licensed to Battelle Memorial Institute.
7,518,886	04/14/09	Virginia Polytechnic Institute	Multiphase soft switched DC/DC converter and active control technique for fuel cell ripple current elimination	A fuel cell having an n-phase transformer isolated phase shift DC/DC converter, a three-phase transformer isolated phase shift DC/DC converter, and/or an active current ripple control.	Research complete; seeking to license.
7,517,604	04/14/09	3M Company	Fuel cell electrolyte membrane with acidic polymer	A fuel cell electrolyte membrane that can be used at high operating temperatures while preserving proton conductivity.	Part of a commercial fuel cell technology project.
7,507,495	03/24/09	BNL	Hydrogen absorption induced metal deposition on palladium and palladium-alloy particles	Methods for producing metal-coated palladium or palladium-alloy particles, and for producing catalysts using the particles.	Being used in continuing research at BNL and seeking to license. Non-exclusive license to N.E. Chemcat Corporation.
7,473,714	01/06/09	Virginia Polytechnic Institute	Materials for use as proton conducting membranes for fuel cells	A family of polymers having pendent sulfonate moieties connected to polymeric main chain phenyl groups. These polymers can be used in proton exchange membranes for fuel cells.	Licensed to Battelle Memorial Institute.
7,456,314	11/25/08	E.I. du Pont de Nemours and Company	Partially fluorinated ionic compounds	Cation-exchange resins that are useful in making proton-exchange membranes for electrochemical cells such as fuel cells.	Still being used in ongoing research efforts.
7,449,111	11/11/08	Arkema Inc.	Resins containing ionic or ionizable groups with small domain sizes and improved conductivity	A polymer that contains at least one acrylic resin or vinyl resin having at least one ionic or ionizable group. The polymer has improved conductivity when formed into a film and can be used in fuel cell membranes.	No longer being used.

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Patent Number	Award Date	Organization	Title	Description	Status
7,419,546	09/02/08	BASF Corporation	Gas diffusion electrodes, membrane-electrode assemblies and method for the production thereof	The invention relates to the production of an improved gas diffusion electrode for fuel cells. A method for forming a noble metal coating on a gas diffusion medium is provided.	Part of a commercial fuel cell technology project.
7,396,880	07/08/08	Arkema Inc.	Blend of ionic (co)polymer resins and matrix (co) polymers	A novel polymeric resin blend useful for forming durable and chemical-resistant films for fuel cell membranes.	No longer being used.
7,373,819	05/20/08	Honeywell International Inc.	Stress sensitive humidity sensor based on a MEMS structure	A humidity sensing apparatus and method include a substrate and a MEMS structure. The MEMS structure comprises a humidity-sensitive material in association with a movable member. Changes in humidity causes movement in the MEMS structure providing an indication of humidity based on a stress within the MEMS structure.	No longer being used.
7,365,121	04/29/08	Virginia Polytechnic Institute	Highly conductive thermoplastic composites for rapid production of fuel cell bipolar plates	A low-cost method of fabricating bipolar plates for use in fuel cells that uses a wet lay process for combining graphite particles, thermoplastic fibers, and reinforcing fibers to produce a plurality of formable sheets.	Research complete; seeking to license.
7,361,729	04/22/08	Virginia Polytechnic Institute	Ion-conducting sulfonated polymeric materials	Sulfonated polymers that can be formed into membranes that may be used in proton exchange membrane fuel cells.	Licensed to Battelle Memorial Institute.
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.
7,270,906	09/18/07	Delphi Technologies, Inc.	Solid-oxide fuel cell module for a fuel cell stack	A novel fuel cell module having four sheet metal parts stamped from flat stock. The parts do not require any forming operations such as folding or dishing, and each part may have a different thickness to suit its function.	Part of an emerging fuel cell technology project.
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 suitable for use in proton exchange membrane fuel cells.	Not licensed and not being used in research at SNL.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
7,214,442	05/08/07	LANL	High specific power, direct methanol fuel cell stack	A fuel cell stack including at least one direct methanol fuel cell. A cathode manifold is used to convey ambient air to each fuel cell, and an anode manifold is used to convey liquid methanol fuel to each fuel cell.	Being used in continuing research at LANL.
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 a commercial 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.	No longer being used.
7,101,643	09/05/06	LBNL	Polymeric electrolytes based on hydrosilyation reactions	New polymer electrolytes that are prepared by in situ cross-linking of allyl functional polymers based on a hydrosilation reaction using a multifunctional silane cross-linker and an organoplatinum catalyst. The electrolyte membranes are insoluable in organic solvents and have high mechanical strength.	Being used in research at LBNL and seeking to license.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,101,527	09/05/06	Iowa State University	Mixed anion materials and compounds for novel proton conducting membranes	The present invention provides new amorphous or partially crystalline mixed anion chalcogenide compounds for use in proton exchange membranes which are able to operate over a wide variety of temperature ranges, including in the intermediate temperature range of about 100 ° C. to 300° C., and new uses for crystalline mixed anion chalcogenide compounds in such proton exchange membranes.	Being used in research at Iowa State University and seeking to license.
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 electrodialysis.	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 University and seeking to license.
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.
6,994,829	02/07/06	PNNL	Fluid processing device and method	A fluid processing unit having first and second interleaved flow paths in a cross flow configuration. The device can be used for vaporization of water, gasoline, and other fluids, and is useful for automotive fuel cell applications requiring rapid startup.	Research complete; seeking to license.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
6,960,235	11/01/05	LLNL	Chemical microreactor and method thereof	A chemical microreactor suitable for generation of hydrogen fuel from liquid sources such as ammonia, methanol, and butane through steam reforming processes when mixed with an appropriate amount of water contains capillary microchannels with integrated resistive heaters to facilitate the occurrence of catalytic steam reforming reactions.	Licensed to Bren-Tronics, Inc.; part of a commercial fuel cell technology project.
6,956,083	10/18/05	LBNL	Single ion conductor cross-linked polymeric networks	The invention relates to the synthesis, characterization, and electrochemical response of a new type of single-ion comb-branch polymer electrolyte that can be used as a proton exchange membrane in fuel cells.	Being used in research at LBNL and seeking to license.
6,926,986	08/09/05	Energy Conversion Devices, Inc.	Fuel cell with encapsulated electrodes	A fuel cell utilizing parallel flow of a hydrogen stream, an oxygen stream, and an electrolyte solution with respect to the electrodes, while maintaining mechanical support within the fuel cell. The fuel cell utilizes encapsulated electrodes to maintain a high air flow rate and low pressure throughout the fuel cell.	No longer being used.
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.
6,921,595	07/26/05	Nuvera Fuel Cells, Inc.	Joint-cycle high-efficiency fuel cell system with power generating turbine	Process for increasing the efficiency of a system comprising a fuel reformer coupled to a fuel cell. Pressurized air and heat generated by the fuel cell are used to make a pressurized air/steam mixture. The air/steam mixture is then fed as an oxidant into a fuel burner; producing a steam-containing exhaust having an expansion potential from the fuel burner; driving an expander using the expansion potential of the steam-containing exhaust; and recovering mechanical energy from the expander in excess of the energy used in compressing the pressurized air.	No longer being used in research/ no longer being pursued.

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Patent Number	Award Date	Organization	Title	Description	Status
6,916,564	07/12/05	Nuvera Fuel Cells, Inc.	High-efficiency fuel cell power system with power generating expander	A hydrogen fuel cell power system with improved efficiency comprising of a fuel cell, hydrogen gas source, compressor for creating a pressurized air stream, and a liquid supply which is heated by waste heat form the power system to produce a pressurized air and steam mixture. The pressurized air/steam mixture, which is preferably used as the oxidant in the fuel cell, is combusted with fuel in a burner to produce a high-temperature steam-laden exhaust stream. The high-temperature steam-laden exhaust stream drives an expander to produce a power output, and a power take-off from the expander uses the expander power to, for instance, drive an electrical generator, or drive other system components.	No longer being used in research/ no longer being pursued.
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.
6,861,169	03/01/05	Nuvera Fuel Cells, Inc.	Cogeneration of power and heat by an integrated fuel cell power system	Methods and apparatus for the cogeneration of power and heat from a fuel cell stack and an associated fuel processor assembly (i.e., a fuel reforming system) to provide both electricity and heating for a particular site, such as a building or a group of buildings.	No longer being used in research/ no longer being pursued.
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.
6,828,057	12/07/04	Energy Conversion Devices, Inc.	Fuel cell with framed electrodes	A fuel cell utilizing parallel flow of a hydrogen stream, an oxygen stream, and an electrolyte solution with respect to the electrodes, while maintaining mechanical support within the fuel cell. The fuel cell utilizes framed electrodes to maintain a high air flow rate and low pressure throughout the fuel cell.	Being used in ongoing research as part of Tactical Fuel Cells at Energy Technologies, Inc.
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.

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6,790,548	09/14/04	General Motors Corporation	Staged venting of fuel cell system during rapid shutdown	A venting methodology and system for rapid shutdown of a fuel cell apparatus used in a vehicle propulsion system.	Being used in continuing research at the company.
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.
6,692,851	02/17/04	General Motors Corporation	Fuel cell stack monitoring and system control	A control method for monitoring the voltage and current from a fuel cell stack.	Being used in continuing research at the company.
6,686,084	02/03/04	Hybrid Power Generation Systems, LLC	Gas block mechanism for water removal in fuel cells	An apparatus and method for removing water from the cathode side of a fuel cell.	No longer being used.
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.
6,670,305	12/30/03	ANL	Free-standing monolithic catalyst with micro-scale channel dimensions	A monolithic catalyst with micro-scale flow channels and methods of making such a monolithic catalyst.	No longer being used in research/ no longer being pursued.
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	University of 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.
6,617,065	09/09/03	Teledyne Energy Systems, Inc.	Method and apparatus for maintaining neutral water balance in a fuel cell system	A method for maintaining a neutral water balance in a fuel cell system, wherein water from the exhaust of a fuel cell stack is recycled for use in the system's humidifiers and other components. The water balance is maintained by adjusting the fuel cell stack operating temperature based on the water level in the system's water reservoir.	No longer being used.

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6,607,854	08/19/03	Honeywell International Inc.	Three-wheel air turbocompressor for PEM fuel cell systems	A fuel cell system that utilizes a pair of parallel turbines engaged to a compressor for increased system efficiency.	No longer being used.
6,602,624	08/05/03	General Motors Corporation	Control apparatus and method for efficiently heating a fuel processor in a fuel cell system	An apparatus and method for efficiently controlling the amount of heat generated by a fuel processor in a fuel cell system. A temperature error between actual and desired fuel processor temperatures is determined; this error is converted to a combustor fuel injector command signal or a heat dump valve position command signal depending upon the type of error.	Being used in continuing research at the company.
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.
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.
6,551,736	04/22/03	Teledyne Energy Systems, Inc.	Fuel cell collector plates with improved mass transfer channels	Fuel cell collector plates with new channel constructions for improving the transportation of gases to the cell's gas diffusion layers.	Research complete; seeking to license.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
6,490,812	12/10/02	PNNL	Active microchannel fluid processing unit and method of making	An active microchannel fluid processing unit.	Exclusive license to Velocys, Inc.
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.
6,455,180	09/24/02	General Motors Corporation	Flexible method for monitoring fuel cell voltage	A method for monitoring the voltage of different groups of cells (a.k.a., "clusters") within a fuel cell stack, wherein the number of cells in a cluster can be varied. The method improves fuel cell stack diagnostic monitoring by enabling identification of individual cells within the stack that are contributing to a voltage drop across the entire stack.	Being used in continuing research at the company.
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
6,451,471	09/17/02	Teledyne Energy Systems, Inc.	Conductivity fuel cell collector plate and method of fabrication	An improved method of manufacturing PEM fuel cell collector plates that increases the electrical conductivity and mechanical strength of the plates.	Research complete; seeking to license.
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.
6,436,561	08/20/02	General Motors Corporation	Methanol tailgas combustor control method	A method for controlling the power, temperature, and fuel source of a combustor used to supply heat to a fuel reformer used for generating hydrogen from liquid fuels (e.g., methanol) in on-board automotive applications.	Being used in continuing research at the company.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,416,893	07/09/02	General Motors Corporation	Method and apparatus for controlling combustor temperature during transient load changes	A method and apparatus for controlling the temperature of a combustor in an automotive fuel cell system. The method includes a fast acting air bypass valve connected in parallel with an air inlet to the combustor.	Being used in continuing research at the company.
6,413,662	07/02/02	General Motors Corporation	Fuel cell system shutdown with anode pressure control	A venting methodology and pressure sensing and vent valving arrangement for monitoring anode bypass valve operating during the normal shutdown of a fuel cell apparatus of the type used in vehicle propulsion systems.	Being used in continuing research at the company.
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.
6,395,414	05/28/02	General Motors Corporation	Staged venting of fuel cell system during rapid shutdown	A venting methodology and system for rapid shutdown of a fuel cell apparatus of the type used in a vehicle propulsion system.	Being used in continuing research at the company.
6,376,112	04/23/02	General Motors Corporation	Controlled shutdown of a fuel cell	A method is provided for the shutdown of a fuel cell system to relieve system overpressure while maintaining air compressor operation, and corresponding vent valving and control arrangement. The method and venting arrangement can be employed in a fuel cell system used for vehicle propulsion.	Being used in continuing research at the company.
6,372,376	04/16/02	General Motors Corporation	Corrosion resistant PEM fuel cell	A PEM fuel cell having electrical contact elements comprising a corrosion-susceptible substrate metal coated with an electrically conductive, corrosion-resistant polymer.	Being used in continuing research at the company.
6,306,531	10/23/01	General Motors Corporation	Combustor air flow control method for fuel cell apparatus	A method for controlling the heat output of a combustor used to provide heat to a fuel reformer in a fuel cell apparatus.	Being used in continuing research at the company.
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.
6,277,513	08/21/01	General Motors Corporation	Layered electrode for electrochemical cells	A fuel cell electrode structure consisting of a current collector sheet and first and second layers of electrode material. The electrode design improves catalyst utilization and water management.	Being used in continuing research at the company.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,268,074	07/31/01	General Motors Corporation	Water injected fuel cell system compressor	A fuel cell system that uses a dry compressor for pressurizing air supplied to the cathode side of the fuel cell. An injector sprays a controlled amount of water onto the compressor's rotor(s) to improve the energy efficiency of the compressor.	Being used in continuing research at the company.
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 Corporation	Method of controlling injection of oxygen into hydrogen-rich fuel cell feed stream	A method of operating a H_2 - O_2 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.
6,255,012	07/03/01	LANL	Pleated metal bipolar assembly	Bipolar plates for electrochemical cells are formed from conductive foils that are supported by a polymer support plate. The polymer support plate can be readily configured with flow fields during a manufacturing process, such as injection molding, without the need for machining. Likewise, the conductive foils can be stamped or corrugated to matching configurations without any need for machining. The resulting structure is inexpensive to form and is compact and lightweight.	Being used in continuing research at LANL.
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 electrodialysis.	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,207,312	03/27/01	Energy Partners, LC	Self-humidifying fuel cell	A self-humidifying polymer electrolyte membrane (PEM) fuel cell assembly that has an ion-exchange membrane interposed between hydrogen and oxygen diffusion layers to form a membrane electrode assembly (MEA).	No longer being used.
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.
6,200,536	03/13/01	PNNL	Active microchannel heat exchanger	An active microchannel heat exchanger with an active heat source and with microchannel architecture. The invention is useful as a liquid fuel vaporizer and/or a steam generator for fuel cell power systems.	Exclusive license to Velocys, Inc.
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, LC	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.
6,171,720	01/09/01	ORNL	Bipolar plate/diffuser for a proton exchange membrane fuel cell	A combination bipolar plate/diffuser fuel cell component that includes an electrically conducting solid material having a porous region and a hermetic region.	Being used in commercially available bipolar plates sold by Porvair Advanced Materials, Inc.
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 with this technology.
6,129,973	10/10/00	PNNL	Microchannel laminated mass exchanger and method of making	A microchannel mass exchanger having a first plurality of inner thin sheets and a second plurality of outer thin sheets is described. The device enables solute molecules in a solvent to pass from the solvent to a mass transfer medium in an efficient manner.	Exclusive license to Velocys, Inc.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,126,723	10/03/00	PNNL	Microcomponent assembly for efficient contacting of fluid	Method and apparatus for a microcomponent assembly that achieves state-of-the-art chemical separation via absorption and/or adsorption mechanisms. The device can be utilized as a fuel processing system in fuel-cell-powered automobiles for removal of catalyst poisons (e.g., H_2S and CO) from the fuel stream.	Exclusive license to Velocys, Inc.
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.
6,103,409	08/15/00	General Motors Corporation	Fuel cell flooding detection and correction	A method and apparatus for monitoring PEM fuel cells to detect and correct flooding.	Being used in continuing research at the company.
6,099,984	08/08/00	General Motors Corporation	Mirrored serpentine flow channels for fuel cell	A PEM fuel cell having serpentine flow field channels, wherein the input/inlet legs of each channel border the input/inlet legs of the next adjacent channels in the same flow field.	Being used in continuing research at the company.
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	Method of monitoring CO concentrations in hydrogen feed to a PEM fuel cell	The CO concentration in the H_2 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 reformate 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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,001,499	12/14/99	General Motors Corporation	Fuel cell CO sensor	The CO concentration in the H_2 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 reformate feed stream.	Being used in continuing research at the company.
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_2 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.
5,916,710	06/29/99	LBNL	Sodium cobalt bronze batteries and a method for making same	A solid state secondary battery utilizing a low cost, environmentally sound, sodium cobalt bronze electrode.	No longer being used.
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.
5,783,152	07/21/98	SRNL	Thin-film fiber optic hydrogen and temperature sensor system	A sensor probe device for monitoring of hydrogen gas concentrations and temperatures.	No longer being used in research; returned to DOE.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
5,776,624	07/07/98	General Motors Corporation	Brazed bipolar plates for PEM fuel cells	A liquid-cooled, bipolar plate separating adjacent cells of a PEM fuel cell comprising corrosion-resistant metal sheets brazed together so as to provide a passage between the sheets through which a dielectric coolant flows.	Being used in continuing research at the company.
5,763,113	06/09/98	General Motors Corporation	PEM fuel cell monitoring system	A method and apparatus for monitoring the performance of PEM fuel cells. Outputs from a cell/stack voltage monitor and a cathode exhaust gas hydrogen sensor are corrected for stack operating conditions, and then compared to predetermined levels of acceptability.	Being used in continuing research at the company.
5,743,646	04/28/98	General Motors Corporation	Temperature sensor with improved thermal barrier and gas seal between the probe and housing	An improved temperature sensor that can be used to measure gas temperature in automotive exhaust systems or in fuel cell subsystems used to generate electric power.	Being used in continuing research at the company.
5,707,755	01/13/98	General Motors Corporation	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	General Motors Corporation	Composite fuel cell membranes	A bilayer or trilayer composite ion exchange membrane suitable for use in a fuel cell. The composite membrane has a high equivalent weight thick layer in order to provide sufficient strength and low equivalent weight surface layers for improved electrical performance.	Being used in continuing research at the company.
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.
5,624,769	04/29/97	General Motors Corporation	Corrosion resistant PEM fuel cell	A PEM fuel cell having electrical contact elements (e.g., bipolar plates) that consist of a titanium-nitride-coated, lightweight metal core, with a passivating, protective metal layer between the core and the titanium nitride.	Being used in continuing research at the company.
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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
5,558,961	09/24/96	LBNL	Secondary cell with orthorhombic alkali metal/ manganese oxide phase active cathode material	An alkali metal manganese oxide secondary cell that can provide a high rate of discharge, cycling capabilities, stability of the cathode material, high specific energy (energy per unit of weight) and high energy density (energy per unit volume).	No longer being used.
5,443,601	08/22/95	LBNL	Method for intercalating alkali metal ions into carbon electrodes	A low cost, relatively flexible, carbon electrode for use in a secondary battery. Methods for producing the electrode are also provided, including intercalating alkali metal salts such as sodium and lithium into carbon.	No longer being used.
5,316,871	05/31/94	General Motors Corporation	Method of making membrane-electrode assemblies for electrochemical cells and assemblies made thereby	A method of making a combination, unitary, membrane and electrode assembly having a solid polymer electrolyte membrane, and first and second electrodes at least partially embedded in opposed surfaces of the membrane.	Being used in continuing research at the company.
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 ca catalyst chamber, a variable speed fan, and a combustion chamber.	Not licensed and not being used for research at LANL.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,492,595	07/23/13	Virent Energy Systems, Inc.	Methods and systems for generating polyols	Methods for generating propylene glycol, ethylene glycol and other polyols, diols, ketones, aldehydes, carboxylic acids and alcohols using hydrogen produced from biomass.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).
8,455,382	06/04/13	Air Products & Chemicals, Inc.	Fabrication of catalyzed ion transport membrane systems	A process for fabricating a catalyzed ion transport membrane having essentially constant oxygen stoichiometry and no anion mobility.	Still being used in ongoing research efforts.
8,410,183	04/02/13	Virent Energy Systems, Inc.	Method for producing bio-fuel that integrates heat from carbon-carbon bond-forming reactions to drive biomass gasification reactions	A low-temperature catalytic process for converting biomass (preferably glycerol recovered from the fabrication of bio-diesel) to synthesis gas (i.e., H_2/CO gas mixture) in an endothermic gasification reaction.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).
8,397,508	03/19/13	University of Colorado	Metal ferrite spinel energy storage device and methods for making and using same	Metal ferrite spinel coatings are provided on substrates, preferably by using an atomic layer deposition process. The coatings are able to store energy such as solar energy, and to release that stored energy, via a redox reaction. The coating is first thermally or chemically reduced. The reduced coating is then oxidized in a second step to release energy and/or hydrogen, carbon monoxide or other reduced species.	Licensed to ALD NanoSolutions, Inc.
8,349,151	1/8/13	Giner Electrochemical Systems, LLC	Universal cell frame for high-pressure water electrolyzer and electrolyzer including the same	A universal cell frame generic for use as an anode frame and as a cathode frame in a water electrolyzer.	Being used in ongoing research. Part of an emerging hydrogen production technology project.
8,349,035	01/08/13	ANL	Autothermal and partial oxidation reformer-based fuel processor, method for improving catalyst function in autothermal and partial oxidation reformer-based processors	Segmented catalyst systems for reforming fuels for use in fuel cells.	Still being used in ongoing research efforts.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,323,614	12/04/12	University of South Carolina	Hydrolysis reactor for hydrogen production	A novel reactor configuration and method for delivering a hydride to a reaction zone in a manner that enables rapid reaction with water to produce hydrogen.	Research complete - licensed/seeking to license.
8,262,755	09/11/12	Air Products & Chemicals, Inc.	Staged membrane oxidation reactor system	An ion transport membrane oxidation system comprising two or more membrane oxidation stages, each stage comprising a reactant zone, an oxidant zone, one or more ion transport membranes separating the reactant zone from the oxidant zone, a reactant gas inlet region, a reactant gas outlet region, an oxidant gas inlet region, and an oxidant gas outlet region.	Still being used in ongoing research efforts.
8,231,857	07/31/12	Virent Energy Systems, Inc.	Catalysts and methods for reforming oxygenated compounds	Catalysts and methods that can reform aqueous solutions of oxygenated compounds such as ethylene glycol, glycerol, sugar alcohols, and sugars to generate products such as hydrogen and alkanes.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).
8,231,697	07/31/12	PNNL	Rapid start fuel reforming systems and techniques	An on-board fuel processor includes a microchannel steam reforming reactor and a water vaporizer heated in series with a combustion gas.	Research complete; seeking to license.
8,226,750	07/24/12	Genesis Fueltech, Inc.	Hydrogen purifier module with membrane support	Hydrogen purifier utilizing a hydrogen-permeable membrane to purify hydrogen from mixed gases containing hydrogen. A purifier module with improved mechanical support for the permeable membrane is described, enabling forward or reverse differential pressurization of the membrane.	Research complete -seeking to license.
8,210,360	07/03/12	Synkera Technologies, Inc.	Composite membranes and methods for making same	Composite membranes that are adapted for separation, purification, filtration, analysis, reaction and sensing. The composite membranes can include a porous support structure having elongate pore channels extending through the support structure.	Being used in ongoing research.
8,198,486	06/12/12	Virent Energy Systems, Inc.	Methods and systems for generating polyols	Methods for generating propylene glycol, ethylene glycol and other polyols, diols, ketones, aldehydes, carboxylic acids and alcohols using hydrogen produced from biomass.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,187,731	05/29/12	University of Colorado	Metal ferrite spinel energy storage devices and methods for making and using same	Metal ferrite spinel coatings are provided on substrates, preferably by using an atomic layer deposition process. The coatings are able to store energy such as solar energy, and to release that stored energy, via a redox reaction. The coating is first thermally or chemically reduced. The reduced coating is then oxidized in a second step to release energy and/or hydrogen, carbon monoxide or other reduced species.	Licensed to ALD NanoSolutions, Inc.
8,172,913	05/08/12	Intelligent Energy, Inc.	Array of planar membrane modules for producing hydrogen	Membrane reactor containing planar membrane modules with top and bottom thin foil membranes supported by both an intermediary porous support plate and a central base which has both solid extended members and hollow regions or a hollow region whereby the two sides of the base are in fluid communication. The membrane reactor operates at elevated temperatures for generating hydrogen from hydrogen rich feed fuels.	Still being used in ongoing research.
8,153,698	04/10/12	Virent Energy Systems, Inc.	Method for producing bio-fuel that integrates heat from carbon-carbon bond-forming reactions to drive biomass gasification reactions	A low-temperature catalytic process for converting biomass (preferably glycerol recovered from the fabrication of bio-diesel) to synthesis gas (i.e., H_2/CO gas mixture) in an endothermic gasification reaction.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).
8,148,583	04/03/12	Air Products & Chemicals, Inc.	Feed gas contaminant removal in ion transport membrane systems	An oxygen ion transport membrane process wherein a heated oxygen-containing gas having one or more contaminants is contacted with a reactive solid material to remove the one or more contaminants.	Still being used in ongoing research efforts.
8,110,022	02/07/12	Genesis Fueltech, Inc.	Hydrogen purifier module and method for forming the same	A hydrogen purifier utilizing a hydrogen permeable membrane, and a gas-tight seal, where the seal is uses a low temperature melting point metal, which forms a seal when heated above the melting point which is greater than the purifier operating temperature. The purifier is constructed such that a degree of isolation exists between the metal that melts to form the seal and the active area of the purifier membrane, so that the active area of the purifier membrane is not corrupted.	Research complete -seeking to license.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,088,261	01/03/12	Gas Technology Institute	CuCl thermochemical cycle for hydrogen production	This invention relates to a method and apparatus for electrochemically producing high porosity, high activity copper powders for high-temperature thermochemical water splitting.	Still being used in ongoing research.
8,070,860	12/06/11	United Technologies Corporation	Pd membrane having improved H_2-permeance, and method of making	Improved palladium membranes for the separation of hydrogen from a gas stream.	Being used in ongoing research.
8,002,854	08/23/11	University of Central Florida	Thermocatalytic process for CO_2-free production of hydrogen and carbon from hydrocarbons	Process and apparatus for sustainable CO_2-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. The apparatus and thermocatalytic process improve the activity and stability of carbon catalysts during the thermocatalytic process and produce both high purity hydrogen (at least, 99.0 volume %) and carbon, from any hydrocarbon fuel, including sulfurous fuels. The process and apparatus can be conveniently integrated with any type of fuel cell to generate electricity.	Research complete; seeking to license.
7,989,664	08/02/11	Virent Energy Systems, Inc.	Methods and systems for generating polyols	Methods for generating propylene glycol, ethylene glycol and other polyols, diols, ketones, aldehydes, carboxylic acids and alcohols using hydrogen produced from biomass.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).
7,988,925	08/02/11	ANL	Fuel processing device	An improved fuel processor for fuel cells is provided whereby the startup time of the processor is less than sixty seconds and can be as low as 30 seconds, if not less. A rapid startup time is achieved by either igniting or allowing a small mixture of air and fuel to react over and warm up the catalyst of an autothermal reformer (ATR).	Still being used in ongoing research efforts.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,981,261	07/19/11	ANL	Integrated device and substrate for separating charged carriers and reducing photocorrosion and method for the photoelectrochemical production of electricity and photocatalytic production of hydrogen	A system for separating oppositely-charged charge carriers that can be used for producing electricity or hydrogen gas.	Still being used in ongoing research efforts.
7,951,283	05/31/11	INL	High temperature electrolysis for syngas production	A method for producing at least one syngas component that involves directly exposing water and carbon dioxide to heat generated by a nuclear power source.	No longer being used in research/no longer being pursued.
7,947,116	05/24/11	Eltron Research & Development, Inc.	Hydrogen separation process	Method for separating a hydrogen-rich product stream from a feed stream comprised of hydrogen and at least one carbon-containing gas, at an inlet pressure greater than atmospheric pressure and a temperature greater than 200°C, to a hydrogen separation membrane system that is selectively permeable to hydrogen, and producing a hydrogen-rich permeate product stream on the permeate side of the membrane and a carbon dioxide-rich product raffinate stream on the raffinate side of the membrane.	Still being used in ongoing research.
7,939,026	05/10/11	INL	Apparatus for chemical synthesis	A method and apparatus for forming a chemical hydride which includes a pseudo-plasma-electrolysis reactor which is operable to receive a solution capable of forming a chemical hydride and includes a cathode and a movable anode. The anode is moved into and out of fluidic, ohmic electrical contact with the solution capable of forming a chemical hydride and when energized produces an oxygen plasma which facilitates the formation of a chemical hydride in the solution.	No longer being used in research/no longer being pursued.
7,932,437	04/26/11	ORNL	Designer proton-channel transgenic algae for photobiological hydrogen production	A designer proton-channel transgenic alga for photobiological hydrogen production that is specifically designed for production of molecular hydrogen through photosynthetic water splitting.	Assigned to inventor - no longer being pursued.
7,926,793	04/19/11	PNNL	Mixing in wicking structures and the use of enhanced mixing within wicks in microchannel devices	Wicking structures and methods utilizing these structures are described. Improved results in fluid contacting processes can be achieved by enhanced mixing within a wicking layer within a microchannel.	Being used in continuing research at PNNL and seeking to license.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,914,683	03/29/11	University of Central Florida	Particles of spilled oil-absorbing carbon in contact with water	Hydrogen generator coupled to or integrated with a fuel cell for portable power applications. Hydrogen is produced via thermocatalytic decomposition (cracking, pyrolysis) of hydrocarbon fuels in oxidant-free environment. The apparatus can utilize a variety of hydrocarbon fuels, including natural gas, propane, gasoline, kerosene, diesel fuel, crude oil (including sulfurous fuels). The hydrogen-rich gas produced is free of carbon oxides or other reactive impurities, so it could be directly fed to any type of a fuel cell.	Research complete; seeking to license.
7,910,373	03/22/11	NREL	H_2O doped WO_3, ultra-fast, high-sensitivity hydrogen sensors	An improved sensor for optically detecting hydrogen gas at low concentrations. The sensor consists of a substrate, a water-doped WO_3 layer coated on the substrate, and a palladium layer coated on the water-doped WO_3 layer.	Research complete; seeking to license.
7,906,079	03/15/11	Catacel Corporation	Stackable structural reactor	A reactor including a monolith having a plurality of fins in an annular arrangement for receiving fluid flow through the reactor. The monolith is disposed within a generally cylindrical outer tube, and around a corrugated inner tube. The reactor includes a device for urging the monolith radially outward, so as to maintain contact between the monolith and the outer tube.	Part of a commercial hydrogen production technology project.
7,897,122	03/01/11	Media & Process Technology	Hybrid adsorptive membrane reactor	A hybrid adsorbent-membrane reactor in which the chemical reaction, membrane separation, and product adsorption are coupled. In the reaction chamber one or more reactants and a catalyst react in a water-gas-shift (WGS) reaction producing at least one desired product and at least one by-product. A membrane selectively permits the desired product and the by-product to pass from the chamber to an adsorbent for the by-product; and an outlet for the desired product.	Still being used in ongoing research. Part of an emerging hydrogen production technology project.
7,879,750	02/01/11	General Electric Company	Anodes for alkaline electrolysis	A method of making an anode for alkaline electrolysis cells used for the production of hydrogen.	Research complete; seeking to license.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,872,054	01/18/11	Virent Energy Systems, Inc.	Method for producing bio-fuel that integrates heat from carbon-carbon bond-forming reactions to drive biomass gasification reactions	A low-temperature catalytic process for converting biomass (preferably glycerol recovered from the fabrication of bio-diesel) to synthesis gas (i.e., H_2/CO gas mixture) in an endothermic gasification reaction.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).
7,850,838	12/14/10	Proton Energy Systems, Inc.	Cold weather hydrogen generation system and method of operation	An enclosed system that produces hydrogen gas from the electrolysis of water. Operation in cold climates is enabled by one or more heat generation devices that prevent the system's components from freezing.	Being used by Proton Energy Systems in a commercial product, FuelGen® Hydrogen Fueling Systems.
7,842,276	11/30/10	University of Central Florida	Catalysts for the evolution of hydrogen from borohydride solution	Organic pigments which can catalyze the decomposition reaction of hydrogen-rich, stabilized, borohydride solutions to generate hydrogen gas. These are useful for on-board hydrogen-consuming devices such as motor vehicles or other combustion engines. The organic pigments can be used in hydrogen generating systems and for controlling the generation of hydrogen gas from metal hydride solutions.	Research complete; seeking to license.
7,818,993	10/26/10	ANL	High-performance flexible hydrogen sensors	Single-walled carbon nanotubes (SWNTs) are decorated with metal nanoparticles to form high-performance flexible hydrogen sensors.	Still being used in ongoing research efforts.
7,771,519	08/10/10	Air Products & Chemicals, Inc.	Liners for ion transport membrane systems	An ion transport membrane system consisting of a pressure vessel, a series of planar ion transport membrane modules in the interior of the pressure vessel, a gas manifold that is in flow communication with each membrane module, and a liner within the inlet/outlet conduits to the pressure vessel and on the interior surface of the gas manifold.	Part of an emerging hydrogen production technology project.
7,767,867	08/03/10	Virent Energy Systems, Inc.	Methods and systems for generating polyols	Methods for generating propylene glycol, ethylene glycol and other polyols, diols, ketones, aldehydes, carboxylic acids and alcohols using hydrogen produced from biomass.	Being used in continuing research at the company; non-exclusive license to Equilon Enterprises, LLC (d.b.a. Shell Oil Products U.S.).

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,745,696	06/29/10	University of California - Berkeley	Suppression of TLA1 gene expression for improved solar conversion efficiency and photosynthetic productivity in plants and algae	Methods and compositions to minimize the chlorophyll antenna size of photosynthesis by decreasing TLA1 gene expression, thereby improving solar conversion efficiencies and photosynthetic productivity in plants, e.g., green microalgae, under bright sunlight conditions.	Non-exclusive license to Benson Hill Biosystems. Part of an emerging hydrogen production technology project.
7,744,733	06/29/10	Proton Energy Systems, Inc.	Gas venting system	A system for venting a moist gas stream resulting from operation of electrochemical cells within an enclosure, and for preventing the water vapor in the moist gas stream from freezing within the enclosure.	Being used by Proton Energy Systems in a commercial product, FuelGen® Hydrogen Fueling Systems.
7,736,609	06/15/10	Ergenics Corporation	Hydrogen purification system	The invention provides a system to purify hydrogen involving the use of a hydride compressor and catalytic converters combined with a process controller.	Research complete; seeking to license.
7,732,174	06/08/10	NREL	Multi-stage microbial system for continuous hydrogen production	The invention relates to a continuous H_2 production system in which photosynthetic O_2 evolution and H_2 photoproduction are separated physically in two separate bioreactors.	Being used in continuing research efforts at NREL and seeking to license.
7,722,853	05/25/10	University of Central Florida	Catalysts for the evolution of hydrogen from borohydride solution	Organic pigments which can catalyze the decomposition reaction of hydrogen-rich, stabilized, borohydride solutions to generate hydrogen gas. These are useful for on-board hydrogen-consuming devices such as motor vehicles or other combustion engines. The organic pigments can be used in hydrogen generating systems and for controlling the generation of hydrogen gas from metal hydride solutions.	Research complete; seeking to license.
7,722,757	05/25/10	ANL	Process for the production of hydrogen from water	A method and device for the production of hydrogen from water and electricity using an active metal alloy. The active metal alloy reacts with water producing hydrogen and a metal hydroxide.	No longer being used in research/no longer being pursued. DOE now owns patent.
7,703,472	04/27/10	Air Products & Chemicals, Inc.	Module isolation devices	Gas flow isolation devices for Ion Transport Membrane (ITM) modules designed for producing purified oxygen from an oxygen-containing gas (e.g., air) or for producing synthesis gas. The devices isolate the flow of gas from one module into one or more other modules that are joined together through one or more common headers.	Part of an emerging hydrogen production technology project.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,695,580	04/13/10	Air Products & Chemicals, Inc.	Method of forming a ceramic to ceramic joint	A method of forming a joint at an interface between two sintered bodies comprising metallic oxides of specific crystal structure. The method can be used to form gas-tight joints between ceramic components in an oxygen separation device.	Part of an emerging hydrogen production technology project.
7,691,775	04/06/10	University of Michigan	Reducible oxide based catalysts	The invention relates to an improved catalyst for the water gas shift reaction, which is used in the production of hydrogen. The catalyst includes a reducible oxide support and at least one noble metal fixed on the reducible oxide support.	Research complete; seeking to license.
7,682,580	03/23/10	Catacel Corporation	Catalytic reactor having radial leaves	All-metal structure, cylindrical reactor for surface catalytic reactions and/or heat exchange and avoids the low conductivity problems associated with the use of packed bed ceramic materials in the manufacture and operation of catalytic reactors. Also, the thermal mismatch between the metal and ceramic portions of prior art reactors eventually leads to pulverization of the ceramic material, thus limiting the useful life of the reactor. This design has leaves that are not spiral, but radially extend outward from the interior of the reactor to its exterior to provide improved heat transfer between the exterior and the interior of the reactor.	No licenses issued & no internal research being done with this patent
7,678,251	03/16/10	Proton Energy Systems, Inc.	System and method for detecting gas	A method for detecting the presence of a specific gas in a mixture of gases resulting from operation of an electrochemical cell.	Being used by Proton Energy Systems in a commercial product, FuelGen® Hydrogen Fueling Systems.
7,666,534	02/23/10	ANL	Electro-catalytic oxidation device for removing carbon from a fuel reformate	An electro-catalytic oxidation device (ECOD) for the removal of contaminates, preferably carbonaceous materials, from an influent comprising an ECOD anode, an ECOD cathode, and an ECOD electrolyte.	Being used in continuing research efforts at ANL.
7,658,788	02/09/10	Air Products & Chemicals, Inc.	Ion transport membrane module and vessel system with directed internal gas flow	An ion transport membrane reactor system which can be used to oxidize a reactant gas feed stream containing hydrocarbons, such as methane, and thereby produce a product gas stream containing hydrogen and carbon oxides.	Part of an emerging hydrogen production technology project.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,651,669	01/26/10	PNNL	Microsystem process networks	Various aspects and applications of microsystem process networks which can be improved by employing ortho-cascading mass, heat, or other unit process operations are described. One such application is the production of hydrogen via steam reformation of hydrocarbons.	No longer being pursued at PNNL; owned by the U.S. Department of Energy.
7,642,405	01/05/10	ORNL	Switchable photosystem-II designer algae for photobiological hydrogen production	A switchable photosystem-II (PSII) designer algae for photobiological hydrogen production. The designer transgenic algae includes at least two transgenes for enhanced photobiological H_2 production wherein a first transgene serves as a genetic switch that can control PSII oxygen evolution and a second transgene encodes for creation of free proton channels in the algal photosynthetic membrane.	No longer being used.
7,604,771	10/20/09	ANL	Thermal method for fabricating a hydrogen separation membrane on a porus substrate	A thermal method of making a hydrogen permeable composition for use in hydrogen separation membranes.	Being used in continuing research efforts at ANL.
7,591,864	09/22/09	University of Central Florida	Catalysts for the evolution of hydrogen from borohydride solution	Organic pigments which can catalyze the decomposition reaction of hydrogen-rich, stabilized, borohydride solutions to generate hydrogen gas. These are useful for on-board hydrogen-consuming devices such as motor vehicles or other combustion engines. The organic pigments can be used in hydrogen generating systems and for controlling the generation of hydrogen gas from metal hydride solutions.	Research complete; seeking to license.
7,588,626	09/15/09	Boston University	Composite mixed oxide ionic and electronic conductors for hydrogen separation	A mixed ionic and electrically conducting membrane that includes a two-phase solid state ceramic composite, wherein the first phase is an oxygen ion conductor and the second phase is an n-type electrically conductive oxide. The membrane can be used to separate hydrogen from a mixture of gases and purify it for use in fuel cells.	Research complete; seeking to license.
7,581,765	09/01/09	Air Products & Chemicals, Inc.	Seal assembly for materials with different coefficients of thermal expansion	An improved seal assembly for couplings and joints between materials with different coefficients of thermal expansion (e.g., metals and ceramics) used in high-temperature gas processing devices.	Part of an emerging hydrogen production technology project.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,575,614	08/18/09	Nuvera Fuel Cells, Inc.	Startup burner	Startup burner design to make fuel reformers with sufficient energy density suitable for automotive use. The design however, compact does not necessarily provide rapid startup. One of the limiting factors in starting up a cold reformer is heating the catalyst contained therein to a desired light off temperature. The burner produces a hot gas emission suitable for heating a catalyst (e.g., a catalyst used in an autothermal reforming (ATR)) to a desired temperature (e.g., the light-off temperature of the catalyst). Preferably the catalyst achieves the desired temperature in about three minutes or less, or more generally in about one-quarter or less of the time required to heat the catalyst without the burner.	No longer being used in research/no longer being pursued.
7,569,293	08/04/09	Nuvera Fuel Cells, Inc.	Methods and systems for efficient operation of integrated fuel cell-fuel reformer systems	Methods and related systems for determining an efficient operating state for an integrated fuel cell/fuel reformer power system. The method optimizes the efficiency of operation of a power system comprising a fuel processor and a fuel cell operating in an integrated way. The operating properties of the system components are used to for controlling and optimizing system efficiency at any desired power output level.	No longer being used in research/no longer being pursued.
7,565,743	07/28/09	Catacel Corporation	Method for insertion and removal of a catalytic reactor cartridge	Cartridge that can be used for catalytic or non-catalytic combustion and/or as a heat exchanger which can be stacked with similar cartridges in a long tube or pipe. The cartridge also requires a method of moving a cartridge into or out of a pipe, and a tool for accomplishing such a transfer.	No licenses issued & no internal research being done with this patent.
7,563,292	07/21/09	ANL	Fuel processor and method for generating hydrogen for fuel cells	A method of producing a H_2 rich gas stream includes supplying an O_2 rich gas, steam, and fuel to an inner reforming zone of a fuel processor that includes a partial oxidation catalyst and a steam reforming catalyst or a combined partial oxidation and stream reforming catalyst.	Being used in continuing research efforts at ANL.
7,559,978	07/14/09	General Electric Company	Gas-liquid separator and method of operation	A system for gas-liquid separation in electrolysis equipment used for hydrogen production.	Research complete; seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
7,556,675	07/07/09	Air Products & Chemicals, Inc.	Feed gas contaminant control in ion transport membrane systems	Methods for constructing ion transport membrane (ITM) reactor systems so that the system's metal components do not react with high-temperature mixtures of steam, methane, and/or synthesis gas, thereby preventing the production of ITM-poisoning contaminant vapors.	Part of an emerging hydrogen production technology project.
7,540,475	06/02/09	PNNL	Mixing in wicking structures and the use of enhanced mixing within wicks in microchannel devices	Wicking structures and methods utilizing these structures are described. Improved results in fluid contacting processes can be achieved by enhanced mixing within a wicking layer within a microchannel.	Being used in continuing research at PNNL and seeking to license.
7,520,917	04/21/09	PNNL	Devices with extended area structures for mass transfer processing of fluids	The invention relates to microchannel devices used for performing fluid processing and heat exchange.	Being used in continuing research at PNNL.
7,513,932	04/07/09	Air Products & Chemicals, Inc.	Planar ceramic membrane assembly and oxidation reactor system	A planar ceramic membrane assembly comprising a dense layer of mixed-conducting multi-component metal oxide material, wherein the dense layer has a first side and a second side, a porous layer of mixed-conducting multi-component metal oxide material in contact with the first side of the dense layer, and a ceramic channeled support layer in contact with the second side of the dense layer.	Part of an emerging hydrogen production technology project.
7,507,690	03/24/09	ANL	Autothermal reforming catalyst having perovskite structure	A novel fuel reforming catalyst with a perovskite structure that can be used to produce hydrogen for use in fuel cells.	Being used in continuing research efforts at ANL.
7,507,384	03/24/09	Nuvera Fuel Cells, Inc.	Preferential oxidation reactor temperature regulation	Hydrocarbon fuel reforming system for reforming a gaseous or liquid hydrocarbon fuel to produce a hydrogen-rich product stream for use in, among other things, fuel cells. A method and apparatus for selective or preferential oxidation of carbon monoxide, and particularly in the control of reactor temperature during this process is provided.	No longer being used in research/no longer being pursued.
7,501,102	03/10/09	Catacel Corporation	Reactor having improved heat transfer	A reactor or heat exchanger with an annular monolith with multiple leaves inside a cylindrical outer tube, and around a corrugated inner tube. The reactor includes a device for urging the monolith radially outward, so as to maintain contact between the monolith and the outer tube. The reactor compensates for metal creep, and virtually insures continued contact between the monolith and the outer tube for heat transfer.	No licenses issued & no internal research being done with this patent.

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Patent Number	Award Date	Organization	Title	Description	Status
7,501,101	03/10/09	PNNL	Microchannel apparatus comprising plural microchannels and methods of conducting unit operations	A microchannel apparatus comprising a header and plural flow microchannels is described in which orifices connect the header and the flow microchannels. Methods of conducting unit operations in the apparatus are also described.	Exclusive license to Velocys, Inc.
7,485,161	02/03/09	Air Products & Chemicals, Inc.	Dehydrogenation of liquid fuel in microchannel catalytic reactor	An improved process for the storage and delivery of hydrogen by the reversible hydrogenation/ dehydrogenation of an organic compound in a microchannel reactor.	Part of an emerging hydrogen production technology project.
7,472,936	01/06/09	Catacel Corporation	Tool for insertion and removal of a catalytic reactor cartridge	A reactor cartridge includes a plurality of spaced-apart monoliths, formed along a tube or other mandrel. Each monolith is formed of a pair of flat and corrugated metal strips, spirally wound around the tube. These strips could be made of solid or screen material. The corrugations are skewed, such that the monolith imparts a swirl to gases flowing through it to promote mixing of gases and better heat transfer from the exterior to the interior of the cartridge. An insertion and removal tool simplifies the procedure for stacking such cartridges in a long pipe, or for removing cartridges from the pipe. The all-metal construction facilitates heat transfer through the entire reactor, and avoids the problems associated with packed ceramic beds.	No licenses Issued & no internal research being done with this patent
7,468,092	12/23/08	Air Products & Chemicals, Inc.	Operation of mixed conducting metal oxide membrane systems under transient conditions	A method of operating an oxygen-permeable mixed conducting membrane having an oxidant feed side, an oxidant feed surface, a permeate side, and a permeate surface. The method consists of controlling the differential strain between the permeate surface and the oxidant feed surface by varying the oxygen partial pressure on either or both sides of the membrane.	Part of an emerging hydrogen production technology project.
7,434,547	10/14/08	Nuvera Fuel Cells, Inc.	Fuel fired hydrogen generator	A system that combines an IC engine with a fuel processor for hydrocarbon fuels and generates and stores hydrogen with high efficiency and low operation cost.	Still being used in ongoing research.
7,429,372	09/30/08	Air Products & Chemicals, Inc.	Hydrogen storage by reversible hydrogenation of pi-conjugated substrates	A novel process for the storage and release of hydrogen by means of a substantially reversible catalytic hydrogenation of extended pi-conjugated substrates.	Part of an emerging hydrogen production technology project.

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Patent Number	Award Date	Organization	Title	Description	Status
7,425,231	09/16/08	Air Products & Chemicals, Inc.	Feed gas contaminant removal in ion transport membrane systems	A method for purification of a gas stream containing contaminants such as volatile metal oxy-hydroxides, volatile metal oxides, and volatile silicon hydroxide. The method consists of contacting the feed gas stream with a reactive solid material in a guard bed to form a solid reaction product, after which the purified gas stream is withdrawn from the guard bed.	Part of an emerging hydrogen production technology project.
7,419,635	09/02/08	NREL	Pd/V_2O_5 device for colorimetric H_2 detection	A sensor structure for chemochromic optical detection of hydrogen gas over a wide response range.	Research complete; seeking to license.
7,367,996	05/06/08	Nuvera Fuel Cells, Inc.	Heat transfer optimization in multi shelled reformers	A hydrocarbon fuel reformers for reforming a gaseous or liquid hydrocarbon fuel into a hydrogen-enriched product stream or reformate for use in hydrogen fuel cells. The reformer consists of coaxially arranged zones, through which reactants and processed streams are cooperatively flowed to accomplish necessary reactions, preheating and thermal efficiency.	Still being used in ongoing research.
7,354,465	04/08/08	Nuvera Fuel Cells, Inc.	Device for cooling and humidifying reformate	A device for cooling and humidifying a reformate stream from a reforming reactor as well as related methods, modules and systems includes a heat exchanger and a sprayer. The heat exchanger is adapted to allow a flow of a first fluid (e.g. water) inside the conduit and to establish a heat exchange relationship between the first fluid and a second fluid (e.g. reformate from a reforming reactor) flowing outside the conduit. The sprayer is coupled to the outlet of the heat exchanger for spraying the first fluid exiting the heat exchanger into the second fluid.	No longer being used in research/no longer being pursued.
7,351,395	04/01/08	Air Products & Chemicals, Inc.	Hydrogen storage by reversible hydrogenation of pi-conjugated substrates	A novel process for the storage and release of hydrogen by means of a substantially reversible catalytic hydrogenation of extended pi-conjugated substrates.	Part of an emerging hydrogen production technology project.
7,344,576	03/18/08	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.
7,340,938	03/11/08	University of Colorado	MIS-based sensors with hydrogen selectivity	Hydrogen-selective metal-insulator-semiconductor sensors which include a layer of hydrogen-selective material.	Licensed to the Electric Power Research Institute.

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Patent Number	Award Date	Organization	Title	Description	Status
7,335,247	02/26/08	Air Products & Chemicals, Inc.	Ion transport membrane module and vessel system	An ion transport membrane reactor system which can be used to oxidize a reactant gas feed stream containing hydrocarbons, such as methane, and thereby produce a product gas stream containing hydrogen and carbon oxides.	Part of an emerging hydrogen production technology project.
7,311,755	12/25/07	Air Products & Chemicals, Inc.	Control of differential strain during heating and cooling of mixed conducting metal oxide membranes	A method of operating an oxygen-permeable mixed conducting membrane having an oxidant feed side and a permeate side. The method consists of controlling the differential strain between the oxidant feed side and the permeate side by varying the oxygen partial pressure on either or both sides of the membrane.	Part of an emerging hydrogen production technology project.
7,297,324	11/20/07	PNNL	Microchannel reactors with temperature control	Microchannel devices and methods of use are disclosed wherein a reaction microchamber is in thermal contact with a heat exchange channel. A catalyst can be provided in the microchamber in sheet form such that reactants flow by the catalyst sheet.	Exclusive license to Velocys, Inc.
7,279,027	10/09/07	Air Products & Chemicals, Inc.	Planar ceramic membrane assembly and oxidation reactor system	Planar ceramic membrane assembly comprising a dense layer of mixed-conducting multi-component metal oxide material, wherein the dense layer has a first side and a second side, a porous layer of mixed-conducting multi-component metal oxide material in contact with the first side of the dense layer, and a ceramic channeled support layer in contact with the second side of the dense layer.	Part of an emerging hydrogen production technology project.
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.
7,272,941	09/25/07	PNNL	Methods for fluid separations, and devices capable of separating fluids	A wick-containing apparatus and methods of separating fluids using wicks.	Being used in continuing research at PNNL.
7,270,905	09/18/07	PNNL	Microsystem process networks	Various aspects and applications of microsystem process networks which can be improved by employing ortho-cascading mass, heat, or other unit process operations are described. One such application is the production of hydrogen via steam reformation of hydrocarbons.	Research complete; seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
7,229,785	06/12/07	NREL	Fluorescence technique for on-line monitoring of state of hydrogen-producing microorganisms	An in situ method for external on-line monitoring of the physiological state of an algal culture inside a closed photobioreactor system to ascertain the culture's production of hydrogen.	Not licensed but still being used in research at NREL.
7,179,323	02/20/07	Air Products & Chemicals, Inc.	Ion transport membrane module and vessel system	An ion transport membrane reactor system which can be used to oxidize a reactant gas feed stream containing hydrocarbons, such as methane, and thereby produce a product gas stream containing hydrogen and carbon oxides.	Part of an emerging hydrogen production technology project.
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	University of Central Florida Research Foundation	Thermocatalytic process for CO_2-free production of hydrogen and carbon from hydrocarbons	A novel process and apparatus for sustainable CO_2-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.
7,148,389	12/12/06	University of Michigan	Selective sorbents for purification of hydrocartons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent which preferentially adsorbs thiophene and thiophene compounds. The adsorption takes place at a selected temperature and pressure, thereby producing a non-adsorbed component and a thiophene/thiophene compound-rich adsorbed component. A further method includes selective removal of aromatic compounds from a mixture of aromatic and aliphatic compounds.	Research complete; seeking to license.
7,125,540	10/24/06	PNNL	Microsystem process networks	Various aspects and applications of microsystem process networks which can be improved by employing ortho-cascading mass, heat, or other unit process operations are described. One such application is the production of hydrogen via steam reformation of hydrocarbons.	Exclusive license to Velocys, Inc.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
7,101,530	09/05/06	Air Products & Chemicals, Inc.	Hydrogen storage by reversible hydrogenation of pi-conjugated substrates	A novel process for the storage and release of hydrogen by means of a substantially reversible catalytic hydrogenation of extended pi-conjugated substrates.	Part of an emerging hydrogen production technology project.
7,094,333	08/22/06	University of Michigan	Selective sorbents for purification of hydrocartons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent which preferentially adsorbs thiophene and thiophene compounds. The adsorption takes place at a selected temperature and pressure, thereby producing a non-adsorbed component and a thiophene/thiophene compound-rich adsorbed component. A further method includes selective removal of aromatic compounds from a mixture of aromatic and aliphatic compounds.	Research complete; seeking to license.
7,094,301	08/22/06	Air Products & Chemicals, Inc.	Method of forming a joint	A method of forming a joint at an interface between two sintered bodies comprising multicomponent metallic oxides of specific crystal structure. Typical sintered bodies are an ion transport membrane (an electrolyte), ceramic tubes, and additional supporting equipment such as seals and conduits.	Part of an emerging hydrogen production technology project.
7,087,211	08/08/06	ANL	Hydrogen production by high temperature water splitting using electron conducting membranes	A device and method for separating water into hydrogen and oxygen.	No longer being used in research/no longer being pursued.
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, Inc.	Integrated reformer and shift reactor	A hydrocarbon fuel reformer for producing diatomic hydrogen gas.	Being used in the New Millenium Project.

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Patent Number	Award Date	Organization	Title	Description	Status
7,063,131	06/20/06	Nuvera Fuel Cells, Inc.	Perforated fin heat exchangers and catalytic support	Perforated fins are provided to improve the capabilities of fin and tube type heat exchangers, and to adapt them for flow outside of the tube that is essentially parallel to the axis of the tube. The fins are made of a thermally conductive material, such as metal, with perforations in the fins. The perforations allow heat exchange with the contents of a tube of a fluid flowing essentially parallel to the axis of the tube, in contrast to conventional fin-tube heat exchangers. The fins may also be bonded to a post or other securing means and inserted into the inside of a tube or other hollow body to improve efficiency of heat exchange. In addition, the fins may carry a catalyst, optionally carried on a washcoat or similar treatment to increase surface area.	No longer being used in research/no longer being pursued.
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 a commercial product, H2 ProGen, by GreenField Compression.
7,053,256	05/30/06	University of Michigan	Selective sorbents for purification of hydrocartons	A method for removing thiophene and thiophene compounds from liquid fuel includes contacting the liquid fuel with an adsorbent which preferentially adsorbs the thiophene and thiophene compounds. The adsorption takes place at a selected temperature and pressure, thereby producing a non-adsorbed component and a thiophene/thiophene compound-rich adsorbed component. The adsorbent includes either a metal or a metal cation that is adapted to form .pi.-complexation bonds with the thiophene and/or thiophene compounds, and the preferential adsorption occurs by .pi.-complexation. A further method includes selective removal of aromatic compounds from a mixture of aromatic and aliphatic compounds.	Research complete; seeking to license.
7,051,540	05/30/06	PNNL	Methods for fluid separations, and devices capable of separating fluids	A wick-containing apparatus and methods of separating fluids using wicks.	Being used in continuing research at PNNL and seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
7,033,570	04/25/06	University 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.	Licensed to Sundrop Fuels, Inc. and still being used in research at the company.
7,029,574	04/18/06	University of Michigan	Selective sorbents for purification of hydrocartons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent which preferentially adsorbs thiophene and thiophene compounds. The adsorption takes place at a selected temperature and pressure, thereby producing a non-adsorbed component and a thiophene/thiophene compound-rich adsorbed component. A further method includes selective removal of aromatic compounds from a mixture of aromatic and aliphatic compounds.	Research complete; seeking to license.
7,011,898	03/14/06	Air Products & Chemicals, Inc.	Method of joining ITM materials using a partially or fully-transient liquid phase	A method of forming a joint at an interface between two sintered bodies comprising multicomponent metallic oxides of specific crystal structure. Typical sintered bodies are an ion transport membrane (an electrolyte), ceramic tubes, and additional supporting equipment such as seals and conduits.	Part of an emerging hydrogen production technology project.
7,011,694	03/14/06	University of Kentucky	CO_2-selective membranes containing amino groups	A CO_2-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_2.	Still being used in on-going research efforts.
6,989,252	01/24/06	NREL	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.
6,986,797	01/17/06	Nuvera Fuel Cells, Inc.	Auxiliary reactor for a hydrocarbon reforming system	An integrated hydrocarbon fuel reforming system for reforming a gaseous or liquid hydrocarbon fuel to produce a hydrogen-rich product stream used in, among other things, hydrogen fuel cells. An improved integrated hydrocarbon reforming system is detailed, including, an autothermal reformer having distinct zones for partial oxidation reforming and steam reforming, an integrated shift bed for reducing carbon monoxide in the product stream, a preferential oxidation reactor, and an auxiliary reactor.	No longer being used in research/no longer being pursued.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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_2O and an oxidant, forming a fuel/H_2O/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 Company	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	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.	Licensed to Sundrop Fuels, Inc. and still being used in research at the company.
6,869,462	03/22/05	PNNL	Methods of contacting substances and microsystem contactors	The invention provides an apparatus and methods for efficiently capturing and separating fluids from gas/liquid streams. One possible application of the invention is for recycling water used in fuel cells.	Being used in continuing research at PNNL and seeking to license.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,783,742	08/31/04	Nuvera Fuel Cells, Inc.	Reactor for producing hydrogen from hydrocarbon fuels	A reformer for producing a hydrogen-rich gas with multiple reaction zones and a product gas collection space. The zones are sequentially adjacent and the flow path directs flow of the reactants in diverging directions. Divergent flow permits flow into and through a zone over more than just a single cross-sectional geometry of the zone or a single cross-section of the flow path. This technique can be used for at lower pressure for flowing the reaction stream so as to reduce the parasitic requirements of the reactor, and can also be used to increase throughput of the reactor.	Still being used in ongoing research.
6,726,893	04/27/04	ANL	Hydrogen production by high-temperature water splitting using electron-conducting membranes	A device and method for separating water into hydrogen and oxygen.	No longer being used in research/no longer being pursued.
6,723,566	04/20/04	NREL	Pd/Ni-WO_3 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.
6,713,040	03/30/04	ANL	Method for generating hydrogen for fuel cells	A method of producing a H_2 rich gas stream includes supplying an O_2 rich gas, steam, and fuel to an inner reforming zone of a fuel processor that includes a partial oxidation catalyst and a steam reforming catalyst or a combined partial oxidation and stream reforming catalyst.	Being used in continuing research efforts at ANL.
6,670,058	12/20/03	University Central Florida	Thermocatalytic process for CO_2-free production of hydrogen and carbon from hydrocarbons	A novel process for sustainable CO_2-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

Patent Number	Award Date	Organization	Title	Description	Status
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	University 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_2S) 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	University 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	University 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.	Part of an emerging hydrogen production technology project.
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.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,468,499	10/22/02	ANL	Method of generating hydrogen by catalytic decomposition of water	A method for producing hydrogen includes providing a feed stream comprising water; contacting at least one proton conducting membrane adapted to interact with the feed stream; splitting the water into hydrogen and oxygen at a predetermined temperature; and separating the hydrogen from the oxygen.	No longer being used in research/no longer being pursued.
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.
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.	Currently in licensing negotiations.
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.
6,391,484	05/21/02	General Motors Corporation	Fuel processor temperature monitoring and control	A method and system for maintaining temperature control in a fuel processor (reformer) used to produce hydrogen for a fuel cell.	Being used in continuing research at the company.
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.
6,302,402	10/16/01	Air Products & Chemicals, Inc.	Compliant high temperature seals for dissimilar materials	A high temperature, gas-tight seal is formed by utilizing one or more compliant metallic toroidal ring sealing elements, where the applied pressure serves to activate the seal, thus improving the quality of the seal. The compliant nature of the sealing element compensates for differences in thermal expansion between the materials to be sealed, and is useful in sealing a metallic member and a ceramic tube at elevated temperatures.	Part of an emerging hydrogen production technology project.
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.	Currently in licensing negotiations.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 colocated 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.
6,162,558	12/19/00	General Motors Corporation	Method and apparatus for selective removal of carbon monoxide	A method and apparatus for reducing the carbon monoxide content of a hydrogen-rich gas.	Being used in continuing research at the company.
6,132,689	10/17/00	General Motors Corporation	Multi-stage, isothermal CO preferential oxidation reactor	A multi-stage, isothermal, carbon monoxide preferential oxidation (PrOx) reactor comprising a plurality of serially arranged, catalyzed heat exchangers, each separated from the next by a mixing chamber for homogenizing the gases exiting one heat exchanger and entering the next.	Being used in continuing research at the company.
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.
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.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,114,400	09/05/00	Air Products & Chemicals, Inc.	Synthesis gas production by mixed conducting membranes with integrated conversion into liquid products	Natural gas or other methane-containing feed gas is converted to a C_5 -C_{19} hydrocarbon liquid in an integrated system comprising an oxygenative synthesis gas generator, a non-oxygenative synthesis gas generator, and a hydrocarbon synthesis process such as the Fischer-Tropsch process. The oxygenative synthesis gas generator is a mixed conducting membrane reactor system.	Part of an emerging hydrogen production technology project.
6,110,861	08/29/00	ANL	Partial oxidation catalyst	A two-part catalyst comprising a dehydrogenation portion and an oxide-ion conducting portion.	Research complete; seeking to license.
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	A 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.
5,929,286	07/27/99	ANL	Method for making hydrogen rich gas from hydrocarbon fuel	A method of forming a hydrogen rich gas from a source of hydrocarbon fuel in which the hydrocarbon fuel contacts a two-part catalyst comprising a dehydrogenation portion and an oxide-ion conducting portion.	Research complete; seeking to license.
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.
5,886,614	03/23/99	General Motors Corporation	Thin film hydrogen sensor	A thin film hydrogen sensor consisting of a flat ceramic substrate, a thin film temperature-responsive resistor, and a thin film hydrogen-responsive metal resistor.	Being used in continuing research at the company.

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Patent Number	Award Date	Organization	Title	Description	Status
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
5,637,415	06/10/97	General Motors Corporation	Controlled CO preferential oxidation	A method for controlling the supply of air to a preferential oxidation reactor in which the CO content of a hydrogen-rich gas stream is reduced.	Being used in continuing research at the company.
5,271,916	12/21/93	General Motors Corporation	Device for staged carbon monoxide oxidation	A method and apparatus for selectively oxidizing carbon monoxide in a hydrogen-rich feed stream.	Being used in continuing research at the company.
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 $LaNi_5$-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
8,426,337	12/11/12	University of Michigan	Metal salt catalysts for enhancing hydrogen spillover	A composition for hydrogen storage including receptor with hydrogen dissociating metal and metal salt doping is configured to spill over hydrogen to the receptor, and the metal salt is configured to increase the rate of the spill over of the hydrogen to the receptor.	Research complete; seeking to license.
8,372,369	02/12/13	University of Michigan	Enhancing hydrogen spillover and storage	Methods for enhancing hydrogen spillover and storage are disclosed. One embodiment of the method includes doping a hydrogen receptor with metal particles, and exposing the hydrogen receptor to ultrasonication during doping. Another embodiment includes doping a hydrogen receptor with metal particles, and exposing the doped hydrogen receptor to a plasma treatment.	Research complete; seeking to license.
8,338,330	12/25/12	University of Michigan	Chemical bridges for enhancing hydrogen storage by spillover and methods for forming the same	A composition for hydrogen storage includes a source of hydrogen atoms, a receptor, and a chemical bridge formed between the source and the receptor. The chemical bridge is formed from a precursor material. The receptor is adapted to receive hydrogen spillover from the source.	Research complete; seeking to license.
8,329,140	12/11/12	LANL	Method and system for hydrogen evolution and storage	A method and system for storing and evolving hydrogen that uses chemical compounds that can be hydrogenated to store hydrogen and dehydrogenated to evolve hydrogen. A catalyst lowers the energy required for storing and evolving hydrogen.	Still being used in ongoing research efforts.
8,268,288	09/18/12	BNL	Regeneration of aluminum hydride	Methods and materials for the formation of hydrogen storage alanes, AlH_x, where x is greater than 0 and less than or equal to 6 at reduced H_2 pressures and temperatures.	Still being used in research and seeking to license.
8,193,113	06/05/12	General Electric Company	Hydrogen storage material and related processes	A metal hydride comprising of a complex hydride and a borohydride catalyst that can be used for hydrogen storage. The borohydride catalyst comprises a BH_4 group, and a group IV metal, a group V metal, or a combination of a group IV and a group V metal.	Research complete, seeking to license.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,153,554	04/10/12	University of South Carolina	Reversible hydrogen storage materials	Process for synthesis of a complex hydride material for hydrogen storage and includes mixing a borohydride with at least one additive agent and at least one catalyst and heating the mixture at a temperature of less than about 600°C. The hydride material comprises of an alkali metal or group IIA metal, aluminum and boron. The material is capable of cyclic dehydrogenation and rehydrogenation and has a hydrogen capacity of at least about 4 weight percent.	Research complete - licensed/ seeking to license.
8,153,020	04/10/12	University of South Florida	Hydrogen-storing hydride complexes	Hydrogen storage material comprising of a complex hydride using light-weight elements or compounds.	Research complete - licensed/ seeking to license.
8,147,796	04/03/12	University of Utah	Hydrogen storage in a combined M.sub.xAlH. sub.6/M'.sub.y(NH.sub.2). sub.z system and methods of making and using the same	Reversible hydrogen storage compositions, methods for reversibly storing hydrogen, and methods of making reversible hydrogen storage compositions.	Research complete; seeking to license.
8,147,788	04/03/12	SNL	Direct synthesis of magnesium borohydride	Method of directly synthesizing an alkaline earth metal borohydride compound and a method to directly produce magnesium borohydride.	Still being used in ongoing research efforts.
8,105,974	01/31/12	SRNL	Destabilized and catalyzed borohydride for reversible hydrogen storage	Hydrogen storage materials, and with improved thermodynamic properties.	No longer being used in research/ no longer being pursued.
8,101,786	01/24/12	LANL	Energy efficient synthesis of boranes	Borane material for hydrogen storage, and an energy efficient synthesis of boranes (boron compounds having at least one B--H bond).	Still being used in ongoing research efforts.
8,076,382	12/13/11	ANL	Porous polymeric materials for hydrogen storage	Porous polymers that have a higher hydrogen storage capacity at ambient temperatures than benchmark materials.	Still being used in ongoing research efforts.
8,003,073	08/23/11	Air Products & Chemicals, Inc.	Autothermal hydrogen storage and delivery systems	Process of releasing the stored hydrogen from hydrogen carrier compositions ("carrier") for use in a fuel cell or internal combustion engine. The methods and apparatus provide a thermally self-sustaining or autothermal catalytic dehydrogenation of a carrier to supply hydrogen wherein the necessary heat for this reaction is derived, at least in part, from an accompanying exothermic dehydrogenation of the carrier.	Research complete; seeking to license.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,963,116	06/21/11	PNNL	Bulk-scaffolded hydrogen storage and releasing materials and methods for preparing and using same	Materials and processes for storing hydrogen, and uses bulk-scaffolded materials, compounds, materials, and combinations that provide storage and release of bulk quantities of hydrogen at lower release temperatures and faster release rates for operation of hydrogen-fueled on-board and off-board devices and applications.	Still being used in ongoing research.
7,951,749	05/31/11	University of Michigan	Enhancing hydrogen spillover and storage	Methods for enhancing hydrogen spillover and storage. One method includes doping a hydrogen receptor with metal particles, and exposing the hydrogen receptor to ultrasonification as doping occurs while another method dopes a hydrogen receptor with metal particles, and exposes the doped hydrogen receptor to a plasma treatment.	Research complete.
7,927,507	04/19/11	HRL Laboratories, LLC	Hydrogen storage compositions	Materials for reversible hydrogen storage that employ an alloy exhibiting reversible formation/deformation of BH_4^- anions. The materials are prepared by combining a metal hydride with a ternary alloy consisting of magnesium, boron and another metal.	Being used in continuing research at the company.
7,897,129	03/01/11	PNNL	Process for synthesis of ammonia borane for bulk hydrogen storage	The invention describes new methods for synthesizing ammonia borane, which shows promise as a chemical hydrogen storage material for fuel-cell-powered applications.	Being used in continuing research at PNNL and seeking to license.
7,846,410	12/07/10	LANL	Regeneration of polyborazylene	The invention provides methods for regenerating ammonia borane, a hydrogen storage material, from polyborazylene.	Being used in continuing research at LANL.
7,837,852	11/23/10	LANL	Energy efficient synthesis of boranes	An energy-efficient method for synthesizing boranes that are used for storing hydrogen. The boranes are prepared at close to ambient temperature without the need for thermal quenching and rapid separation, and without the energy cost of generating active metal hydrides.	Being used in continuing research at LANL.
7,790,133	09/07/10	UOP, LLC	Multi-component hydrogen storage material	A reversible hydrogen storage material that shows improved performance at low temperatures compared with binary systems such as MgH_2-$LiNH_2$.	Research complete; seeking to license.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,790,013	09/07/10	Safe Hydrogen, LLC	Storing and transporting energy	A method for safely storing and transporting energy in the form of hydrogen. Hydrogen is released from water by a process such as electrolysis. The released hydrogen is then stored and transported in a metal hydride slurry, which can be mixed with water to release the hydrogen at an end-use location.	No longer being used.
7,781,109	08/24/10	SNL	Hydrogen storage and integrated fuel cell assembly	A system in which housings for hydrogen storage materials are located in close proximity to a fuel cell stack. Heat generated from operation of the fuel cell stack is used to help drive the endothermic dehydrogenation reactions for releasing hydrogen from the storage materials.	Being used in continuing research at SNL.
7,754,641	07/13/10	General Electric Company	Hydrogen storage material and related processes	A hydrogen storage material consisting of a complex hydride and a borohydride catalyst. The catalyst improves the hydrogenation/dehydrogenation kinetics of the complex hydride.	No longer being used.
7,736,531	06/15/10	LANL	Composition and method for storing and releasing hydrogen	A chemical hydrogen storage system that couples an endothermic reaction (which releases hydrogen) to an exothermic reaction to achieve overall thermodynamic neutrality.	Being used in continuing research at LANL.
7,713,506	05/11/10	LANL	Metal aminoboranes	Metal aminoboranes of the formula $M(NH_2BH_3)_n$ have been synthesized. The aminoboranes can be dehydrogenated to form hydrogen and a reaction product. The reaction product can react with hydrogen to form a hydrogen storage material.	Being used in continuing research at LANL.
7,678,362	03/16/10	Ford Motor Company	High density hydrogen storage material	A hydrogen storage material that is a combination of $LiBH_4$ with MH_x, wherein greater than about 50% of M comprises Al.	Being used in ongoing research.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,666,807	02/23/10	SRNL	Hollow porous-wall glass microspheres for hydrogen storage	Coated hollow glass microspheres are used as part of a hydrogen storage system. The hollow glass microsphere wall defines a series of pores. The pores facilitate the placement of a hydrogen storage material within the interior of the hollow glass microsphere. The porosity of the hollow glass microspheres can be modified by either altering or reducing the overall pore size or by coating the individual hollow glass microspheres. The hydrogen storage material is sealed within the interior of the hollow glass microspheres. The coating and/or the controlled pore size enables the selective absorption of hydrogen gas through the walls of the hollow glass microsphere while isolating the hydrogen storage material encapsulated therein from other external gases and fluids.	No longer being used in research/ no longer being pursued.
7,645,902	01/12/10	LANL	Acid-catalyzed dehydrogenation of amine-boranes	A method of dehydrogenating an amine-borane using an acid-catalyzed reaction. The method may be used to generate hydrogen for portable power sources such as fuel cells.	Being used in continuing research at LANL.
7,625,547	12/01/09	Ford Motor Company	High density hydrogen storage material	A hydrogen storage material that is a combination of $LiBH_4$ with MH_x, wherein greater than about 50% of M comprises Ti, V, Cr, Sc, Fe, or combinations thereof.	Being used in ongoing research.
7,608,233	10/27/09	SNL	Direct synthesis of calcium borohydride	A method for directly preparing an alkaline earth metal borohydride, i.e. $Ca(BH_4)_2$, from the alkaline earth metal hydride and the alkaline earth metal boride. The calcium borohydride product can be used to reversibly store and release hydrogen.	Being used in continuing research at SNL.
7,544,837	06/09/09	LANL	Base metal dehydrogenation of amine-boranes	A method of dehydrogenating an amine-borane using a base metal catalyst. The method may be used to generate hydrogen for portable power sources such as fuel cells.	Being used in continuing research at LANL.
7,521,037	04/21/09	BNL	Regeneration of aluminum hydride	The invention provides methods and materials for the formation of hydrogen storage alanes, AlH_x, where x is greater than 0 and less than or equal to 6 at reduced H_2 pressures and temperatures.	Being used in continuing research at BNL and seeking to license.

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.
7,384,574	06/10/08	SRNL	Hydrogen storage material and process using graphite additive with metal-doped complex hydrides	A hydrogen storage material having improved hydrogen absorption and desorption kinetics is provided by adding graphite to a complex hydride such as a metal-doped alanate. The incorporation of graphite into the complex hydride significantly enhances the rate of hydrogen absorption and desorption and lowers the desorption temperature needed to release stored hydrogen.	Research complete; seeking to license.
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.
7,303,736	12/04/07	LLNL	Nanostructured materials for hydrogen storage	A system for hydrogen storage comprising a porous nano-structured material with hydrogen absorbed on the surfaces of the porous nano-structured material. The system of hydrogen storage comprises absorbing hydrogen on the surfaces of a porous nano-structured semiconductor material.	Research complete; seeking to license.
7,191,602	03/20/07	LLNL	Storage of H_2 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.
7,160,530	01/09/07	NREL	Metal-doped single-walled carbon nanotubes and production thereof	A method for the production of single-walled carbon nanotubes that can be used for reversibly storing hydrogen at ambient conditions with low energy input requirements.	Being used in research at NREL but no licensees.
7,094,387	08/22/06	SRNL	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 SRNL but no licensees. Part of an emerging hydrogen storage technology project.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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.	No longer being used.
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.
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 ongoing research at Vodik Labs LLC.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 power 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.	No longer being used.
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.	No longer being used.
6,262,328	07/17/01	SRNL	Container and method for absorbing and reducing hydrogen concentration	A method for absorbing hydrogen from an enclosed environment.	Being used in research at SRNL but no licensees.
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.	No longer being used.
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	SRNL	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 SRNL but no licensees.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 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	SRNL	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 SRNL but no licensees.
5,296,438	03/22/94	SRNL	Dimensionally stable metallic hydride composition	The invention relates to a metallic hydride composition that can undergo repeated hydrogen absorption/desorption cycles without disintegrating, and a process for making such a composition.	Research complete; seeking to license. Part of an emerging hydrogen storage technology project.

Appendix C:
Commercially Available Technology Descriptions

C.1 Fuel Cell Technologies

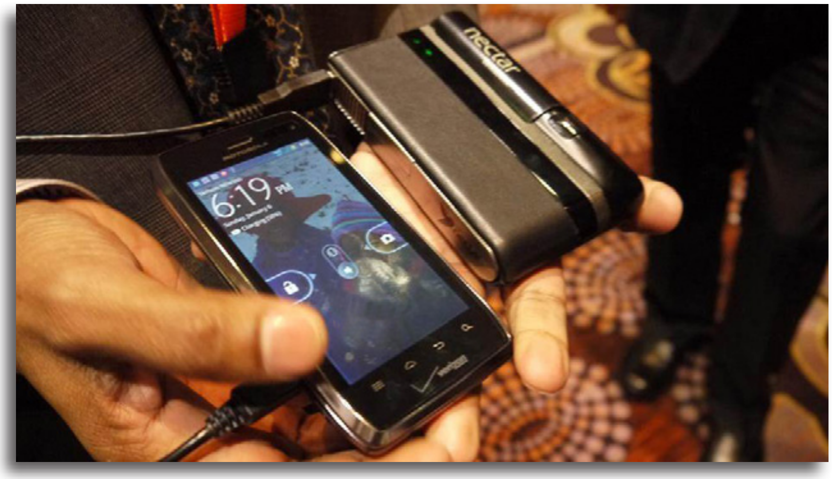
A Silicon-Based Solid Oxide Fuel Cell for Portable Consumer Electronics: nectar™

With assistance from FCTO, Lilliputian Systems, Inc. (LSI), has developed a miniature fuel cell for the consumer portable power market, the nectar™ Mobile Power System. The nectar Mobile Power System is a compact, lightweight and portable device that can power and charge many of the consumer electronic devices on the market today. Nectar uses LSI's solid oxide fuel cell (SOFC) which is fabricated on a silicon chip and is fueled by butane from an on-board pod, or cartridge. Within the fuel cell, the butane is converted into hydrogen and carbon monoxide, which react with oxygen ions to give off water, carbon dioxide, heat, and free electrons. The electrons flow through an external circuit and are used to charge a device's battery. The fuel cell is vacuum packaged to minimize heat loss. Micro solid oxide fuel cells have been approved by the Federal Aviation Administration to be carried and used by passengers aboard airline flights.[1]

Initially, nectar will plug into various portable electronics via a USB cable connection, but the company has begun development work on versions that can be incorporated directly into higher-power devices such as tablets and laptops. LSI plans to supply key components to original equipment manufacturers, who will manufacture the complete systems.

LSI's nectar Portable SOFC Butane Powered Charging System

[1] For more information: http://www.nectarpower.com/



Charging Consumer Smart Phone with nectar

Technology History
Developed by LSI in partnership with Lawrence Livermore National Laboratory, Alfred University and the Missouri University of Science and Technology.

Applications
Can be used as an alternative to conventional wall outlet and battery-based devices for charging portable consume electronics.

Capabilities
- Delivers 2.5 watts of power with a run time of more than 30 hours per cartridge.[1]
- Achieves a 5 times improvement in volumetric energy density and a 10 times increase in gravimetric energy density compared with lithium-ion battery alternatives.[1]

Benefits
Efficiency
Increases energy efficiency and reduces carbon footprint relative to using electricity provided from a wall outlet.[2]

Portability
Provides on-the-go power and eliminates the need for a wall outlet to re-charge electronic devices.

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[1] For more information: http://www.nectarpower.com/
[2] For more information: http://blog.laptopmag.com/forget-wall-adapters-completely-with-nectar-mobile-power

Bio-Fueled Solid Oxide Fuel Cells

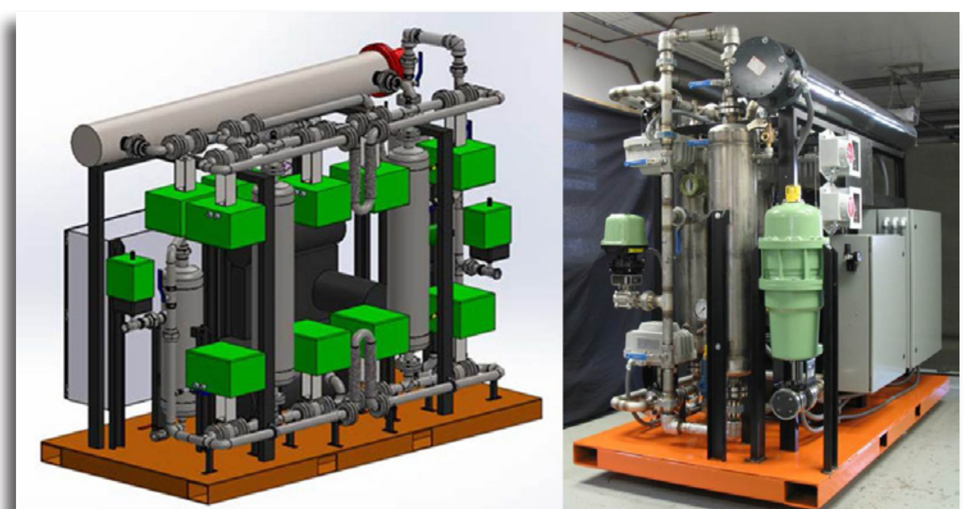
Commercial Technology

With assistance from DOE SBIR grants (Phase III Xcelerator grant) TDA Research, Inc. (TDA) has identified a catalyst for converting syngas to ethanol. TDA developed a homogeneous catalyst dissolved in an ionic liquid that aids stabilizing the catalyst to: control selectivity; and provide temperature control. The homogeneous catalytic process was optimized for economic scaleup, enabling the use of biomass-derived synthesis gas for large-scale production of ethanol. TDA have converted syngas to ethanol while minimizing production of side products like methane.

TDA have also developed, demonstrated and commercialized a sorbent, SulfaTrap™, that can remove both hydrogen sulfide and organic sulfur species from biogas, reducing their concentration < 10 parts per billion. The sorbent enables the production of a nearly sulfur-free biogas to replace natural gas in solid oxide fuel cell (SOFC) power plants while reducing greenhouse gas emissions from fossil fuels.[1] The sorbent bed operates downstream of a bulk desulfurization system as a polishing bed and removes any residual hydrogen sulfide (H_2S) and other organic sulfur species from the biogas. TDA will extend the use of the sorbent to biogas by integrating it into a 2kW SOFC system, where it will desulfurize the incoming gas, in order to prevent degradation of the fuel cell stacks and poisoning of the catalysts used in the fuel processor. The system will use a biogas from an anaerobic digester at Cal-DeNier Dairy, Grand Valley, CA. The system is an enabling technology that allows small-scale fuel cell CHP systems to operate on biogas as an alternative to natural gas and is intended for use in any industry employing anaerobic digesters, such as wastewater treatment, food processing, and agriculture applications.

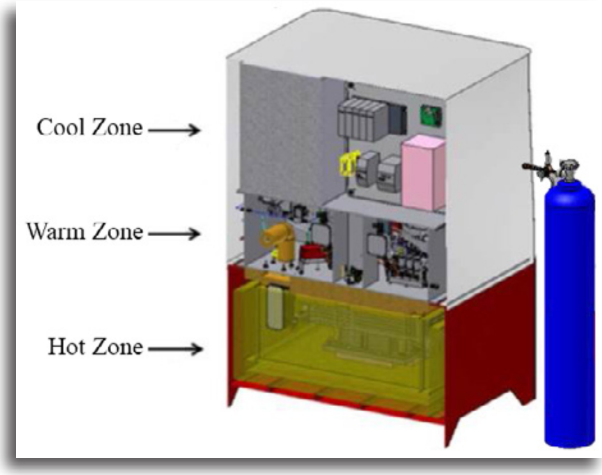
Technology History

- Developed by TDA Research Inc. (www.tda.com)
- Commercialized in 2011, available from SulfaTrap LLC (www.sulfatrap.com).



TDA's Skid-Mounted Field-Deployable Prototype Biogas Clean-Up System

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/pd091_alptekin_2013_p.pdf



2 kWe SOFC Stack Module Test Skid for Integration with Biogas Clean-Up System

Applications
Can be used for producing ultraclean biogas for use in fuel cells using opportunity fuels such as anaerobic digester gas.

Capabilities
- Provides biogas for CHP and SOFC operation in waste-to-energy applications.
- Achieves sulfur removal, up to 17.5% wt. capacity (lb. of sulfur per lb. of sorbent).[1]
- Provides regenerability, small form-factor, and reduced replacement frequency.[1]

Benefits
Cost Savings
Provides a process to produce biogas using sorbents and selective catalysts.

Energy Savings
Provides a route to ethanol from a domestic supply — cellulosic feedstock.

Environment
Enables the use of SOFC technology in waste-to-energy applications (e.g. biogas).

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/pd091_alptekin_2013_p.pdf

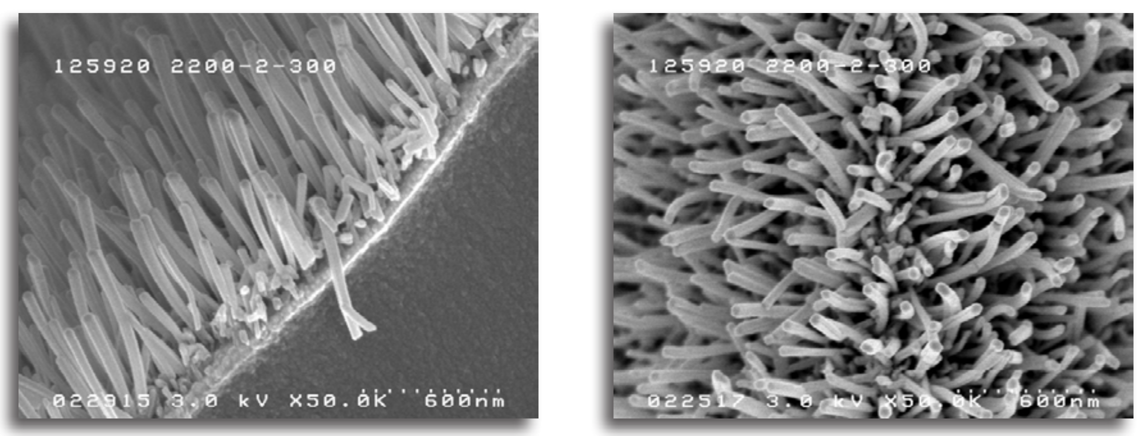
Cathode Catalysts and Supports for PEM Fuel Cells

Commercial Technology

3M Company, with assistance from FCTO, has developed a membrane electrode assembly (MEA) that demonstrates improved performance and durability for fuel cell applications.[1] The MEAs use 3M nanostructured thin film (NSTF) catalyst electrodes and a 3M ion exchange membrane to achieve high performance with less precious metal than current state-of-the-art constructions.[1] 3M uses high-volume-capable pilot line equipment to manufacture the catalyst coated membranes as roll-goods for improved quality and lower costs.[1]

3M developed MEAs that meet system operating conditions of higher temperature and low humidification, use less precious metal than current state-of the-art constructions, have improved stability and durability, and are made by processes amenable to high-volume manufacturing.[1]

The 3M NSTF catalyst support and deposition system eliminates the durability issues associated with carbon corrosion of conventional dispersed Pt supported on carbon blacks. The NSTF ternary alloy catalysts exhibit increased catalyst specific activity. New NSTF anode catalysts with microgram quantities of oxygen evolution reaction (OER) catalysts added to the already low NSTF Pt can improve the fuel cells lifetime under start-up/shut-down and degrading cell reversal events. Combined with the new 3M low equivalent weight membranes, the MEAs demonstrate an increased 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. The NSTF cathode catalysts continue to be developed and integrated with the latest 3M membranes. 3M is currently selling MEAs to select fuel cell developers for automotive, pure H_2/O_2 and electrolyzer applications.[2]



Scanning Electron Micrographs of the New NSTF Catalysts

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review08/fc_1_debe.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review13/fc006_atanasoski_2013_o.pdf

Technology History

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

Applications

Can be used in 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 high-volume compatible roll-good processes for fabricating components.
- Satisfies several DOE accelerated durability tests.[1]
- Results in higher current and power density with reduced catalyst loading.[1]

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.[1]

Durability

Eliminates carbon support degradation and improves durability under startup and shutdown conditions.[2]

Performance

Higher current density performance at lower catalyst loadings due to reduced electrode thickness.[1]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review08/fc_1_debe.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review13/fc006_atanasoski_2013_o.pdf

Compact, Multi-Fuel Solid Oxide Fuel Cell (SOFC) System

Technology Management, Inc. (TMI), with funding from FCTO through the Edison Materials Technology Center, developed an integrated reformer/solid oxide fuel cell (SOFC) system that operates on many fuels.

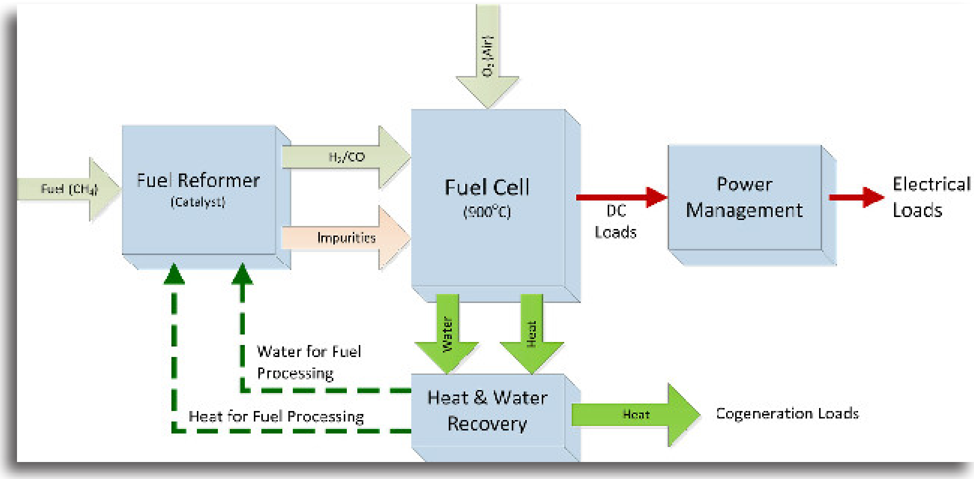
TMI's AnywherEnergy© system is used for kilowatt-class applications that require continuous power in locations where the utility grid is unreliable or unavailable or that serve as a second source of continuous power. Example applications include power for military or disaster relief teams, off-grid homes and villages, cell towers, or fortification of solar installations now using batteries and backup generators. The design allows the use of high-volume, low-cost fabrication techniques, ease of cell and stack assembly, and straight-forward thermal integration of the catalytic steam reforming with the fuel cell stack.

Technology History

- Original SOFC technology developed by Standard Oil of Ohio and acquired by TMI from British Petroleum.

- Currently engineering and field testing full-scale systems at end-user sites in preparation for manufacturing scaleup and original equipment manufacturer licensing.

TMI's AnywherEnergy System Using Multi-Fuel SOFC Technology



Key Components of TMI's AnywherEnergy System

Applications

Can be used as a primary or back-up source of clean, quiet, continuous power in locations with no or unreliable power grids.

Capabilities

- Provides continuous 24/7 power availability.[1]
- Achieves clean exhaust and quiet operation allowing indoor use.[1]
- Operates on multiple fuels including natural gas, propane, military JP-8, diesel and biofuels like biodiesel and vegetable oils.[1]
- Provides scalable power and redundancy by using multiple modules in parallel.

Benefits

Cost Savings

Offers a simple cell and system design for low-cost, automated manufacturing.

Efficiency

Provides two to three times greater efficiency than a comparable-sized diesel-driven generator.[2]

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[1] For more information: http://www.tmi-anywherenergy.com/
[2] For more information: http://www.tmi-anywherenergy.com/Market_Opportunities.html

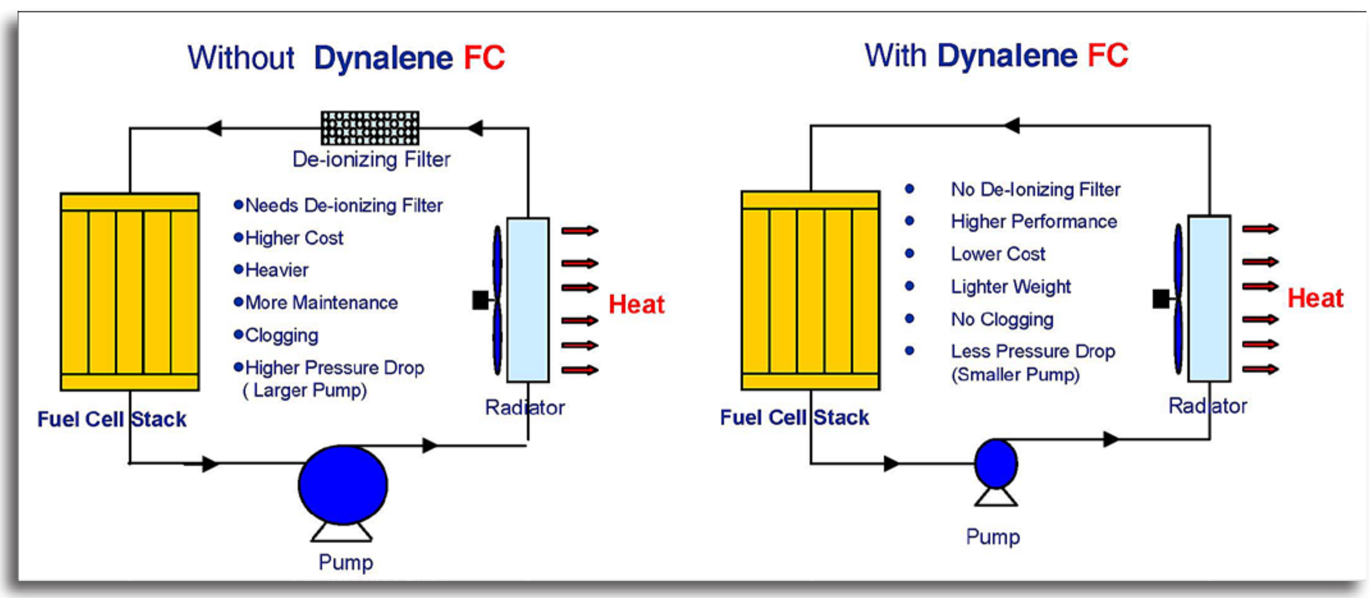
Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells

Commercial Technology

Dynalene, Inc., with funding from DOE SBIR grants, the Fuel Cell Technologies Office and private industry support, has developed a complex coolant fluid (CCF), Dynalene FC. 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 several fuel cell systems that have operated continuously for more than seven months.[1] The Dynalene FC demonstrates compatibility with common materials used in the fuel cell cooling loop.

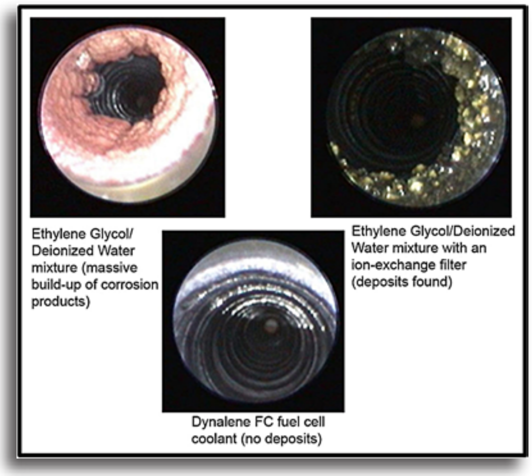
Technology History

- Developed by Dynalene, Inc., with FCT and private industry support; working on production issues centered on manufacturing the nanoparticle used in the coolant.
- Currently producing and selling Dynalene FC and Dynalene LC coolant to multiple customers for fuel cell, automotive, power systems and electronics applications.



Comparison of Basic De-Ionized Water/Glycol System with Dynalene FC System

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_j_3_mohapatra_2011.pdf



Fuel Cell Coolant Channels With and Without Dynalene FC

Applications

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

Capabilities

- Maintains low corrosion rates on stainless steel and aluminum heat exchangers as well as yellow metals such as copper and brass.[1]
- Demonstrates a lower rate of increase in electrical conductivity during continuous operation and a lower viscosity, which increases pumping efficiency.[1]
- Works to stabilize particles, which can lead to flocculation and deposition on flow channels.[1]

Benefits

Cost Savings

Eliminates the need for de-ionizing filters in fuel cells, reducing the overall cost of ownership and maintenance.[1]

Productivity

Enables fuel cells to stay on-line without frequent changing of the de-ionizing filter.[1]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_j_3_mohapatra_2011.pdf

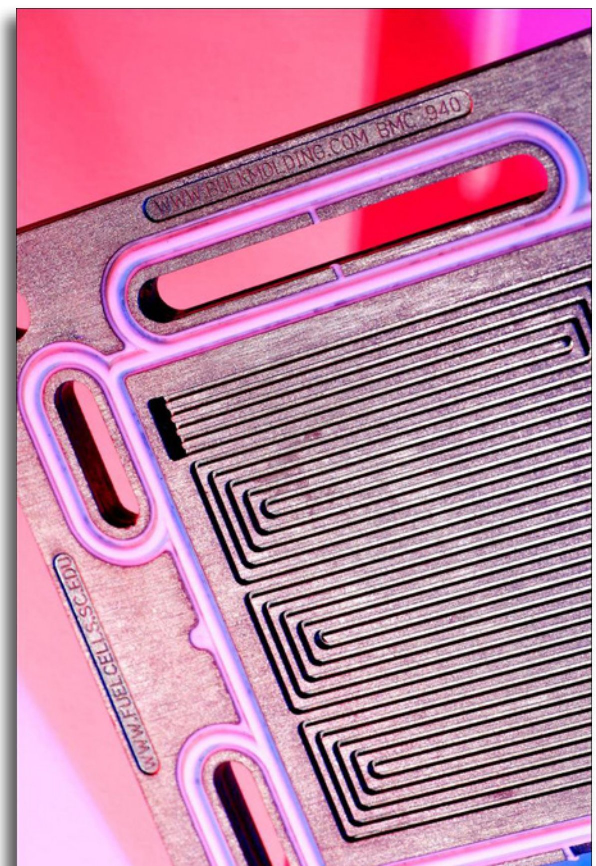
Conductive Compound for Molding Fuel Cell Bipolar Plates

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 FCTO. Initial formulations developed in 1998 and 1999 yielded some commercialization by BMCI in 2000.

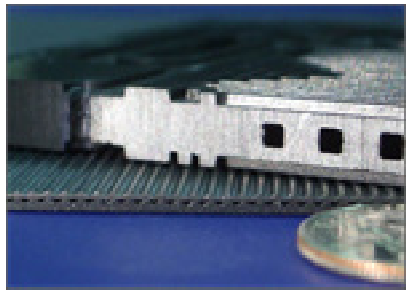
BMC 955, the latest addition to BMCI's fuel cell related product line, provides durability in the corrosive, high temperature environment of high temperature PEM applications. Based upon a phenolic resin system, it looks and processes much like BMCI's low temperature line of fuel cell products.

Technology History

- Developed and being marketed by BMCI using patented LANL technology. Adopted by several producers for stationary and transportation applications.
- Became commercially available in 2000.



Bulk Molding Compounds, Inc. (BMCI), has developed and commercialized a graphitized thermoset vinyl-ester compound for molding bipolar plates.



Decrease in Plate Thickness in Bonded Bipolar Assemblies

Applications
Can be used where bipolar plate assemblies are needed for PEM cells in stationary, automotive, and portable power. A phenolic resin version with similar appearance and moldability is now available for high temperature PEM applications.

Capabilities
- Provides improved through- and in-plane conductivity with chemical and corrosion resistance to survive the fuel cell environment.
- Uses a conductive vinyl-ester adhesive to minimize contact resistance and improve conductivity in making bipolar plate assemblies.[1]

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.[2]

Product Quality
Offers part flatness, creep resistance, and overall dimensional stability by using proven thermoset technology.[3]

Productivity
Allows for large-volume commercial production because flow and cooling channels are directly molded into the part. Reduces process cycle times while maintaining critical properties.[3]

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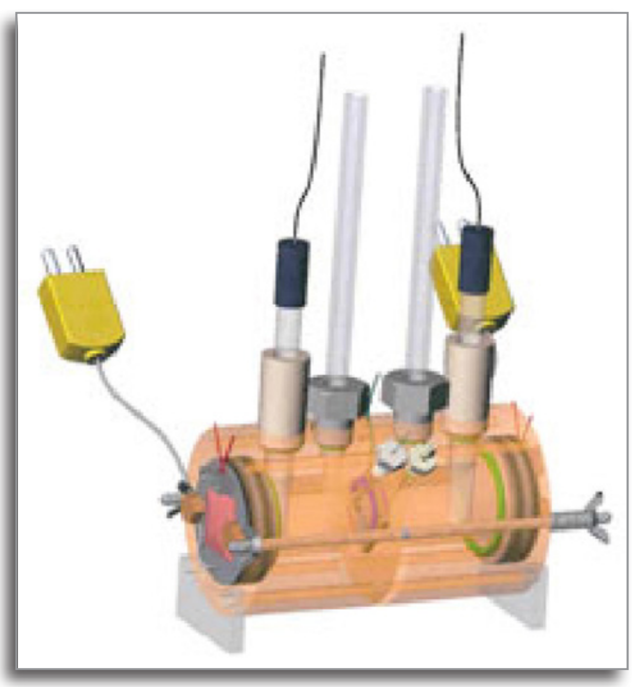
[1] For more information: http://www.bulkmolding.com/_uploads/pdf/spepaperII.pdf
[2] For more information: http://www.google.com/patents/US6248467
[3] For more information: http://www.bulkmolding.com/datasheets/informational/BMC_940.pdf

Corrosion Test Cell for PEM Bipolar Plate Materials

Fuel cells are composed of multiple bipolar plates (BPPs). 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 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 FCTO. 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 by Fuel Cell Technologies.

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.[1]

Benefits

Cost Savings

Reduces costs by using corrosion cells and accessory equipment rather than the traditional fuel cell test stands.[1]

Efficiency

Allows materials to be screened without fabrication of BPPs and multiple cells to screen multiple materials at the same time, reducing development time.[1]

Versatility

Provides an intermediate level of screening for BPP materials between potentiostatic measurements and long-term fuel cell tests.[1]

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[1] For more information: http://www.google.com/patents/US6454922

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

Commercial Technology

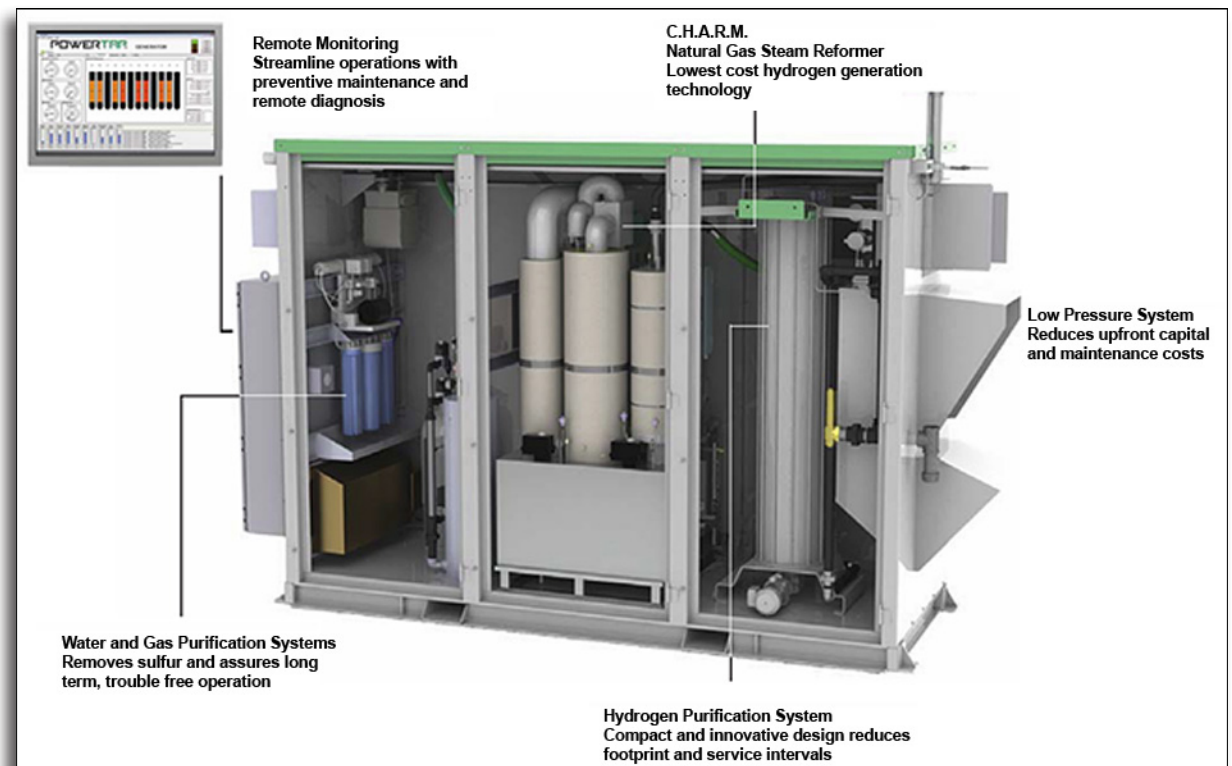
Nuvera Fuel Cells, Inc., conducted a development program to advance fuel processing technology for distributed hydrogen generation by addressing the technical barriers of durability, cost, and manufacturability. This work was performed under a collaborative effort with FCTO and was called CHARM™ (Cost-effective High-efficiency Advanced Reforming Module). The CHARM program's focus was to develop a system with the lowest life-cycle cost and was the enabler for Nuvera's PowerTap™ Hydrogen Generator. When combined with Nuvera's Hydrogen Station, PowerTap provides a cost-effective fueling solution for fuel-cell-powered material-handling equipment.

Technology History

- Developed by Nuvera Fuel Cells, Inc.
- Commercialized in 2009 as part of Nuvera's PowerTap technology, an integrated hydrogen generation and refueling system.

Applications

Can be used for on-site hydrogen generation and delivery to enable adoption of fuel-cell-powered material-handling equipment (e.g., forklift fleets) and automobiles. May also be used for on-site hydrogen production for gas commodity markets (merchant hydrogen).



Cut-Away View of Nuvera's CHARM-Based PowerTap Hydrogen Generator

PowerTap Hydrogen Generation and Refueling System

Capabilities

- Generates pure (99.995% +) hydrogen at rates of up to 56 kg per day.[1, 2]
- When coupled with fuel cell forklift trucks, reduces greenhouse gas emissions compared with grid-charged batteries or internal combustion engines.[1, 2]

Benefits

Cost Savings

Offers on-site, hydrogen generation from natural gas and eliminates transportation charges associated with delivering hydrogen via bottles or tube trailers.

Durability

Reduces the effects of thermal cycling and supports long product life through its system design.[3]

Versatility

Offers scalable hydrogen production rates and purification levels to suit the needs of applications from fuel cell vehicles to merchant hydrogen.

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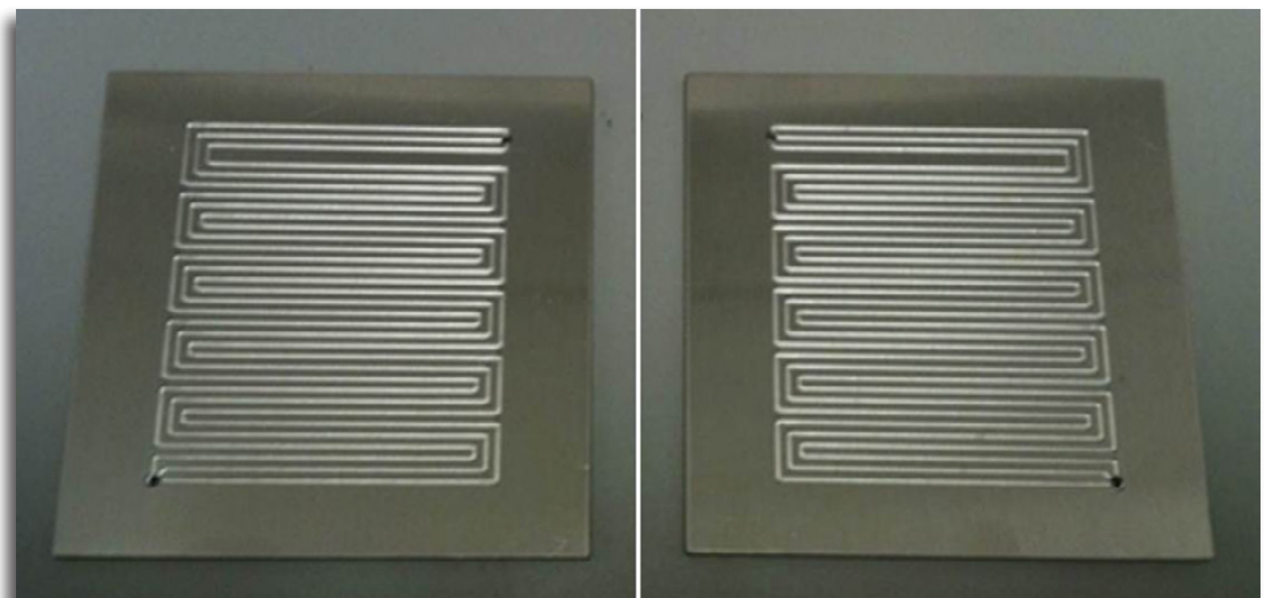
[1] For more information: http://www.nuvera.com/index.php/products-services/powertap-hydrogen-generation-appliance-rc/powertap-on-site-hydrogen-generation
[2] For more information: http://www.hydrogen.energy.gov/pdfs/htac_may2012_nuvera.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/review11/h2ra008_block_2011_o.pdf

FARADAYIC® ElectroEtching of Stainless Steel Bipolar Plates

Using funding from DOE SBIR grants, Faraday Technology developed a low-cost, high-volume metal bipolar plate manufacturing process. The manufacturing process, the FARADAYIC® ElectroEtching Process, is based on electrochemical through-mask etching. The process involves patterning a photoresist mask on the surface of the bipolar plate to protect specific areas during the electroetching process. A pulsed electric field is applied between the bipolar plate substrate and a counter electrode submerged in a benign solution to remove the metal not protected by the photoresist mask. This results in the formation of the gas flow field channels on the surface of the bipolar plate.

Technology History

- Developed by Faraday Technology, Inc., a subsidiary of Physical Sciences Inc, in collaboration with the University of South Carolina's IUCRC Fuel Cell Center.
- Became commercially available in 2012.



Sample 430 Stainless Steel Bipolar Plate (anode right and cathode left) with Gas Flow Fields Formed Using the FARADAYIC® ElectroEtching Process

FARADAYIC ElectroEtching Process for Manufacturing PEM Bipolar Plates.

Applications

Can be used in PEM fuel cell stacks intended for both stationary and automotive applications.

Capabilities

- Maintains plate flatness and plate parallelism since flow fields are formed via a non-contact process.[1]
- Enables inexpensive manufacturing of both simple and complicated flow field designs.[1]

Benefits

Cost Savings

Reduces the overall manufacturing cost of the bipolar plate through use of a high-volume batch process with low capital equipment and tooling costs.[1]

Versatility

Capable of forming complex shaped flow fields in a variety of metals and alloys.[1]

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[1] For more information: http://www.faradaytechnology.com/PDF%20files/Machining/FARADAYIC%20ElectroEtching%20of%20Stainless%20Steel%20Bipolar%20Plates.pdf

GCtool: Fuel Cell Systems Analysis Software Model

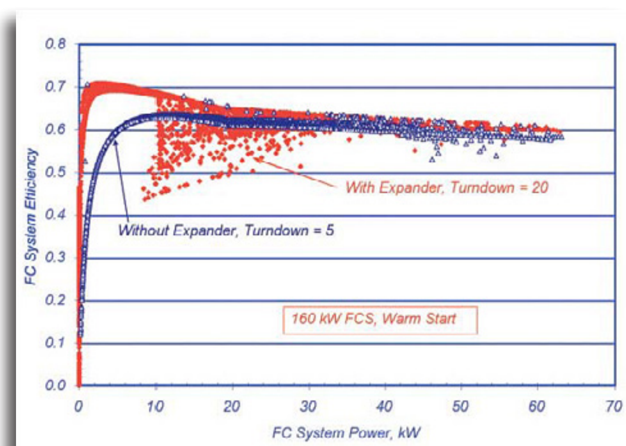
Commercial Technology

Argonne National Laboratory, with support from FCTO, 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.

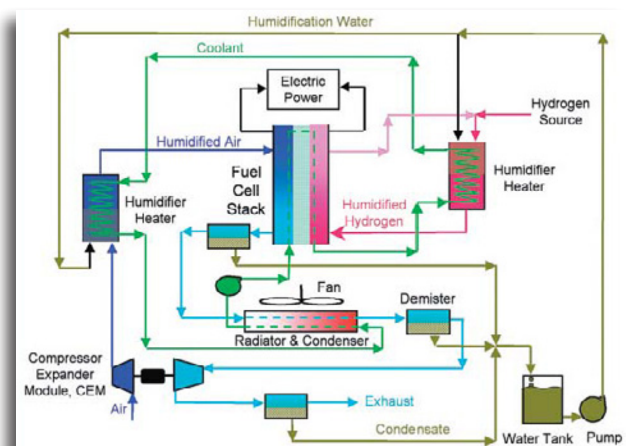
The GCtool can also be used to analyze a variety of automotive hydrogen storage options, some of which have an off-board regeneration component. GCtool can help determine the hydrogen storage system's gravimetric and volumetric capacities, hydrogen charge and discharge rates, and both on-board and off-board process energy efficiencies. 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 numerous parameter sweeps and also performs constrained optimization where specific constraint definition is not a prerequisite for system operation.

Technology History

Developed and commercialized by Argonne National Laboratory.



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

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.[1]
- Allows for simulations that can represent duty cycles, such as the various automotive driving schedules, for various applications.[1]
- Allows users to change the baseline information and corresponding library details for alternative configurations.[1]
- Can be used to model pressurized fluidized-bed combustion and integrated gasification/combined-cycle power plants and other coal combustion systems.[1]

Benefits

Cost Savings

Enables users to test and validate models without incurring the time and costs of building a prototype.[2]

Efficiency

Allows modeling and simulation of systems with rapid turnaround time for analysis and troubleshooting.[2]

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.[1]

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[1] For more information: http://www.anl.gov/technology/project/gctool-design-analyze-and-compare-fuel-cell-systems-and-power-plants
[2] For more information: http://www.transportation.anl.gov/modeling_simulation/gctool.html

GenDrive™ Fuel Cell Power System

Plug Power Inc. developed an improved power source for electric forklift fleets. The GenDrive system consists of a hydrogen fuel cell stack, lithium-ion batteries for situations requiring high power draw (e.g., rapid acceleration), a compressed hydrogen storage tank, and other balance-of-plant components. The GenDrive comes in a range of models to meet the power requirements of Class-1, -2, and -3 forklifts and has been designed to fit into existing forklift battery compartments for easy fleet conversion. The system provides constant voltage throughout the duration of a shift, thereby eliminating the equipment performance degradation experienced with lead-acid batteries. Refueling with hydrogen takes three minutes or less and can be done by the forklift operators using a dispenser that is similar to a gas pump for automobiles. The quick refueling maximizes the amount of productive time that operators spend moving product out on the floor. In addition to productivity enhancement, the GenDrive also reduces the amount of CO_2 emissions attributable to forklift fleet operation compared with batteries recharged by grid-generated electricity.[1]

With assistance from FCTO (as part of the American Recovery and Reinvestment Act), forklift fleets powered by the GenDrive are operating at several large distribution centers across the country. Companies participating in these fleet deployments include Sysco Corporation, FedEx Freight, Wegmans Food Markets, Inc., Whole Foods Market, Inc., Kimberly-Clark Corporation, and Coca-Cola Bottling Co. Consolidated. These demonstrations of the GenDrive technology in real-world operational settings are helping Plug Power evaluate and optimize the unit's performance.

Technology History

- Developed and commercialized by Plug Power Inc.
- Currently being used at several large material-handling centers across the United States. Over 4,000 units and 12 million operating hours logged. Preparing to enter European marketplace- "Hy-pulsion".

Class-1, -2, and -3 Forklifts (shown from left to right) Powered by Plug Power's GenDrive Fuel Cells

[1] For more information: http://www.plugpower.com/Files/GD1%20TC.pdf

Plug Power's Class-1, -2, and -3 GenDrive Units (shown from left to right)

Applications

Can be used as an alternative to lead-acid batteries for powering electric forklift fleets at high-throughput warehouses, distribution centers, and manufacturing facilities.

Capabilities

- Provides 1.6 - 11 kW of continuous power (depending on model).[1]
- Maintains constant voltage throughout the entire shift, without the performance degradation of batteries.[1]

Benefits

Ease of Adoption

Available in multiple models that fit into the existing battery compartments of all major OEM material-handling equipment.

Emissions Reductions

Reduces CO_2 emissions attributable to forklift fleet operation compared with batteries recharged by grid-generated electricity.[1]

Productivity

Provides rapid refueling times (60-180 seconds, depending on model), allowing operators to spend more time moving product out on the floor.[1]

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[1] For more information: http://www.plugpower.com/Files/GD1%20TC.pdf

High Speed, Low Cost Fabrication of Gas Diffusion Electrodes for Membrane Electrode Assemblies

Commercial Technology

BASF, with FCTO funding, has built upon their previous work on catalysts in developing high throughput manufacturing processes for the gas diffusion electrodes (GDEs) that go into high temperature membrane electrode assemblies(MEAs). This new phase of development has resulted in reduced labor cost to manufacture gas diffusion electrodes (GDEs) a further 50% from their previous work to an overall 75% cost reduction.[1] Furthermore, BASF have scaled up their material preparation operation to support an increase in cloth-based GDE throughput.[1] These productivity increases were achieved through development of on-line quality control methods to determine platinum concentration and distribution during the coating process. The on-line mapping of platinum guides the ink deposition process and provides immediate feedback on uniformity. BASF also further developed the materials and scaled-up the production of stable inks of carbon black or catalyzed carbon black and hydrophobic binder for manufacturing GDEs. The process and material improvements have reduced the number of applications needed per pass and hence increased product throughput.[1]

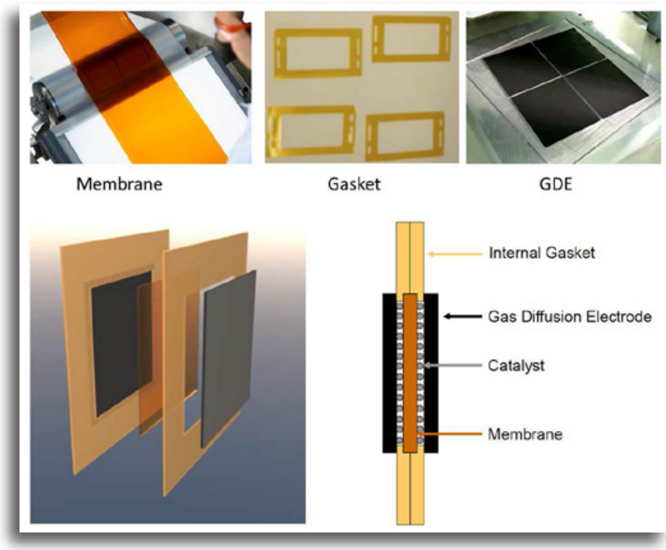
As part of this cost saving initiative, BASF has been developing GDEs using lower cost substrates such as non-woven carbon fiber materials ("carbon paper") which are ~30% lower in cost compared to the carbon cloth at higher volumes. The porosity, hydrophobicity, and absorption properties of the carbon papers are totally different than carbon cloth, and required development of entirely new classes of inks for the micro-porous layer, anode, and cathode electrodes. This work resulted in proof-of-principle for achieving a further 30% cost reduction and even higher throughputs.[1] In March 2012, BASF released a new product in their Celtec® product line, the Celtec® P1100W MEA. This is the first new product release using BASF's newly developed high-throughput coating process for manufacturing GDEs.

Technology History

- Developed by BASF in collaboration with Case Western Reserve University.
- New product from this work commercially deployed since Q2 2012 (Celtec® P1100W MEA).

BASF's New Manufacturing Equipment for Low Cost GDE's

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/mn007_decastro_2012_o.pdf



BASF Manufactured Components for Fabricating MEAs

Applications
Can be used in manufacturing high temperature PEM fuel cells for a wide variety of stationary and mobile power systems.

Capabilities
- Manufacturing specification now guided by "six sigma" methodology.
- Reduces variation of catalyst coating by 80%.[1]
- Achieves proof-of-principle for "one pass" MPL and catalyst coating on carbon paper.[1]
- Demonstrates a 30% reduction in platinum loading compared to best cloth-based anodes without losing performance.[1]

Benefits
Cost Savings
Reduces labor and material costs by >30%.[1]

Manufacturability
Increases production throughput by a factor of four with improved product quality and performance.[1]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/mn007_decastro_2012_o.pdf

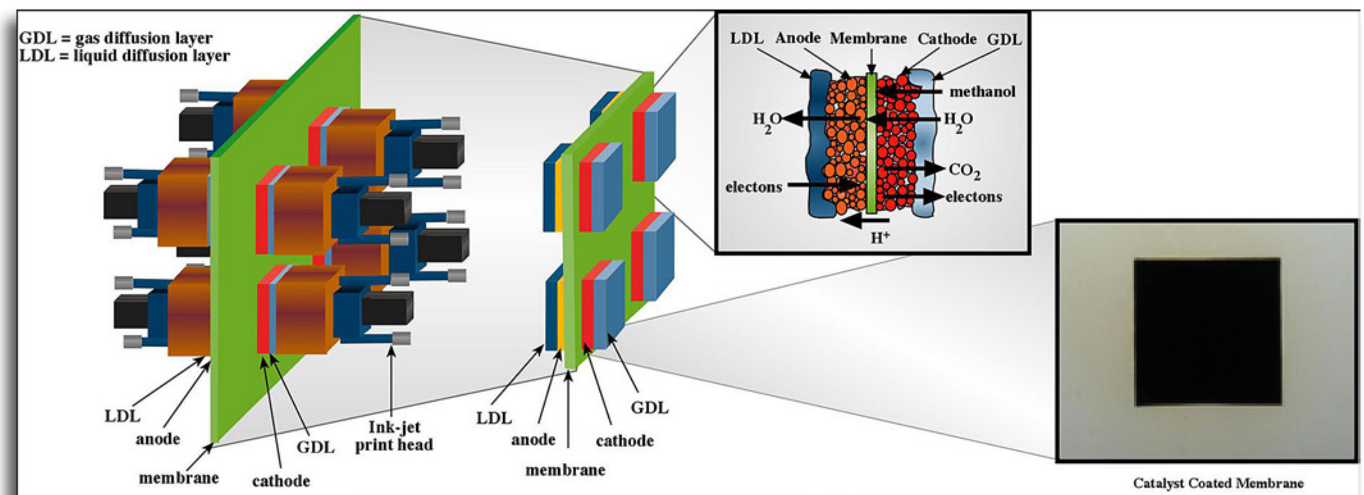
Improved Catalyst Coated Membrane (CCM) Manufacturing

Commercial Technology

Cabot Corporation developed a spray deposition manufacturing technology along with specialized inks and catalyst powders. Cabot received development funding from FCTO 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 electrocatalyst inks with a limited amount of capital investment per volume demand and has a simpler manufacturing process.[1] It also improves CCM performance and possesses a high degree of flexibility to meet various DMFC customers' requirements.[1]

This manufacturing technology allows high-volume production of CCMs/MEAs with lower platinum content and higher fuel cell performance.[1] This technology can be 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.

In March 2009, Cabot sold the manufacturing line to IRD Fuel Cells, LLC, a U.S.-based affiliate of the Danish company IRD Fuel Cell Technology A/S. Cabot and IRD have entered into joint development and supply agreements to manufacture improved MEAs incorporating Cabot's electrocatalysts. IRD will operate the manufacturing line, which will remain at its current location in Albuquerque, New Mexico. Cabot will focus its efforts on making further improvements to its fuel cell electrocatalyst products.



Catalyst Coated Membrane Manufacturing Process

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress08/vi_2_ryan.pdf

Technology History

- Developed by Cabot Corporation.
- IRD Fuel Cells, LLC now operating MEA manufacturing process. IRD are further developing the process and MEA materials.

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/MEAs for fuel cells.[1]
- Reduces the amount of precious metals needed in fuel cells.[1]

Benefits

Cost Savings

Reduces the cost of manufacturing CCMs/MEAs and the amount of expensive precious metals used in a fuel cell.[1]

Productivity

Allows higher production and higher yields.[1]

Versatility

Spray deposition system allows quick changeover to different materials.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress08/vi_2_ryan.pdf

Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods

Commercial Technology

NuVant Systems Inc., with a DOE SBIR grant, developed the Arraystat 25-channel potentiostat and Array Fuel Cell. This system enables the user to simultaneously probe 25 electrodes on a fuel cell MEA.[1] NuVant then improved the Arraystat technology with the addition of the Array Flow Manifold, which provides reactants at controlled temperature, humidity and flow rate to the Array Fuel Cell. The Arraystat can switch out (i.e. open circuit) any number of electrodes while others are tested either in parallel or sequentially. The Array Fuel Cell system maintains uniform temperature and flow conditions across the entire active area of the MEA. The working/array side of the MEA consists of 25 independent disk electrodes.[1] A single counter electrode doubles as a reference electrode when charged with hydrogen flow. This technology enables electrode components to be evaluated under reactor conditions. More recently low current versions of the Arraystat have been developed and are in use by photoelectrochemists in DOE-sponsored solar fuels programs.[1]

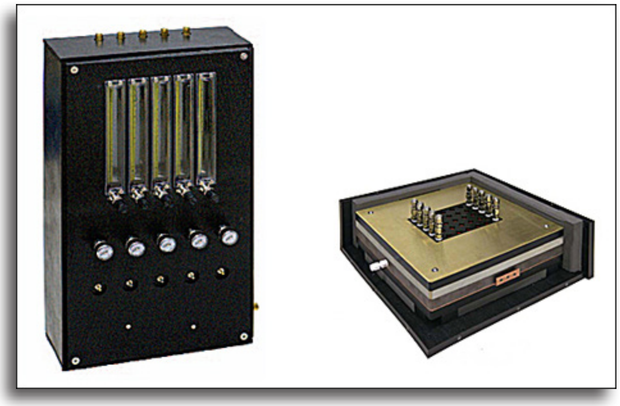
The system also comes with user friendly Arrayware software, which can control the Arraystat, up to 12 temperature controllers, and up to 6 mass flow controllers. The software allows users to write and execute sequences of variables to be analyzed. In addition to the system components and software, NuVant now offers installation and short training courses to facilitate customer in-house preparation of fuel cell electrodes.

Technology History

- Developed by NuVant Systems Inc., with research starting in 2004.
- Sold first commercial Arraystat in 2006 and first commercial Array Fuel Cell in 2007.

NuVant's Automated 25-Channel Array Potentiostat (Arraystat)

[1] For more information: http://nuvant.com/products/potentiostat_galvanostat/multichannel/arraystat-5-25-cycling-channels/



NuVant's Array Flow Manifold (left) and Array Fuel Cell

Applications

Can be used to test fuel cell and battery components, electroplating processes, biomedical devices, electrochemical sensors and photoelectrochemical devices. The equipment is also applicable to electrosynthesis and corrosion studies, flow field development, and computational modeling validation.

Capabilities

- Measures and records data simultaneously from 25 electrodes on a fuel cell MEA.[1]
- Provides reactants at controlled temperature, humidity, and flow rate via the Array Flow Manifold for consistent conditions across the entire MEA active area.[1]
- Enables electrode components to be evaluated under normal reactor conditions.[1]

Benefits

Accuracy

Eliminates random error introduced by multiple test stands by using a single common counter electrode.[1]

Cost Savings

Reduces costs associated with MEA testing because of the high throughput achieved with a single test station.

Versatillity

Allows the user to apply complex sequences of test parameters to any number of the array electrodes in parallel or sequentially.[1]

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[1] For more information: http://nuvant.com/products/potentiostat_galvanostat/multichannel/arraystat-5-25-cycling-channels/

Integrated Manufacturing for Membrane Electrode Assemblies

BASF Fuel Cell, Inc., with funding from FCTO, developed a membrane electrode assembly (MEA) fabrication process using improved electrode structures and catalysts and a durable membrane. The assembly used a design for the gas diffusion electrode (GDE) which incorporated the "fine gradient" ELAT™ electrode (trademark derived from Electrode, Los Alamos Type), resulting in assemblies that could run longer with more stable voltages.[1] By modifying the fine gradient structure, performance was improved when operating at lower relative humidity. The fine gradient approach also decreased precious metal loading, resulting in reduced material costs.[1] All the electrode, catalyst, GDE and MEA structures were initially fabricated using coating equipment to facilitate the assessment of a high volume manufacturing process. This work subsequently generated commercialized spin-off products for gas diffusion electrodes, electrocatalysts, and MEAs for direct methanol fuel cells.

BASF developed and commercialized Celtec®-P MEAs for high temperature PEM fuel cells. The Celtec®-P MEAs have a high tolerance to carbon monoxide in the hydrogen fuel stream, which makes the fuel reforming step far simpler and less costly. With new support from the FCTO, BASF continued development work comprised of two main areas. The first area was in-line process monitoring of product variation so that a product specification could be established and quality assurance limits set. This was enabled by using an x-ray fluorescence (XRF) analyzer to monitor GDE uniformity as a function of coating speed. The second area was developing a process compatible coating material formulation (inks) to reduce the number of coating passes at increased coating speed, width and length, effectively tripling process throughput with a reduction in coating defects. BASF has also investigated using carbon paper instead of carbon cloth as a substrate to reduce costs. This phase of the research is ongoing as it will be necessary to develop suitable ink properties and process parameters to operate with the cheaper carbon paper substrate.

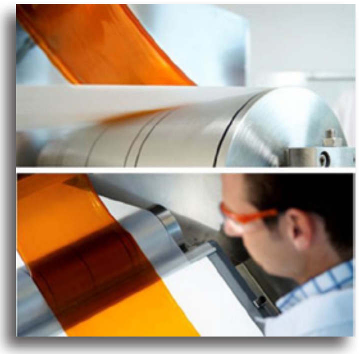
BASF manufactures the developed GDE and MEA materials at its integrated fuel cell facility in Somerset, New Jersey which opened in mid-2009. The facility houses a scaled up version of the coating process developed during the initial materials and process research phase. The facility houses the entire assembly line processing raw materials into finished product. While the manufacturing technology allows customization, BASF is stressing standardization with three main sizes of MEAs in order to reduce cost. The Celtec®-P MEAs are currently used in numerous fuel cell applications using reformed hydrogen as a fuel, most notably micro combined heat and power systems of 1-5kW. In March 2012, BASF released another product in the Celtec®-P product line, the Celtec® P1100W MEA. This new product release is the first product released that is manufactured using BASF's newly developed high-throughput coating process for manufacturing GDEs.

Technology History

- Developed by BASF in partnership with DuPont Fuel Cells, Nuvera Fuel Cells, Spire Biomedical Corp, Northeastern University, and Case Western Reserve University.
- Previously manufactured products include: electrocatalysts, gas diffusion electrodes, and MEAs for direct methanol fuel cells.

BASF's High-Speed Coating Machine with XRF Monitoring

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review06/fc_18_tsou.pdf



BASF's Roll Membrane Manufacturing Process

Applications

Can be used in high temperature PEM fuel cells used for backup power systems, auxiliary power units, and residential combined heat and power systems.

Capabilities

- Allows fuel cells to operate at temperatures of 120-180°C without the need for humidification.[1]
- Achieves long term stability for more than 20,000 hrs with only a small voltage drop.[1]
- Eliminates the need for complex membrane hydration equipment such as: air humidifiers, water pumps, tanks, valves, and cleaning systems.[1]

Benefits

Cost Savings

Reduces amount of precious metal catalyst used in MEAs without a loss in performance.[2]

Durability

Increases MEA anode tolerance to carbon monoxide poisoning, thereby allowing operation at 1-2% CO.[1]

Versatility

Offers customizable fabrication to fit customers' MEA size requirements.[1]

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[1] For more information: http://www.fuel-cell.basf.com/cm/internet/Fuel_Cell/en_GB/content/Microsite/Fuel_Cell/Products/Celtec-P_1000
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review06/fc_18_tsou.pdf

Lifetime Improvements for PEM Fuel Cells

DuPont Fuel Cells, with funding from FCTO, 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 stabilization technology.[1] This stabilization technology combats the chemical degradation problem and can increase the lifetime of fuel cell polymer membrane electrode assemblies, thereby reducing early failure replacement costs.[1]

The stabilization technology approach resulted in a chemically stable Nafion® polymer technology that is eight times more stable than before.[1] The modified materials have survived more than 4,000 hours in a fuel cell accelerated test, which included load and relative humidity cycles.[1] These 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 chemically stabilized polymer.

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

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review06/fc_5_escobedo.pdf

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.
- Currently marketing the mechanically reinforced Nafion XL membrane.

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.[1]
- Achieves improved lifetime in fuel cell applications.[1]

Benefits

Cost Savings

Reduces replacement costs because of increased membrane durability.[1]

Durability

Improves membrane lifetime in accelerated lifetime testing for simulating an automotive drive-cycle.[2]

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[1] For more information: http://www2.dupont.com/FuelCells/en_US/products/nafion_xl_membrane.html
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review06/fc_5_escobedo.pdf

Low-Cost PEM Fuel Cell Metal Bipolar Plates

Commercial Technology

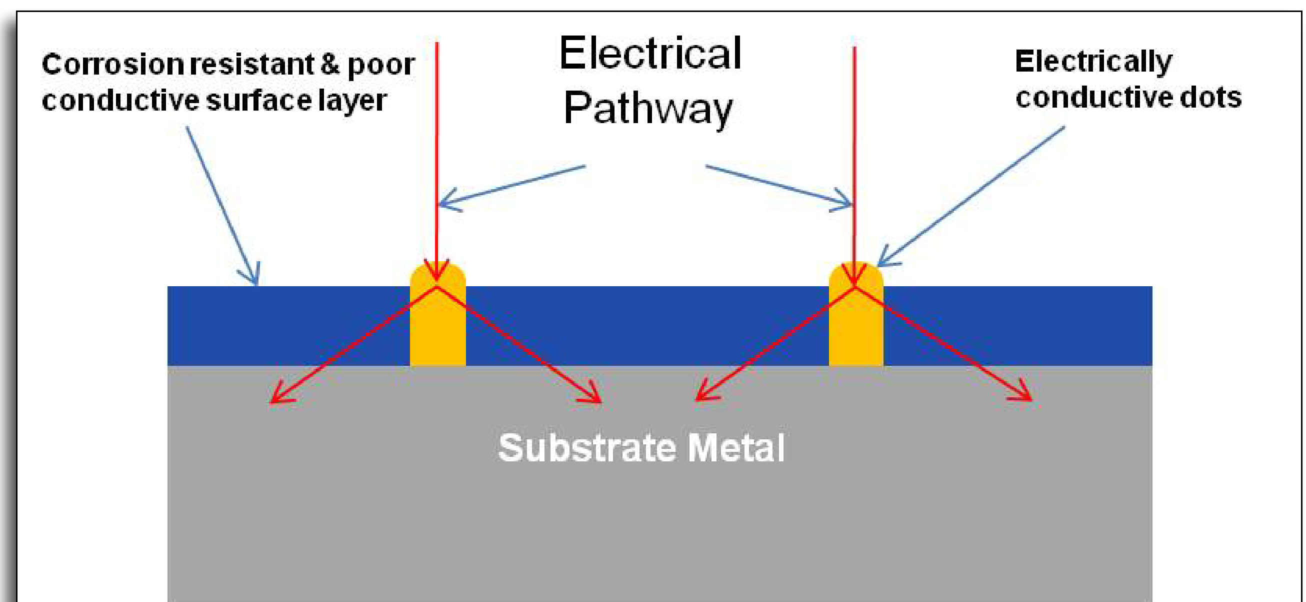
TreadStone, Inc., with funding from FCTO, has developed a corrosion-resistant metal bipolar plate. Typically, for protection and durability, the entire bipolar plate surface is coated with an electronically conductive, corrosion-resistant material and requires high-cost materials and processing techniques. TreadStone's approach selectively coats the plate surface and maintains low-contact resistance between the plates and gas diffusion layer (GDL). TreadStone's process coats the majority of the plates using a low-cost, corrosion-resistant, non- (or poor) conductive material. A corrosion-resistant, high-conductivity material (such as gold) is used to form the electron transport paths (conductive dots), which penetrate the nonconductive layer. The high distribution density of the conductive dots ensures a uniform current distribution between the GDL and metal bipolar plates.[1]

TreadStone's development of the metal bipolar plate process, which deposits the conductive dots on stainless steel substrates, has examined various contact materials: palladium/gold composites, and carbon nanotubes and conductive carbides. TreadStone's fuel cell metallic plates have been designed and optimized for portable, stationary, and automobile applications. In particular, a 10-cell, 2.5-kW short stack for automobile application has been tested at Ford Motor Company with no sign of corrosion of the metal plates after the 1,000-hour test. Recently, TreadStone has extended the application of this technology in anion exchange membrane (AEM) fuel cells, PEM electrolyzers, and flow cells for energy storage applications.

Technology History

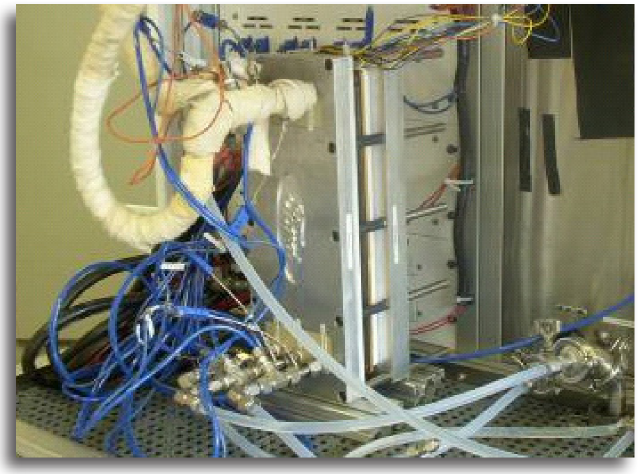
- Developed by TreadStone Technologies, Inc.

- Commercialized in 2011.



TreadStone's Corrosion-Resistant Metal Plate Design

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_h_1_wang_2011.pdf



Fuel-Cell Stack Using TreadStone's Bi-polar Plates on the Testing Station at Ford Motor Company

Applications

Can be used in PEM fuel cells for automobile, stationary, and portable power applications in addition to other electrochemical devices.

Capabilities

- Reduces electrical contact resistance by selective material deposition on aluminum plates followed by application of gold dots or other materials for AEM fuel cell applications.[1]
- Produces corrosion-resistant, cost-effective metallic bi-polar plates for fuel cell and other electrochemical applications.[1]
- Reduces the cost of fuel cell metal plate coatings to as low as $0.30/plate and achieves high rates of gas transport as well as high separation factors/high purity.[1]

Benefits

Cost Savings

Reduces costs by using commercially available, stainless steel, low-cost carbon steel or aluminum as substrate materials and by reducing or eliminating the use of expensive electrically conductive materials.[1]

Manufacturability

Optimizes the fabrication process for large-scale manufacturing.[1]

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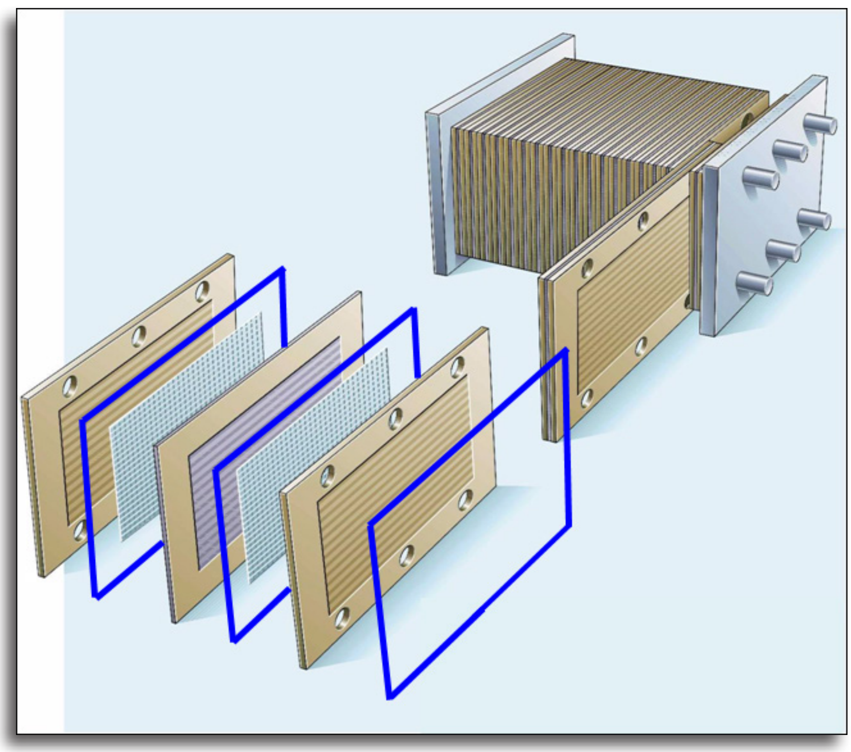
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_h_1_wang_2011.pdf

Manufacture of Durable Seals for PEM Fuel Cells

With funding from FCTO through the National Center for Manufacturing Sciences, Freudenberg-NOK General Partnership (FNGP) has developed and commercialized durable seals for PEM fuel cells. FNGP uses a custom elastomer material that exhibits improved 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.[1] A low-cost, long-life alternate carrier material is also being used. Based on the new elastomer and carrier material, FNGP can now provide an interfacial seal design by molding the elastomer onto the carrier material. A high-volume manufacturing process was also incorporated to make this design feasible.

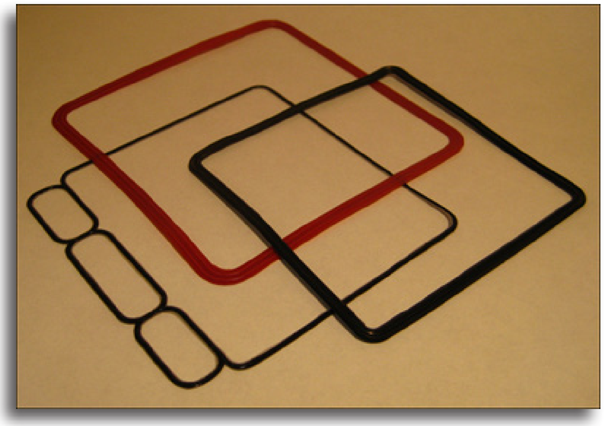
Technology History

- Developed by FNGP in partnership with UTC Power.
- Began research in 2006, with commercialization in 2009.



Exploded View of a Typical PEM Fuel Cell Stack Assembly Showing FNGP's Durable Seals in Blue

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress07/x_1_ryan.pdf



FNGP's Durable Seal for PEM Fuel Cells

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

Capabilities
Allows the seals to survive the electrochemical environment while reducing catalyst poisoning concerns in the fuel cell.[1]

Benefits
Durability
Displays superior chemical and mechanical property stability compared with conventional silicones and low levels of ionic contaminants.[1]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress07/x_1_ryan.pdf

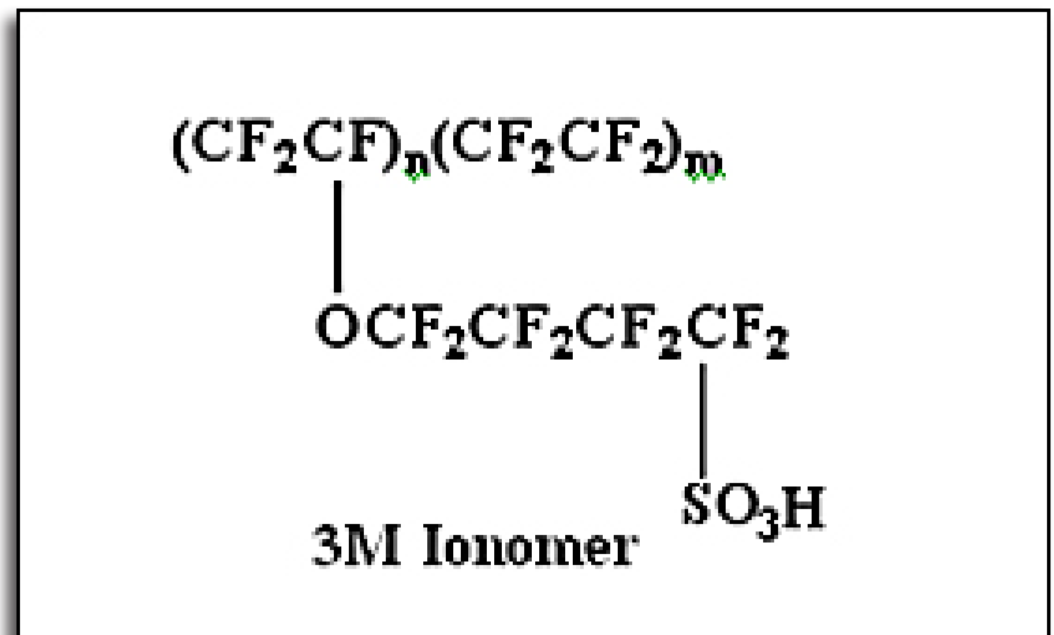
Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions

3M Company, funded in part by FCTO, has developed a low equivalent weight (EW), perfluorinated sulfonic acid-based (PFSA) membrane with improved chemical and mechanical stability, and proton conductivity.[1] This membrane allows 3M to provide MEAs with improved durability and performance. The new polymer structure and membrane processing methods provide mechanical properties, that, with improved polymer chemistry and stabilizing additives, increases lifetime by 10 to 100 times.[1] MEAs with these membranes have run over 18,000 hours in accelerated testing protocols and over 10,000 hours in stacks. The lower EW ionomer provides higher conductivity at low humidification, which allows higher operating voltages.[1]

Under the FCTO Program, membranes were developed with new side-chain chemistries, stabilizing and conductivity enhancing additives, and membrane fabrication processes that provide further improvements in conductivity and durability under hot (up to 120ºC) dry conditions.[1]

Technology History

- Commercialized in 2006.
- Introduced an improved 20 micron membrane in 2009.



The 3M Ionomer With Lower Equivalent Weight Side Chain than Standard PFSA Ionmers

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/fc034_hamrock_2011_o.pdf

Membrane Windows in a Roll Good Film Subgasket

Applications
Can be used in PEM fuel cells for transportation, stationary, and back-up power applications.

Capabilities
Increases conductivity under dry operating conditions.

Benefits
Cost Savings
Provides lower cell resistance/improved performance under hot and dry conditions and allows the use of fewer cells to meet power specifications, which means less humidification or cooling equipment required.[1]

Efficiency
Provides higher cell voltage in fuel cell systems running at higher temperatures and/or lower humidification, allowing greater fuel efficiency.[1]

Performance
Improves system performance by enabling operation under a wider range of temperature and humidity.[1]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/fc034_hamrock_2011_o.pdf

Novel Manufacturing Process for PEM Fuel Cell Stacks

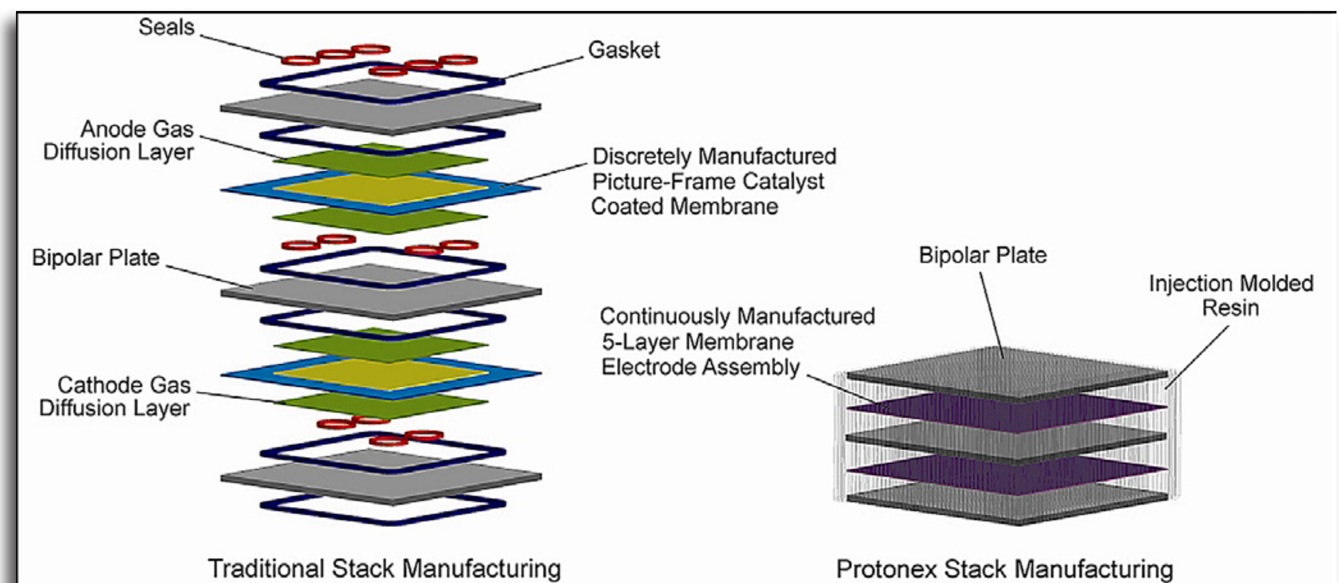
Protonex Technology Corporation developed a manufacturing method that eliminates the labor-intensive stacking/alignment and multiple component design of conventional stack fabrications. This new process was refined with funding from FCTO through the National Center for Manufacturing Sciences. Protonex uses a one-step molding process that creates the manifold structure and seals the stack and five-layer membrane electrode assemblies (MEAs). The process is compatible with 5-layer MEAs generated in continuous roll coating operations.

Three portable power system products have used this new manufacturing process. The M250-B product is for commercial users and the M250-CX and M300-CX products are for military customers. Currently, 250-watt and 300-watt systems are being supplied to the U.S. military, and the U.S. Army has funded further improvements in the system.

Technology History

- Developed and commercialized by Protonex Technology Corporation to manufacture portable power systems for military and commercial use.

- Delivered over 50 M250-CX and M300-CX systems through 2012.



Protonex Injection-Molded Stack Versus Traditional Stack Assembly

Protonex Technology Fuel Cell Stacks

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.[1]
- Reduces part count and complexity and manufacturing cycle time.[1]

Benefits

Cost Savings

Lowers costs by using lower tolerance and fewer components.[1]

Efficiency

Offers part count reduction and improved (lower) manufacturing time.[1]

Reliability

Uses adhesive-based seals to improve stack reliability and robustness over traditional compression-based seals.[2]

Versatility

Is easily automated, uses membrane electrode assemblies more efficiently, and reduces the need for tension members.[2]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/htac_june2011_protonex.pdf
[2] For more information: http://www.protonex.com/technology/proton-exchange-membrane

Portable Reformed Methanol Fuel Cells

Commercial Technology

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 FCTO, 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 has passed extreme environmental testing that meets military standards.[1] 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 five-gallon fuel tank will supply 12,500 watt-hours of energy.[1]

For applications requiring larger amounts of mobile power, UltraCell has recently developed the XX55™ fuel cell. The XX55 delivers 50 watts of continuous power and up to 85 watts of peak power. Both models can be used for a wide variety of mobile and stationary electronics applications, including: radio and satellite communication gear, remote or mobile surveillance systems, laptop computers, and battery charging. For extended missions, UltraCell now offers a full line of fuel tank options to meet a variety of capacity and runtime needs. This enables critical sensors or video surveillance systems to run for weeks or months at a time with a power supply and fuel source package that is easily transportable by a single person. The fuel cell systems offer weight-savings over traditional batteries; one XX25 fuel cell coupled to a five-gallon fuel tank provides the same amount of energy as sixty BA-5590 batteries, with a 70% weight savings.[1]

XX25 (Sand) and XX55 (Black) Fuel Cells with Portable Pack Unit

[1] For more information: http://www.ultracell-llc.com/assets/Extended_Runtime_Data_Sheet_25-Oct-2013.pdf

Extended Runtime Fuel Options (250cc Cartridge to 5 Gallon Tank)

Technology History

- Developed and being marketed by UltraCell, LLC.
- Won "Best Soldier System Innovation & Technology" at the Soldier Technology USA 2008 Conference.
- Commercialized in 2007.

Applications

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

Capabilities

- Supplies up to 25 or 50 watts of continuous power with hot swapping of methanol fuel cartridges.[1]
- Can be hybridized with external batteries for high power peaks and with up to 5 gallon fuel tanks for long run time.[2]

Benefits

Durable

Has passed military standard testing (MIL-STD-810F Environmental Testing) for extreme conditions[3].

Portable and Versatile

The XX55 weighs three kilograms, can be used with different size fuel cartridges or an external fuel source, and offers various voltages (12 to 30 volts).[1]

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[1] For more information: http://www.ultracell-llc.com/assets/XX55_Data_Sheet_26-Jun-2013.pdf
[2] For more information: http://www.ultracell-llc.com/assets/Extended_Runtime_Data_Sheet_25-Oct-2013.pdf
[3] For more information: http://www.sciencedirect.com/science/article/pii/S1464285907703103

PureMotion® Model 120 Fuel Cell Power Plant

The PureMotion Model 120 Fuel Cell Power Plant (FCPP) was developed by UTC Power using funding from FCTO. The PureMotion 120 is based on proton exchange membrane (PEM) technology, and maximizes fuel efficiency via ambient pressure operation. The power plant's modular design maximizes uptime and simplifies routine maintenance.[1] Testing performed by the National Renewable Energy Laboratory has shown fuel cell buses powered by the PureMotion 120 to exhibit up to twice the fuel efficiency compared with traditional diesel-fueled buses.[1]

The PureMotion 120 has been powering a fleet of 6 transit buses (2 fielded currently) that have successfully demonstrated revenue service operation since 2005. This fleet has accumulated over 49,000 hours of operation and 490,000 miles in transit revenue service as of May 2011. Fuel cell stacks in the fleet leader bus have accumulated over 7,000 hours of operation at rated power without a single cell replacement. This success has led to the expansion of the bus fleet. Sixteen new fuel cell buses powered by the second generation of UTC Power's PureMotion 120 entered transit revenue service in late 2010. Twelve of the new buses have begun service in California by AC Transit and other transit agency partners, and four are being used by CT TRANSIT in Connecticut. These new buses are lighter, have improved batteries and are more fuel efficient than the previous generation.[2]

In late 2010, UTC Power was awarded a $14.4M cost share project under the National Fuel Cell Bus Program to develop a third generation fuel cell power plant. This multi-year project is focused on providing a less costly, smaller and more durable product for the commercial marketplace.

Technology History

- Developed and commercialized for the transit bus market by UTC Power now owned by ClearEdge Power.
- Deployed first unit in 2005 with a total of six units delivered by 2007. Sixteen additional units with improved performance were delivered in 2010.

Next Generation CT TRANSIT Fuel Cell Bus powered by the PureMotion Model 120 FCPP

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/tv008_eudy_2012_o.pdf
[2] For more information: http://gofuelcellbus.com/uploads/NFCBP_CALSTART_Progress_Report_2011.pdf

The PureMotion Model 120 FCPP

Applications

Can be used to power hydrogen-fueled vehicles or as a modular stationary 120-kW power source (with appropriate power management and interface controls).

Capabilities

- Generates up to 120 kW of power.[1]
- Achieves increased fuel efficiency compared with conventional diesel-fueled buses.[1]

Benefits

Durability

Demonstrated on-road operation in excess of 11,000 hours without a single fuel cell replacement.[1]

Environment

Eliminates the greenhouse gas emissions and excessive noise associated with operation of traditional diesel-fueled buses.[1]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/tv008_eudy_2012_o.pdf

Reduction in Fabrication Costs of Gas Diffusion Layers

Commercial Technology

Ballard's Material Products Division, now AvCarb LLC, with funding from FCTO, developed the GDL manufacturing process. Costs are lowered by reducing the number of process steps, implementing on-line process control tools, improving manufacturing efficiencies, and determining the relationship between process parameters and key GDL properties.[1] A new continuous mixing process was developed to replace a slow batch mixing process. Additionally, a Many-At-A-Time (MAAT) coating process was developed to reduce the number of passes the product makes through the coating line. Process control tools such as noncontact thermocouples and basis weight sensors were integrated into the process for improved process controls.

The company increased process efficiency by modifying the process for 33-inch-wide substrate material, "full-width" processing, versus 16.5 -inch-wide or "half-width" processing. They increased substrate coating efficiency by developing the chemical coatings (inks) to be compatible with a multiple coating process (MAAT) to eliminate multiple coating passes and lengthy batch processing. In addition to the processing equipment and material changes, in-line process parameter monitoring was implemented to establish and understand, via modeling, how process parameters related to GDL properties and to control these properties within specification limits. The GDLs processed using the newly implemented process changes showed no reduction in performance when evaluated in short and full cell stacks. Overall, the effort has resulted in increased productivity and cost reduction and has established the necessary parameters to design a Greenfield Facility that can produce GDLs at volumes (10,000,000 m^2) and costs (<$4/kW).[1]

Technology History

- Owned and operated by AvCarb, LLC.
- Achieved production of 800-mm-wide, 800-m-long continuous rolls of GDL material.

AvCarb's Continuous GDL Roll Manufacturing

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/vi_2_morgan_2011.pdf

AvCarb's Continuous Mixing and Multilayer Coating Equipment

Applications

Can be used in a variety of fuel cell applications, e.g., materials handling, backup power, and transportation.

Capabilities

- Improves GDL uniformity and production quality.[1]
- Increases GDL production capacity for near-term fuel cell markets.[1]
- Allows next-generation GDLs to be designed with properties tailored for specific fuel cell applications.[1]
- Reduces the fabrication costs and provides a path to reach the 2015 DOE cost target of $5/kW.[1]

Benefits

Cost Reduction

Reduces costs using high-volume manufacturing.[1]

Flexibility

Achieves process flexibility for specific customer product needs.[1]

Manufacturability

Increases capacity by four to nine times.[1]

Product Quality

Achieves uniformity using real-time process monitoring.[1]

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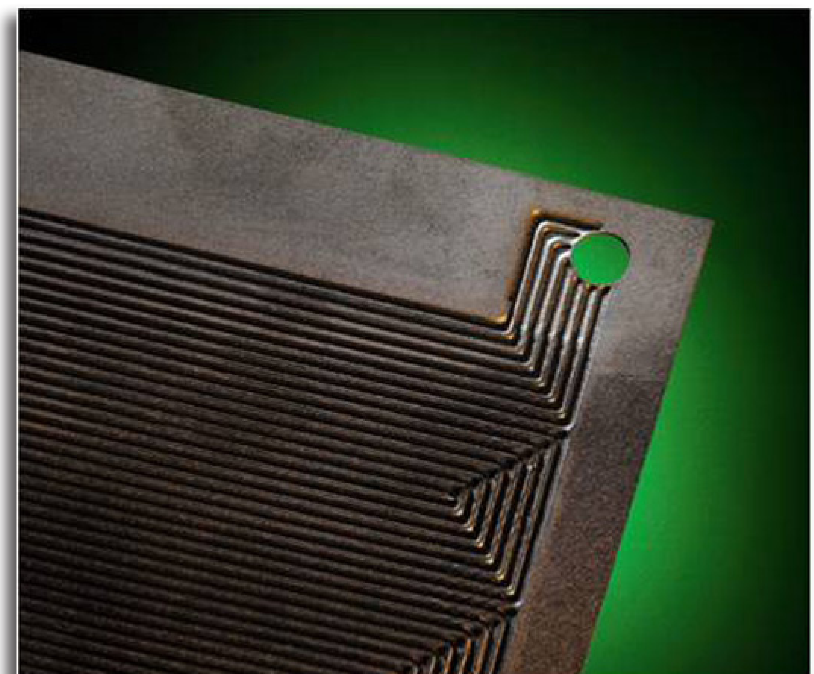
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/vi_2_morgan_2011.pdf

Scale-Up of Carbon-Carbon Composite 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 FCTO, 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.[1] Porvair's cost analyses showed that the Porvair plate could meet automotive volume pricing of less than $4 per kilowatt.[1] Plate performance meets or exceeds the performance of competitive products, including state-of-the-art, expensive machined graphite products.[1]



Fully Molded Porvair Bipolar Plate

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review05/fc22_haack.pdf

Technology History

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

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.[1]
- Minimizes contact resistance between cells.[1]
- Resists the corrosive environment in the fuel cell.[1]
- Reduces the weight of the fuel cell stack compared with graphite plates.[1]

Benefits

Cost Savings

Provides high-volume manufacturing with no machining, reducing the cost of the plates.[2]

Performance

Resists the corrosive environment in the fuel cell.[1]

Weight Reduction

Provides a lightweight product with a density of about 1.2 grams per cc.[3]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress07/v_b_3_haack.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review05/fc22_haack.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/review06/fc_33_haack.pdf

C.2 Production/Delivery Technologies

FuelGen® Hydrogen Fueling Systems

Commercial Technology

Proton Energy Systems, Inc., as part of a demonstration project managed by EVermont and funded by FCTO, 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.[1]

In the FuelGen polymer electrolyte membrane (PEM) electrolysis unit, water is electrolyzed and broken down into its molecular components of H_2 and O_2. The H_2 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. Additional systems are currently in operation in Hempstead, New York, and Rolla, Missouri.[2]

Technology History

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

Proton Energy Systems' FuelGen 65 Hydrogen Fueling Station

[1] For more information: [U.S. National Outreach and Hydrogen Standards Development, Winter 2009]

[2] For more information: http://www.fuelcells.org/pdfs/h2fuelingstations-US.pdf

FuelGen Station in Las Vegas, NV

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 up to 65 kg/day (large unit) of hydrogen at up to 400 psi.[1]
- Produces 99.999% purity hydrogen.[1]
- Uses a power conservation mode during standby.[1]

Benefits
Purity
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.

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[1] For more information: http://www.pogc.com.au/brochures/Proton-On-Site/HOGEN-C-Series.pdf

H2 ProGen: A Total Supply Solution for Hydrogen Vehicles

Commercial Technology

The H2 ProGen System is an integrated, on-site hydrogen generation and dispensing system that provides a 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 FCTO.

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.

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.

H2 ProGen Hydrogen Dispensing Station

H2 ProGen Unit in Transit

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 50 kg of hydrogen per day.[1]

Benefits

Cost Savings

Integrates the key hydrogen station components at the factory into the H2 ProGen system, 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.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review06/tv_4_liss.pdf

High Performance Palladium-Based Membrane

Commercial Technology

Pall Corporation, with funding from FCTO, developed a Pd-based membrane that is designed to work as a selective barrier to only let H_2 pass through. A mixed gas stream comes into the membrane device and is separated into two outlet streams, one containing near pure H_2 at low pressure and the other containing CO_2 and other components of the incoming gas at high pressure. The near pure H_2 is the end product or fuel for fuel cell vehicles.

Pall Corporation developed this membrane after research in the fields of Pd-membrane technology, high-temperature material analysis, and inorganic membrane product development and manufacturing. The resulting membrane enables the design of a cost-effective natural gas reforming system. Pall Corporation combined the reforming process with the water gas shift reaction to create a membrane reactor that has enabled additional cost savings.[1] The membrane device has a relatively small footprint, minimizing the overall plant size. The membrane design focused on the requirements of distributed hydrogen production for fuel cell vehicles. A H_2 refueling station requires up to 1,500 kg per day of 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

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/pd005_damle_2011_p.pdf

AccuSep® Palladium Membrane Module

Technology History

- Being developed by Pall Corporation in partnership with the Colorado School of Mines and the Oak Ridge National Laboratory.
- Commercialized Pd-alloy composite membrane on ceramic coated AccuSep® support media in 2011.

Applications

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

Capabilities

- Allows for near ideal separation of H_2 from other gas stream components.
- Achieves 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 H_2 production process.

Versatility

The membrane is readily amenable to small-, medium-, or large-scale industrial commercialization

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Hydrogen Distributed Production System

Commercial Technology

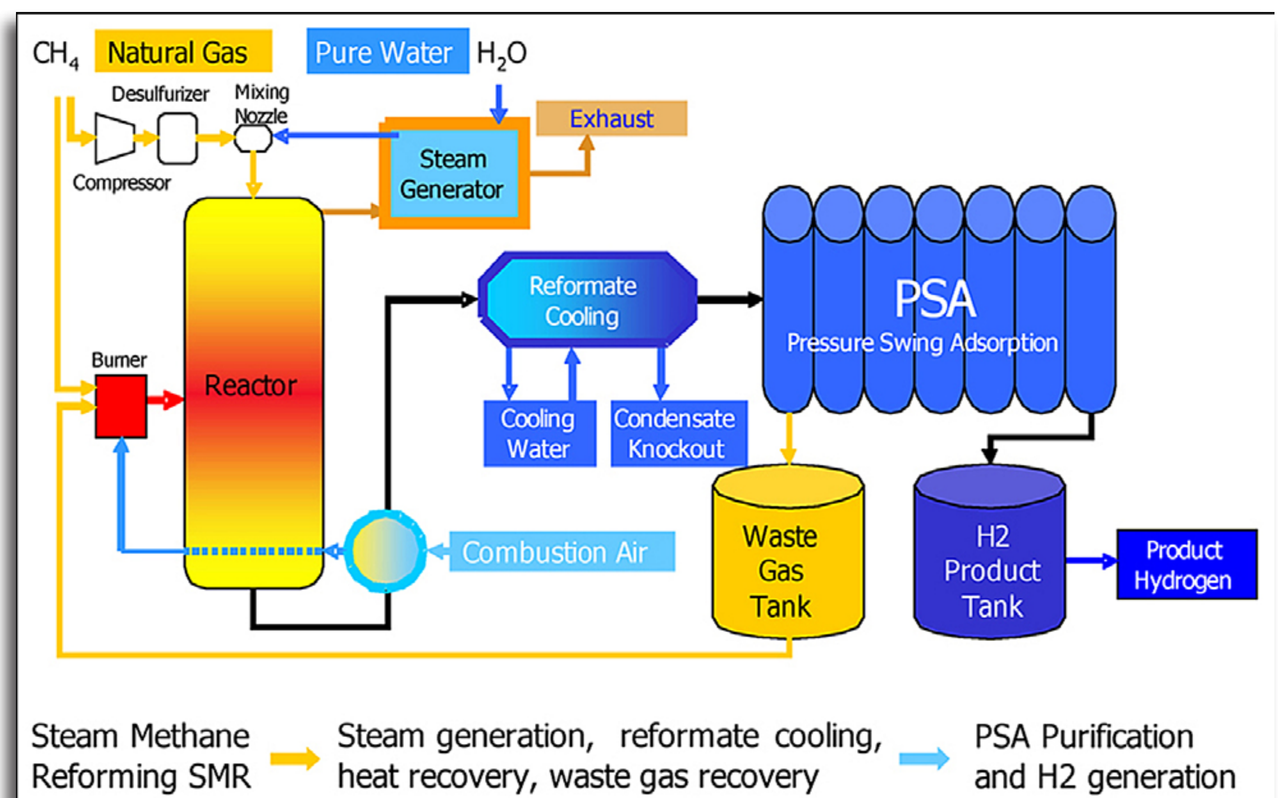
H_2Gen Innovations, Inc., with support from FCTO, developed compact steam methane reformers to address many of the acknowledged technical barriers that exist in the hydrogen production marketplace. On-site production of hydrogen eliminates transportation costs and enables end-users to directly control their hydrogen supply.

H_2Gen built and installed over 40 commercial hydrogen generation module (HGM) steam methane reformers with capacities from 113 kg/day (2,000 scfh HGM-2000 model) to 565 kg/day (10,000 scfh HGM-10000 model). The HGM eliminates the need to develop a national-scale hydrogen delivery infrastructure before sufficient fuel cell vehicles are on the road. In addition to providing a method for producing hydrogen for fuel cell vehicles, the HGM is also a cost-effective solution for the high-purity hydrogen needs of the industrial gas, chemical processing, pharmaceutical, and electronics industries.

At the end of 2009, H_2Gen sold its technology to Air Liquide, one of the world's leading industrial gas companies. Air Liquide provides bulk gases and related services to a diverse base of customers, including those in the chemical, food, pharmaceutical, metals, and automotive industries. Air Liquide will continue to offer on-site hydrogen solutions based on H_2Gen's technology.

Technology History

- Developed and launched in 2008 by H_2Gen Innovations, Inc., in partnership with Süd Chemie, Inc.
- Acquired by Air Liquide in December 2009.



Components of the HGM-10000

HGM-10000 Unit

Applications

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

Capabilities

- Achieves fuel efficiency of up to 73% high heating value and provides up to 99.999% pure hydrogen.[1]
- Produces a 200 or 300 psig hydrogen product and allows remote monitoring without the need for staffing.[1]

Benefits

Increased Capacity

Has five times the capacity of the previous HGM-2000 model.[1]

Modular Design

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

Production Cost Savings

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

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[1] For more information: http://www.osti.gov/scitech/servlets/purl/1008179

Hydrogen Generation from Electrolysis

Proton Energy Systems, Inc., with funding from FCTO, 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.[1] After further funding from the FCT 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.[2] In 2011, the HOGEN C series began to be sold. The HOGEN C is a larger, 65 Kg/day, unit than the S and H series.[3]

Through 2012 over 1300 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

[1] For more information: http://www.pogc.com.au/brochures/Proton-On-Site/HOGEN-S-Series.pdf
[2] For more information: http://www.fuelcellstore.com/en/pc/pdf/hogen_h.pdf
[3] For more information: http://www.pogc.com.au/brochures/Proton-On-Site/HOGEN-C-Series.pdf

Technology History

- Developed and marketed by Proton Energy Systems, Inc.
- Commercialized the HOGEN S series in 1999, HOGEN H series in 2004 and the HOGEN C series in 2011.

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%.[1]

Benefits

Ease of Integration

Provides 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.

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[1] For more information: http://www.pogc.com.au/brochures/Proton-On-Site/HOGEN-C-Series.pdf

Hydrogen Safety Sensor for Energy Applications

Commercial Technology

NexTech Materials, Ltd., with funding from FCTO (through the Edison Materials Technology Center) and the Ohio Third Frontier Program, has developed a hydrogen sensor, the SenseH_2™. Designed for hydrogen monitoring, the sensor is a solution for many applications. It includes a patent pending chemi-resistive ceramic sensor element, electronic controls, and an electronic signal output that is calibrated to measure hydrogen content in air, by providing a voltage output corresponding to 0 to 100% of the lower flammability limit. It offers a combination of features: high selectivity to hydrogen over other combustible gases and volatile organic compounds, rapid response and recovery, and linear and repeatable output corresponding to a broad range of hydrogen concentrations.[1] Sensors designed for gas flow streams underestimate hydrogen concentration in lower flow rate or static conditions. Modifying the sensor and packaging controls, NexTech has reduced the flow sensitivity of the SenseH_2 to provide an accurate and stable measurement of hydrogen over a wide range of flow conditions.

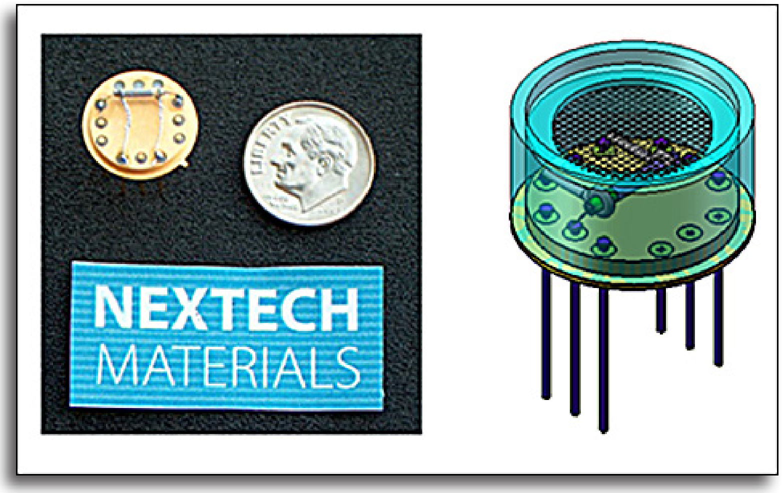
The SenseH_2, which made its debut at the Fuel Cell Expo in Japan in March 2010, is being commercialized by NTM Sensors, a newly created division of NexTech Materials. NTM Sensors intends to introduce several new products aimed at reduction of greenhouse gas and polluting emissions.

Technology History

- Developed by NexTech Materials, Ltd., beginning in May 2005.
- Commercialized in March 2010 and being marketed by NexTech Materials as the SenseH_2.

NexTech's SenseH_2 Hydrogen Sensor

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review04/fc_42_knight_04.pdf



Ceramic Sensor Element used in the SenseH_2

Applications

Can be used to detect hydrogen for the safe handling and implementation of hydrogen among fuel cell developers and electrolysis system developers and at distribution points in the emerging hydrogen infrastructure. The sensor also has applicability in many existing markets, including battery monitoring, semiconductor manufacturing, and laboratory safety monitoring.

Capabilities

- Detects the presence of hydrogen in air at concentrations from 0.2-4% H_2 in air, even under widely varying temperature and humidity conditions.
- Selectively measures hydrogen in the presence of carbon monoxide, methane, and volatile organic compounds.
- Responds and recovers rapidly, enabling measurement of transient leaks without false positives or signal saturation.

Benefits

Cost Savings

Offers low materials and fabrication cost at high production volumes.

Performance

Provides durability and reliability with fast response and recovery times.

Versatility

Accurately measures hydrogen over a wide concentration range, even in widely varying application conditions.

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ME100 Methanol Reforming Hydrogen Generator

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 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.

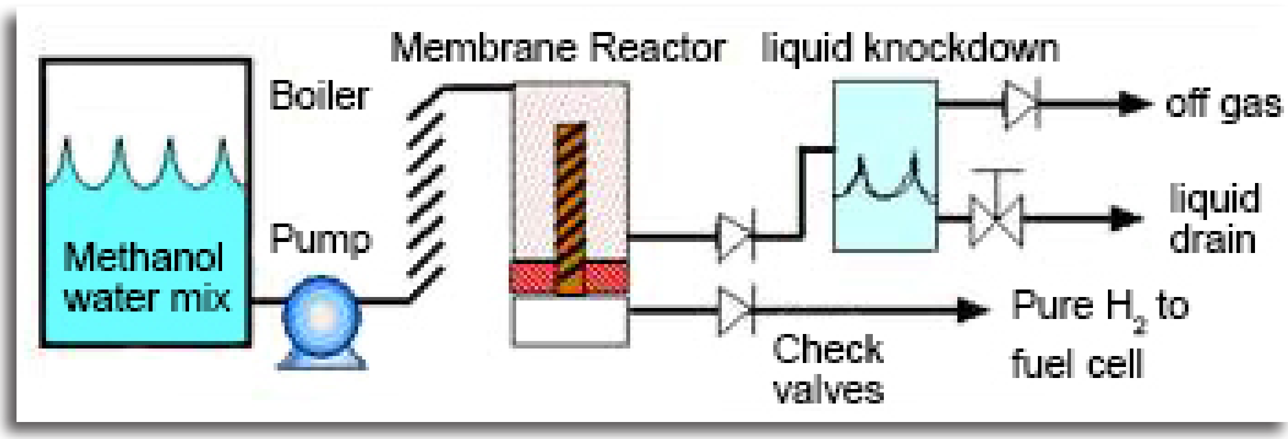
REB developed the membranes used in hydrogen generation reactors with support from FCTO and a DOE SBIR grant. REB designed and developed a form of membrane reactor steam reformer that allows heat transfer so that quantities of high purity hydrogen could be generated in a small volume process by reforming 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 faster and in a 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 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.

Technology History

- Developed and marketed by REB Research & Consulting to provide improved delivery of high-purity hydrogen.
- Have been selling hydrogen membrane reactors and various sizes of ME100 hydrogen generator systems since 2002.

The ME100 Generator System



Schematic of ME100 Reactor and Flows

Applications

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

Capabilities

- Produces high purity hydrogen (99.99995% pure) at a cost far lower than bottled gas.[1]
- Delivers continuous hydrogen output at a variable rate of up to 10 kg per day and at pressures up to 40 psig.[1]

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. Is safer and lighter than hydrogen bottles, eliminating the need for hydrogen inventory.

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[1] For more information: http://www.rebresearch.com/me100.html

Membrane Structures for Hydrogen Separation

Commercial Technology

Genesis Fueltech, Inc., with the help of DOE SBIR grants, developed a thin, pore-free membrane to be used in a hydrogen purifier module to separate hydrogen from other gases. 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. 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.[1, 2]

Technology History

- Developed by Genesis Fueltech, Inc., starting in 2005.
- Technology has been licensed.
- Commercialized the product in 2009.

Genesis Fueltech's Model 20L Reformers

[1] For more information: http://sbirsource.com/sbir/awards/136255-membrane-structures-for-hydrogen-separation
[2] For more information: http://www.google.com.mx/patents/US8110022

$$CH_3OH + H_2O \longrightarrow 3H_2 + CO_2$$

Methanol Reforming Reaction

Applications

Will be used to provide 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 less expensive than conventional units.[1]

Productivity

Can scale existing designs for industrial applications.

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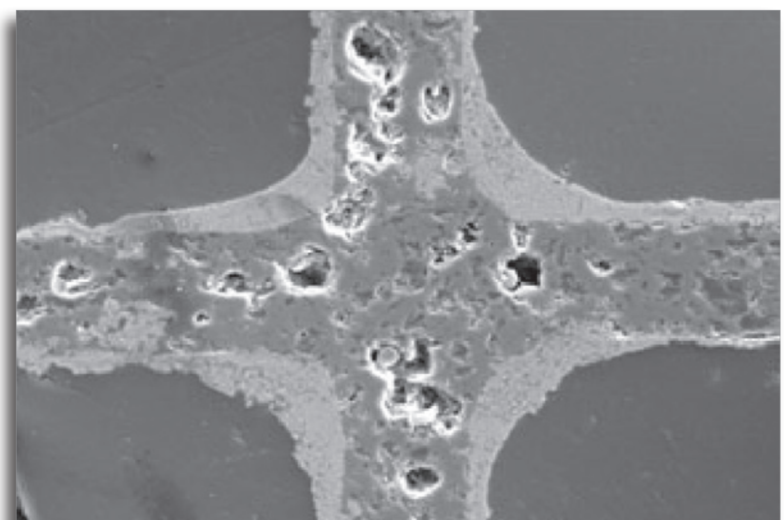
[1] For more information: http://sbirsource.com/sbir/awards/136255-membrane-structures-for-hydrogen-separation

Nanoscale Water Gas Shift Catalysts

Commercial Technology

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 FCTO. 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 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 (350ºC to 450ºC) and one for lower-temperature WGS reactions (250ºC to 350ºC). 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.

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).

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PEM Electrolyzer Incorporating a Low-Cost Membrane

Commercial Technology

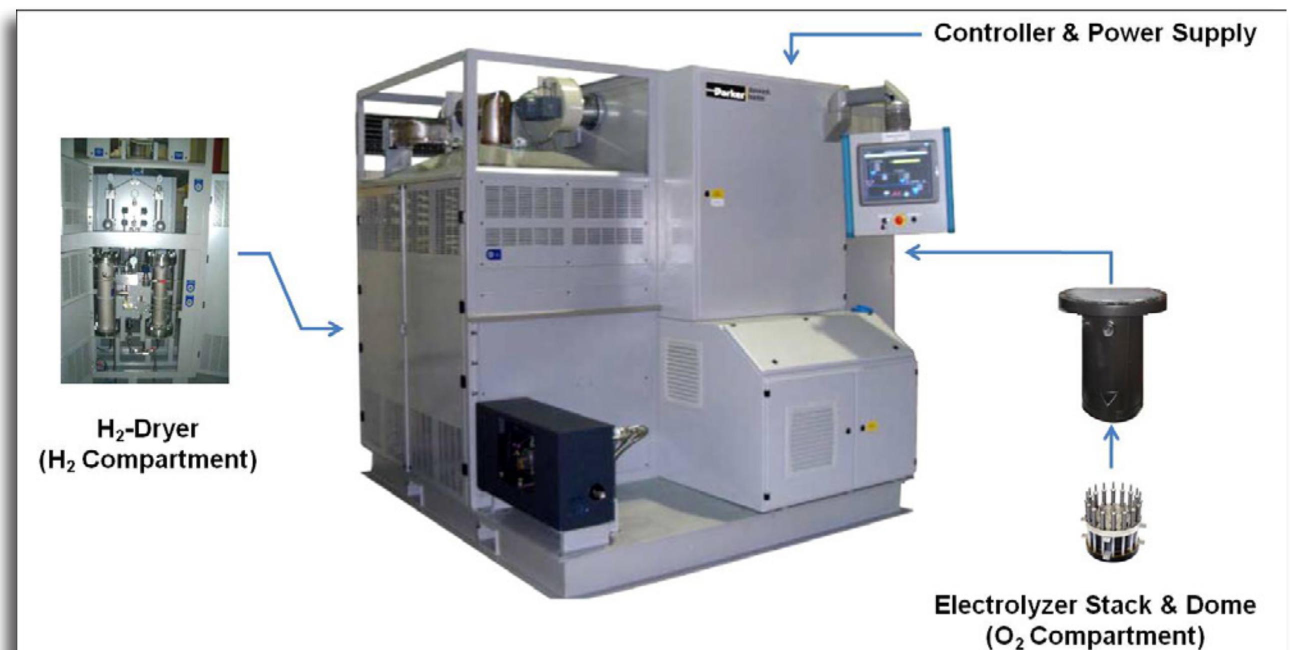
With funding from DOE SBIR grants and the FCTO, Giner Electrochemical Systems (GES), LLC, has developed proton exchange membrane (PEM)-based electrolyzer technologies that improve electrolyzer efficiency and reduce capital costs.[1] GES developed a dimensionally stable membrane (DSM™) with a support structure that minimizes changes in the membrane's dimensions (swelling/contraction) under high-pressure operation or changes in water content. This stability increases the membrane's durability and operational lifetime. A carbon-coated titanium cell separator (impermeable sheet that separates the hydrogen and oxygen compartments in the electrolyzer stack) was also developed that provides performance (electrically conductive and resistant to hydrogen embrittlement) at a fraction of the cost of niobium/zirconium cell separators. Additional cost-reducing features of the stack include an increased cell active area, a decrease in part count per cell (from 41 to 11), a 75% reduction in catalyst loading, and the use of molded thermoplastic cell frames. These technologies have combined to reduce the capital cost of the electrolyzer stack from >$2,500/kW in 2001 to <$500/kW in 2010, with projections of <$400/kW by 2012.[1]

GES and its partner, Parker Hannifin Corporation, are currently working to assemble a full electrolyzer system that will produce 0.5 kg-H_2/hr at an operating pressure of 350 psig. The system has been reviewed for safety considerations and includes a pressurized dome that encloses the electrolyzer stack for safety.

Technology History

- Developed and commercialized in 2011 by GES, in partnership with Parker Hannifin Corporation and the Virginia Polytechnic Institute and State University.

- Currently selling electrolyzer stacks and full electrolyzer systems.



GES's PEM Electrolyzer System

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/pd030_hamdan_2012_o.pdf

GES's 60 Cell Fuel Cell Stack

Applications

Can be used as an on-site source of hydrogen at industrial facilities, as an enabling technology for fuel cell vehicles, and as an energy storage device for renewable power generation that occurs during low demand times (e.g., wind).

Capabilities

- Produces 0.5 kg-H_2/hr at an operating pressure of 350 psig.[1]
- Uses a 27-cell electrolyzer stack with an active area of 290 cm^2 per cell.[1]

Benefits

Cost Savings

Reduces electrolyzer stack capital cost by using low-cost materials, lower catalyst loading, and a reduced part count per cell.

Durability

Uses components with long operating lifetimes (estimated at 55,000 hours for the DSM and >60,000 hours for the carbon/titanium cell separators).

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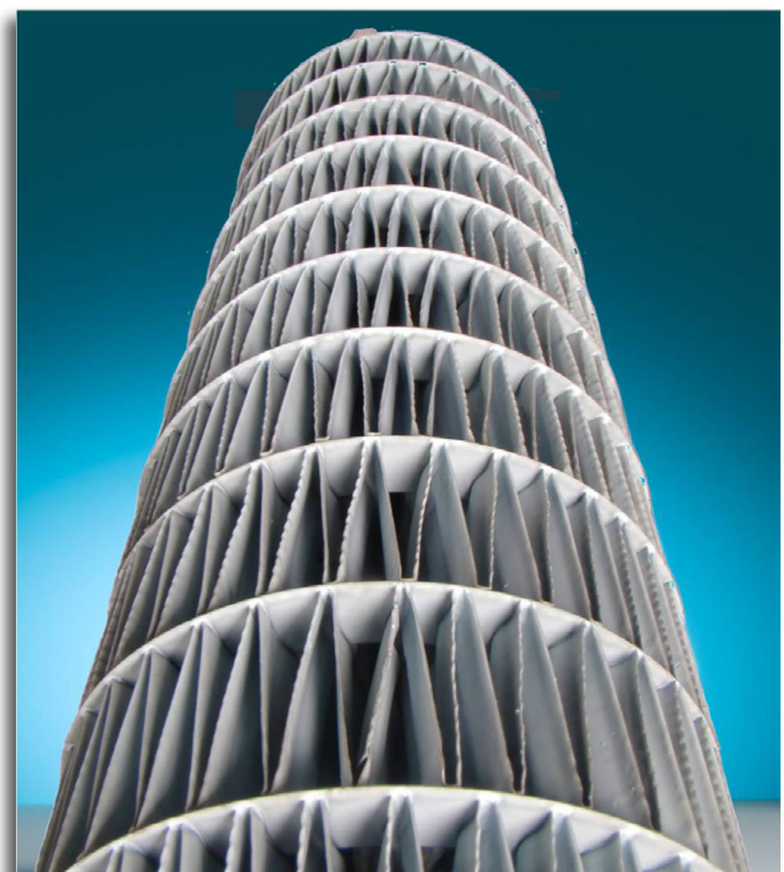
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/pd030_hamdan_2012_o.pdf

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

Catacel Corporation, with funding from FCTO, through the Edison Materials Technology Center, 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. Catacel's SSR technology leverages the heat transfer properties that thin foil structures have over ceramic pellets, which traditionally are used in hydrogen produced via steam methane reforming. SSR addresses the limited ability of the ceramic media to transfer heat from the combustion taking place outside the tubes, through the tube walls, and throughout the reaction occurring inside the tubes. The SSR's heat transfer properties reduces the temperature difference between the combustion and reforming zones, allowing lower furnace fuel combustion or reforming at higher flow rates of methane and steam.[1] In addition, SSR is a rigid and lightweight structure that does not have the failure modes associated with pellets and eliminates the periodic replacement required for ceramic packed beds, increasing the system's overall performance. Catacel's SSR demonstration plant, a commercial facility that produces hydrogen for a large steel mill, has been operating since 2008 and has surpassed 35,000 hours of operation.

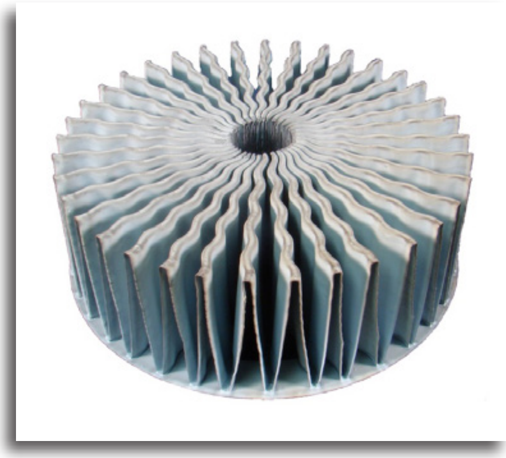
Technology History

- Developed by Catacel Corporation in partnership with Hydro-Chem, a subsidiary of the Linde Group, and the University of Toledo.
- SSR technology has been installed in international as well as national locations.



SSR Metal Fins Coated with High Activity Reforming Catalyst

[1] For more information: http://catacel.com/SSR-stackable-structural-reactor/



SSR Fin Arrangement

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.
- Retrofits into existing plant equipment without modification.

Benefits
Cost Savings
Lowers operating costs by enabling increased throughput or lower energy consumption. Also eliminates the periodic replacement of media.[1]

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

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[1] For more information: http://catacel.com/SSR-stackable-structural-reactor/

TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery

Commercial Technology

Lincoln Composites, Inc., with funding from FCTO, has developed large composite tanks and optimized hauling systems for storing and transporting energy gases, including compressed hydrogen gas. The TITAN™ Module is an International Organization for Standardization (ISO) frame system that is already in use worldwide for compressed natural gas. The ISO frame consists of four 38.5-ft-long units for a total capacity of 1600 lbs of compressed hydrogen at 3,600 psi (250 bar). The frame offers one solution for both transportable and stationary tanks and decreases the amount of infrastructure and equipment required. The larger tank size requires fewer valves and fittings, which increases system reliability and reduces costs. The larger diameter also means thicker tank walls, which make the tank more robust and damage tolerant. The Lincoln Composites' TITAN™ Module provides users with more than two times the compressed gas payload of steel tube trailers.[1] Lincoln Composites has addressed industry demand for more hauling capacity with the TITAN5™ system. The truck and semitrailer are lighter and, combined with increased payload, results in fewer trips from depot to point of use to meet customer demand. Fewer over-the-road deliveries not only increase public safety but reduce fuel consumption, capital expenditure for trucks and trailers, maintenance costs, and traffic congestion.

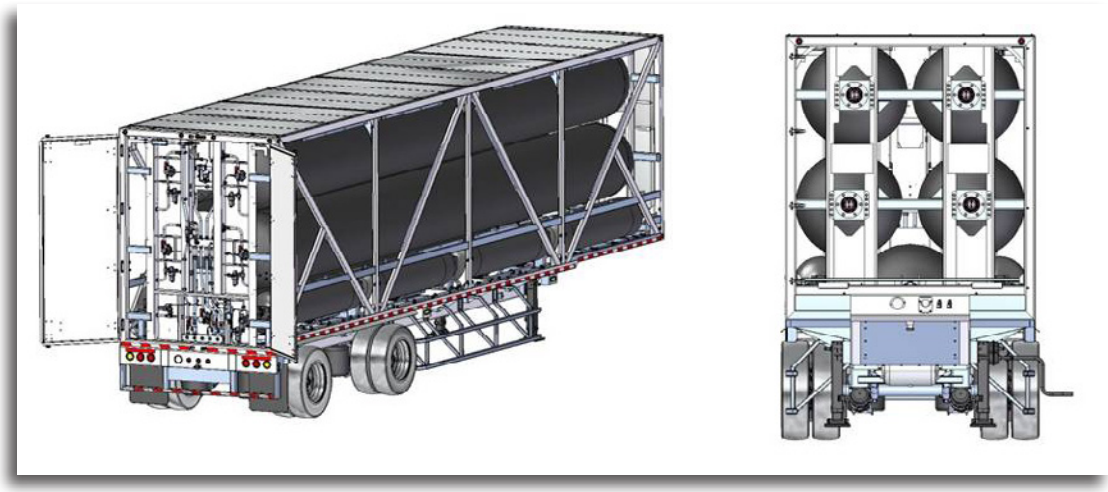
The capacity of the baseline TITAN5™ Trailer can be increased to 1775 lb by adding smaller pressure vessels in the available internal spaces flanking the lower tank to create the TITAN5™ Magnum configuration. Further capacity increases could also be achieved by increasing the system's operating pressure. Lincoln Composites will consider development and requalification of the TITAN product family at higher pressure when industry reaches consensus on pressure ratings for compressed hydrogen infrastructure and market demand offsets requalification costs.

Technology History

- Developed by Lincoln Composites, Inc.
- Now available in standard and higher capacity magnum configurations.
- Commercialized in 2011 and available worldwide (U.S. Department of Transportation Special Permit SP-14951).
- In planning stages for developing systems for higher pressures to meet future hydrogen industry performance and safety standards.

Lincoln Composites' 3,600 psi TITAN™ Tank and Frame System

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/iii_7_baldwin_2011.pdf



TITAN5™ Trailer Magnum Configured For Increased Capacity

Applications

Can be used to transport and store hydrogen and other compressed gases.

Capabilities

- Stores 616 kg of compressed hydrogen at 3,600 psi (250 bar).[1]
- Achieves a performance of 0.018 kg of hydrogen per liter of tank volume and 0.06 kg of hydrogen per kg of tank weight.[1]

Benefits

Cost Savings

Reduces costs by improving volumetric hydrogen storage capacity and hauling efficiency compared with conventional tube trailers.

Durability

Demonstrates ability to meet strength (burst and pressure cycling), environmental (corrosive fluids, extreme temperatures), and durability (flaw tolerance, penetration) targets.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/iii_6_knudsen_2012.pdf

C.3 Storage Technologies

Hydrogen Composite Tanks

Quantum Fuel Systems Technologies Worldwide, Inc., in cooperation with FCTO, designed 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.[1]

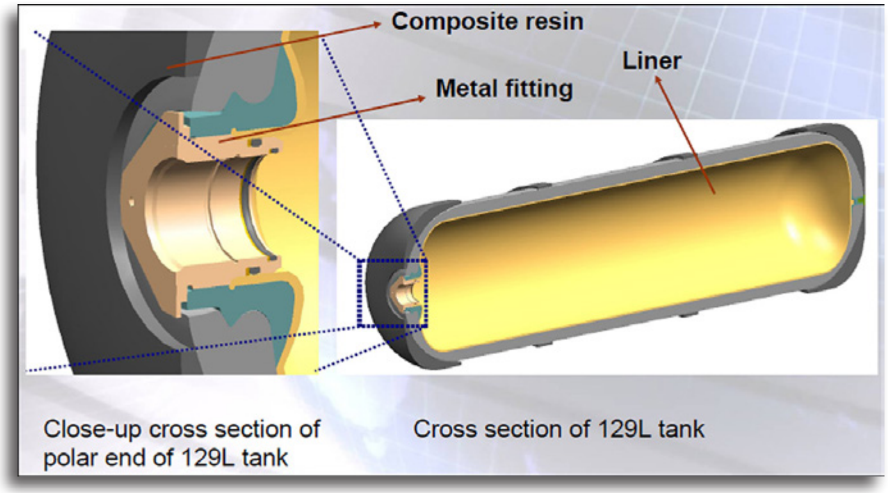
While the initial tanks have been a commercial success, Quantum continued to optimize the design with the aim of decreasing tank cost while maintaining structural performance. Current commercially available products use premium-grade materials to support challenging structural requirements for burst pressure. These materials require special design features and complex manufacturing techniques, which increase both the time of fabrication and the overall expense of the system. In order to meet the goals set for tank optimization, the following tasks were performed: (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.

Technology History

- Developed by Quantum Fuel Systems Technologies Worldwide, Inc., and commercially offered in 2001.
- Storage tank systems have primarily been sold to major automobile manufacturers.
- Optimized tank design to achieve safety and structural performance targets while reducing cost, weight, and size.

Quantum's Hydrogen Storage System

[1] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/32405b27.pdf



Quantum Technologies' Optimized 129L Tank

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 49% compared with equivalent-sized storage tanks at 5,000 psig.[1]
- Increases the safety and reliability of hydrogen storage and fuel delivery systems, exceeding current regulatory qualification requirements.

Benefits

Capacity

Offers high capacity, lightweight and fully validated high-pressure hydrogen storage systems that have been tested in the field.

Cost Effectiveness

Optimized tank designs reduce system expense by using cost-competitive materials with high structural integrity.

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.

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[1] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf

Sodium Silicide (NaSi) Hydrogen Generation System

Commercial Technology

With funding from FCTO, SiGNa Chemistry has developed a technology that uses a stable, room-temperature reaction between sodium silicide (NaSi) and water to generate hydrogen. NaSi and its derivatives are non-flammable, air-stable powders that are energy dense, safe to handle, chemically dormant before user activation, and do not degrade over time.[1] The chemical reaction generates hydrogen gas at pressures from 2 psi to 30 psi, with nontoxic, water-soluble sodium silicate as the only byproduct.

SiGNa can customize their NaSi cartridges to suit the shape and electricity generation needs of a particular application, including flatpacks for electronics and conformable cartridges for wearable fuel cell systems. Rapid and dynamic responses to start, stop, and restart commands are also possible. The cartridges are hot-swappable, enabling extended runtimes without an interruption of power. Power output is consistent over the entire runtime, without the degradation associated with batteries.

In addition to its performance features, SiGNa's technology is also safe and environmentally friendly. The NaSi powder can be stored in a dry-air container without oxidizing and has a demonstrated storage life of more than 5 years. The sodium silicate byproduct is nontoxic, environmentally benign and remains in the original fuel cartridge for easy recycling or disposal.[1]

SiGNa is currently supplying NaSi powder and customized cartridges to the Swedish fuel cell company myFC for use in their PowerTrekk™ fuel-cell-based charger for portable electronics. The PowerTrekk is expected to make its U.S. retail debut in April 2013. With a grant from the U.S. Agency for International Development (USAID), SiGNa also developed a NaSi-fueled, fuel-cell-powered generator that can be deployed in developing countries. The NaSi canisters can also aid in disaster relief efforts by powering emergency response systems, medical refrigerators, and telecommunications equipment.

SiGNa Chemistry's NaSi Powder Cartridges (left) and 300-W Fuel Cell Generator (right)

[1] For more information: http://signachem.com/wp-content/uploads/2013/10/3.1_NaSi-White-Paper-WEB.pdf

NaSi Cartridge being inserted into a PowerTrekk recharger

Technology History

- Developed and commercialized by SiGNa Chemistry, Inc.
- Supplying customized NaSi canisters to the Swedish fuel cell company myFC for use in their PowerTrekk fuel-cell-based charger for portable electronics.
- Worked with the USAID to develop a NaSi-fueled, fuel-cell-generator for use in developing countries.
- Working with a leading fuel cell developer to develop a 5-W hydrogen supply system for consumer electronics; product release is scheduled for April 2013.

Applications

Can be used to generate hydrogen for portable fuel cell applications (<3 kW) such as backup power, battery recharging, remote telecommunications back up, emergency response equipment, and charging personal electronic devices (e.g., digital cameras, laptops, cell phones, and GPS units).

Capabilities

- Generates reliable power that is not impacted by weather (as with solar-powered devices).
- Offers a higher energy density (energy per unit of mass) than batteries.
- Scalable (1 W to 3 kW) for a wide range of applications and future technology needs.
- Many different cartridge shapes are possible, including flat packs and bendable cartridges.

Benefits

Cost Savings

Reduces costs by using a room-temperature reaction, which does not require an expensive catalyst to produce hydrogen.

Safety

Uses a solid powder reactant that does not ignite or oxidize when exposed to air and is stable over all practical temperatures (-55°C to 300°C).

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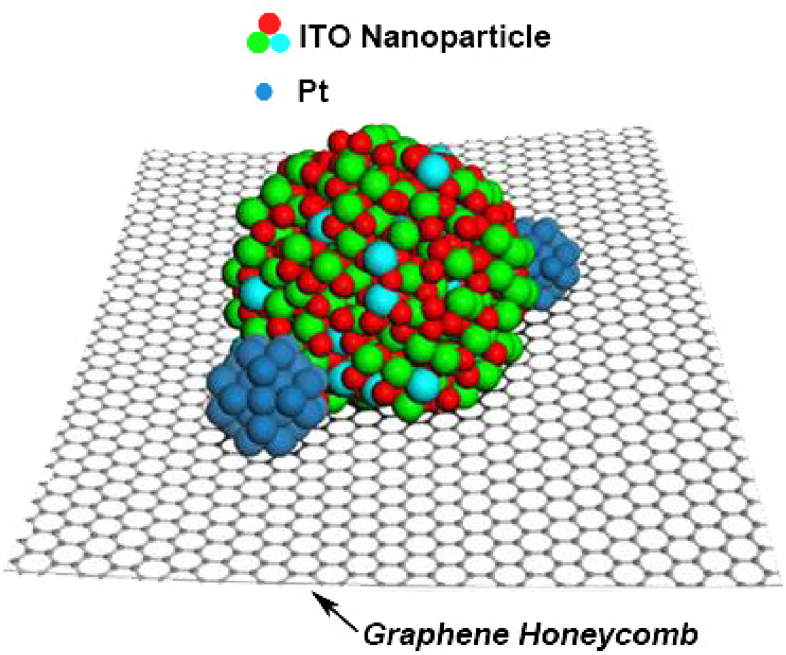
Appendix D:
Emerging Technology Descriptions

D.1 Fuel Cell Technologies

Alternative and Durable High-Performance Cathode Supports for PEM Fuel Cells

Emerging Technology

With assistance from FCTO, Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), and other collaborators are developing a technology to increase the durability of cathodes for PEM fuel cells. This technology takes advantage of the stable interface between platinum (Pt), a conductive metal oxide (CMO), and a carbon support. The stable interface provides conductive carbon for electron percolation and strong Pt-CMO bonding, which prevents catalyst migration and agglomeration.[1, 2] Producing these cathodes with CMO-modified carbon hybrid supports involves a solvothermal reaction of carbon with metal oxide precursors, followed by Pt nanoparticle loading using a chemical reduction method.



PNNL's Cathode Support Showing Triple Junction Formation

Technology History

Developed by PNNL, ORNL, the University of Delaware, Princeton University, and the Automotive Fuel Cell Cooperation Corporation.

Applications

Can be used for automotive or stationary fuel cell applications.

Capabilities

- Produces low carbon and noncarbon cathode catalyst supports for PEM fuel cells.
- Enables commercialization of transportation fuel cells.

Benefits

Performance

Provides higher activity because of the Pt-CMO synergy.

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Website: http://www.pnnl.gov

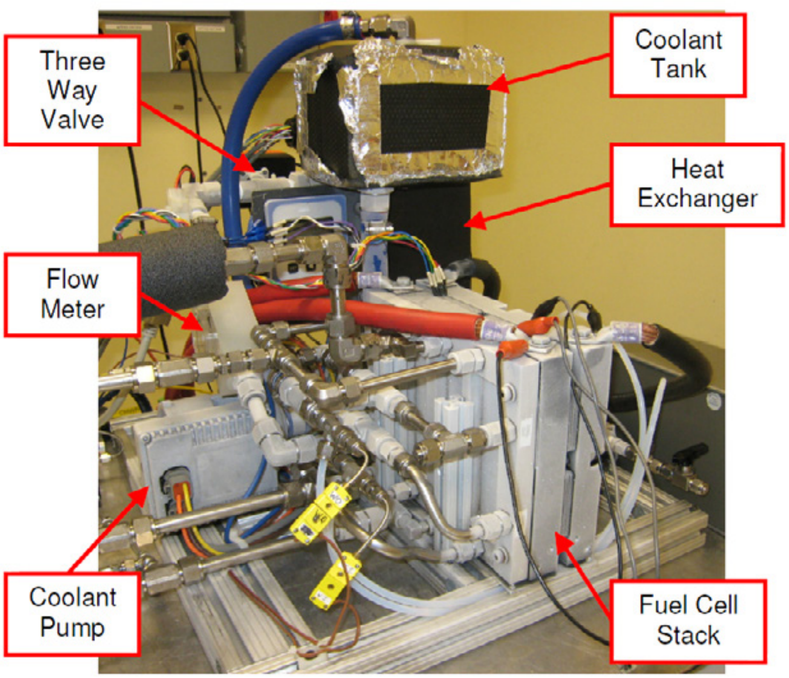
[1] For more information: http://www.princeton.edu/~cml/assets/pdf/pu_11_133kou.pdf
[2] For more information: http://sciencemag.org/content/211/4487/1121

CIRRUS: Cell Ice Regulation and Removal Upon Start-up

Emerging Technology

Nuvera Fuel Cells, Inc., with FCTO funding, developed novel fuel cell stack designs, coolant systems, and operational procedures that improve fuel cell performance under subfreezing conditions. Nuvera's original stack design, the Andromeda™ fuel cell, achieved DOE's targets for a quick start (30 seconds or less) from -20°C and less than 5 MJ of energy consumption for the complete start-up and shutdown cycle.[1] However, the thermal mass of the Andromeda prevented that stack architecture from achieving the -40°C target. To meet the extreme low temperature start goal, Nuvera developed a stack technology, the Orion™.[2] The Orion exploits higher current density operation (1.3 A/cm^2) to increase the power density of the stack (300 W per cell) and reduce its thermal mass, enhancing freeze starting ability.[2]

Testing with the Orion included developing an integrated coolant loop using ethylene glycol in order to more closely simulate freeze start conditions in an automotive system.[2] The stack design has demonstrated a startup to 50% of rated power in 28 seconds at -20°C and uses less than 3 MJ of energy for a complete start-up and shutdown cycle.[2]



Nuvera's Test Station for Fuel Cell Freeze Start Testing

Technology History

- Developed by Nuvera Fuel Cells, Inc. in partnership with W.L. Gore & Associates, Inc., SGL Technologies, and the University of Delaware.
- Development work completed and the current focus is on commercialization of the technology.

Applications

Can be used to improve fuel cell performance in applications involving sub-freezing conditions, such as automobiles, forklifts, backup power systems, and auxiliary power units.

Capabilities

- Achieves 50% of rated power in 28 seconds from a startup temperature of -20°C (DOE quick start target is 30 seconds).
- Uses only 2.94 MJ of energy for a complete startup and shutdown cycle (41% below DOE target of 5 MJ).
- Starts unassisted from -40°C.[2]

Benefits

Cost Savings

Reduces system costs by increasing fuel cell stack power density and improving water purging procedure prior to cold shutdown.

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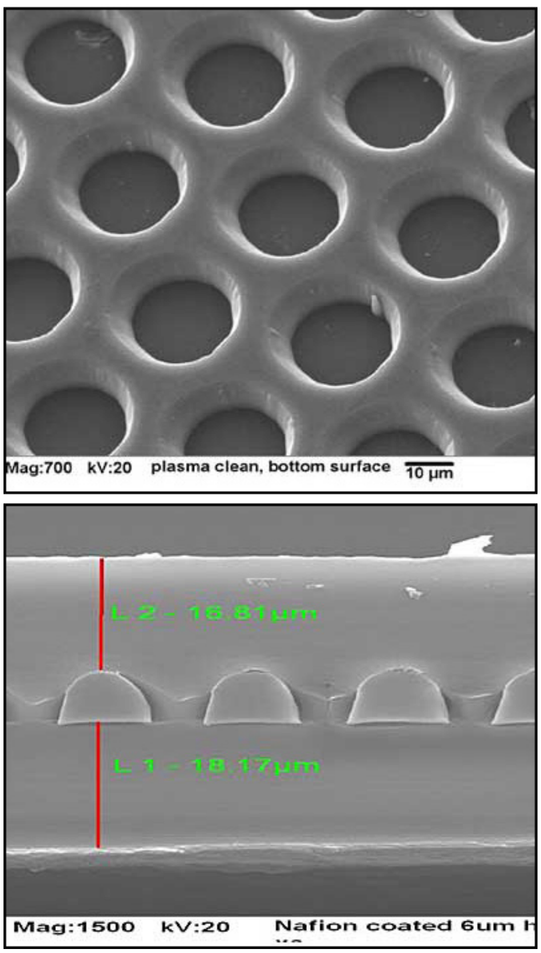
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review09/fc_38_conti.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review10/fc014_blanchet_2010_o_web.pdf

Dimensionally-Stable High-Performance Membrane

With funding from DOE SBIR grants and the FCTO, Giner Electrochemical Systems, LLC, is developing a membrane. Improved mechanical properties of their dimensionally stable membrane are achieved by using a high-strength support structure fabricated from high-performance engineering plastics.[1] 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.[1] Thus, higher performance, especially at lower relative humidity levels, can be achieved. Based on microfabrication technology, support structures can be fabricated with a continuous process. The membrane's property can be controlled by design and engineering of the patterns.[1]



Micrographs of Giner's Dimensionally Stable Membrane

Technology History

- Developed by Giner Electrochemical Systems, LLC.
- Continuing work on the Phase III 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.
- Improves 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.

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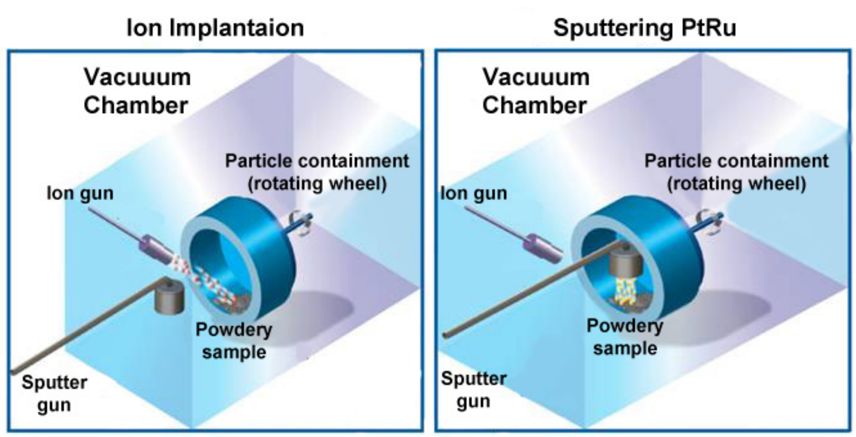
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/fc036_mittelsteadt_2013_o.pdf

Direct Methanol Fuel Cell (DMFC) Anode Catalysts

Emerging Technology

With assistance from FCTO, the National Renewable Energy Laboratory (NREL) and the Colorado School of Mines (CSM) have developed a DMFC technology with improved anode MOR catalytic activity and durability for platinum-ruthenium (PtRu) on carbon.[1] The work is focused on developing next-generation anode catalyst materials, based on a new technology, to accelerate commercialization and market adoption of DMFCs for consumer electronics applications. The catalyst-support interactions were optimized by ion-implanting (doping) the carbon support with a specific dosage of nitrogen and nitrogen functionalities (e.g., pyrollic, pyridinic, and graphitic).[1] While other dopant types were also found to have an effect on MOR activity and durability, nitrogen demonstrated the best improvement to date.[1]

The catalyst-carbon matrix is manufactured using a synergistic ion implantation and magnetron sputtering of metallic catalyst (PtRu) on high surface area carbon powders using a rotator reactor.[2]



NREL's Pt-Ru Catalyst Ion Implantation and Sputter Deposition Process

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review10/fc041_dinh_2010_o_web.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/v_j_1_dinh.pdf

Technology History

- Developed by NREL and CSM.
- Continuing work on correlating sputter-implantation parameters with catalyst structure and MOR performance and durability.

Applications

Can be used in constructing fuel cells for portable power applications.

Capabilities

- Improves catalyst performance and durability.
- Produces catalyst compositions on high surface area carbon materials using PtRu nanoparticles from a single composition PtRu alloy.

Benefits

Cost Savings

Reduces the material cost of the catalyst by an optimized deposition process, enhanced catalyst activity and improved durability.[1]

Manufacturability

Provides a dry scalable process for ion implantation and sputter deposition to high-surface-area carbon materials.

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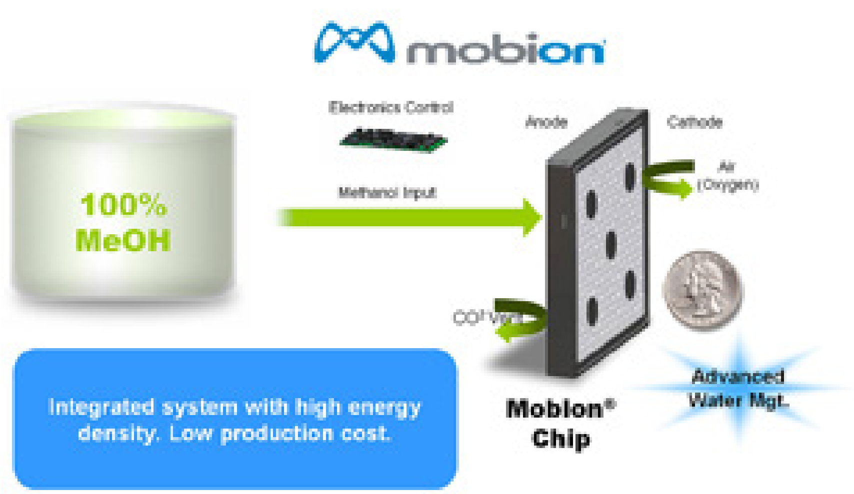
Direct Methanol Fuel Cell for Handheld Electronics Applications

Emerging Technology

MTI Micro Fuel Cells, Inc., with FCTO 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.

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.[1] 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.[2]



MTI Micro Fuel Cells' Mobion Technology

Technology History

- Developed by MTI Micro Fuel Cells, Inc., in partnership with the Methanol Foundation.
- Continued improvements to the unit are being made based on the result of field tests. Codes and standards work and approval are proceeding with a number of government agencies.[2]

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 (0ºC to 40ºC) and at any humidity level.[3, 4]

Benefits

Manufacturability

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

Performance

Achieves a power density of over 80 mW/cm^2 with a fuel energy of over 1.4 Whr/cc.[4]

Versatility

Allows fuel cartridge to be changed out while the device is operating, with no loss in power.[1]

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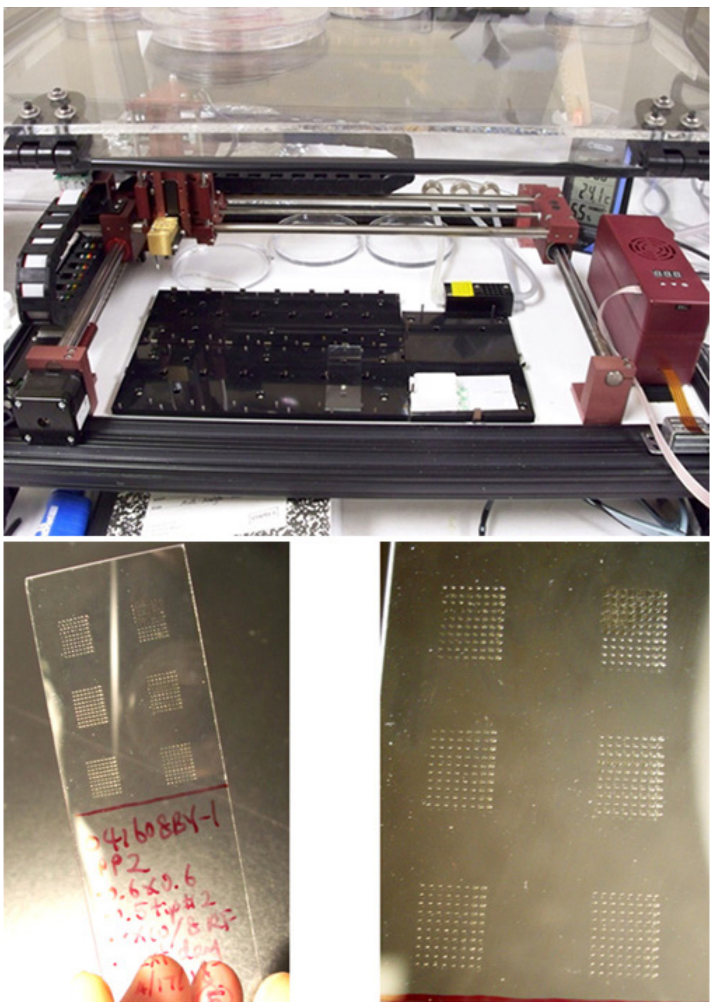
[1] For more information: http://www.mtimicrofuelcells.com/technology/product-direction.asp
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review10/ar-rah2001_carlstrom_2010_o_web.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/xi_1_carlstrom.pdf
[4] For more information: http://www.mtimicrofuelcells.com/technology/break-through.asp

Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors

Emerging Technology

With the help of DOE SBIR grants, InnoSense, LLC, is developing manufacturing processes, based on direct-write inkjet technology, for the high-volume fabrication of both the components and the complete sensor system. A high-volume fabrication process is being developed that will eliminate the individual calibration of each sensor by making many identical sensors in one batch.[1] 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, producing no arc or spark.



InnoSense's Sensor Fabrication Process Using Pin-Printing Techniques

Technology History

Developed by InnoSense, LLC, starting in 2006.

Applications

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

Capabilities

- Produces hydrogen sensors with improved consistency batch to batch.
- Uses pin-printing technology to fabricate hydrogen sensors.[1]

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.

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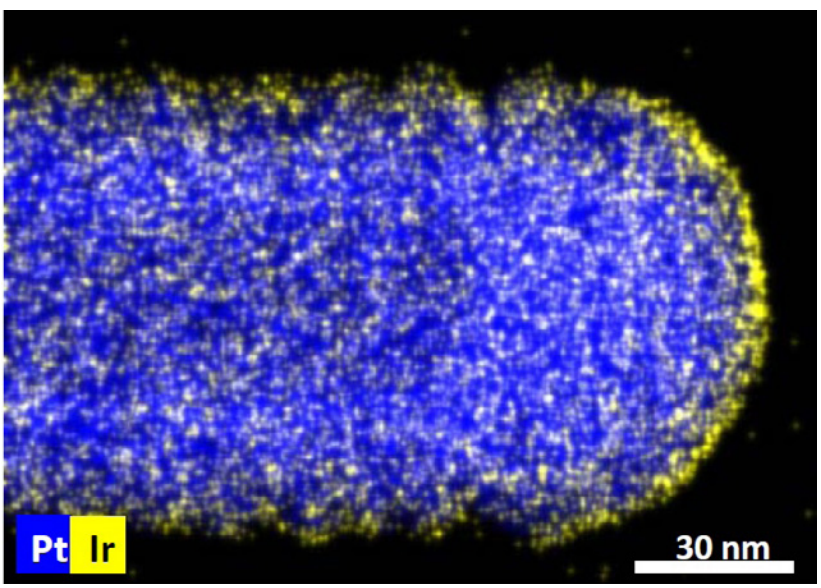
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress06/x_sbir.pdf

Durable Catalysts for Fuel Cell Protection During Transient Conditions

Emerging Technology

3M Company, with funding from FCTO, is developing catalyst materials to alleviate the damaging effects of transient conditions within the fuel cells. The materials are being developed by modifying the catalyst's behavior such that oxidation of water instead of carbon corrosion is the preferred reaction. For preferential oxidation to occur, the cathode potential is maintained near 1.23 volts, which is needed for water oxidation. Maintaining this cathode potential requires multiple regions of anodic activity and the presence of an oxygen evolution reaction catalyst. By balancing the reduction and oxidation reactions within the fuel cell, overpotential for a given current demand is reduced and lessens carbon and platinum dissolution.[1]

3M has developed nanostructured catalyst materials that address the specific reaction control requirements at each electrode.[1]



Energy Dispersive Spectroscopic Map of 3M's Self-Protecting Catalyst

Technology History

Developed by 3M Company and industry partners.

Applications

Can be used during transient conditions.

Capabilities

- Controls oxidation and reduction reactions at fuel cell electrodes to prevent self-destruction.
- Achieves DOE technical targets for performance, platinum group metal loading, and durability.[1]

Benefits

Cost Savings

Decreases cost by reducing the amount of high-cost material required.[2]

Durability

Improves durability by controlling catalyst reaction behavior during transient conditions.[1, 2]

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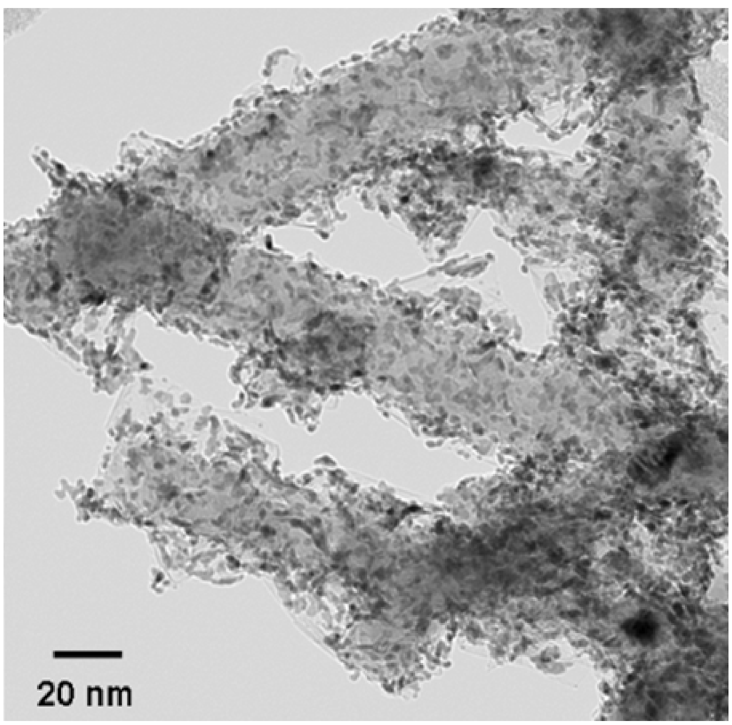
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_3_atanasoski_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review13/fc006_atanasoski_2013_o.pdf

Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells

Emerging Technology

Nanosys, Inc., with FCTO funding, has developed a catalyst support technology for use in hydrogen fuel cell vehicles. The technology is based on engineered nanostructures that improve performance characteristics. The nanowires consist of a silicon carbide (SiC) core with a conformal shell of thin and highly crystalline conductive nanographite. The nanographite, which extends from the nanowire surface, increases the total nanowire surface area to 125 m^2/g and protects the nanowire core against corrosive attack.[1] The network formed by the nanowires is robust and highly conductive and allows the fuel to access the catalyst particles deposited on the nanowire surface. At the same time, the highly interconnected network of electric conductors and electrolyte inherent to this structure provides efficient electron and proton transport in the catalyst layers of the membrane electrode assembly.[2, 3]



Platinum Catalyst Deposited on Nanosys' Silicon Carbide Nanowires

Technology History

Developed by Nanosys, Inc.

Applications

Can be used to increase performance and durability and reduce costs of PEM fuel cells.

Capabilities

Increases nanowire surface area to 125 m^2 per gram.

Benefits

Cost Savings

Enables high power density operation using reduced amounts of precious metal catalyst.[1]

Durability

Resists corrosive attack by acids or alkalis by using a nanographite shell covalently bonded to the silicon carbide (SiC) nanowire core.[1]

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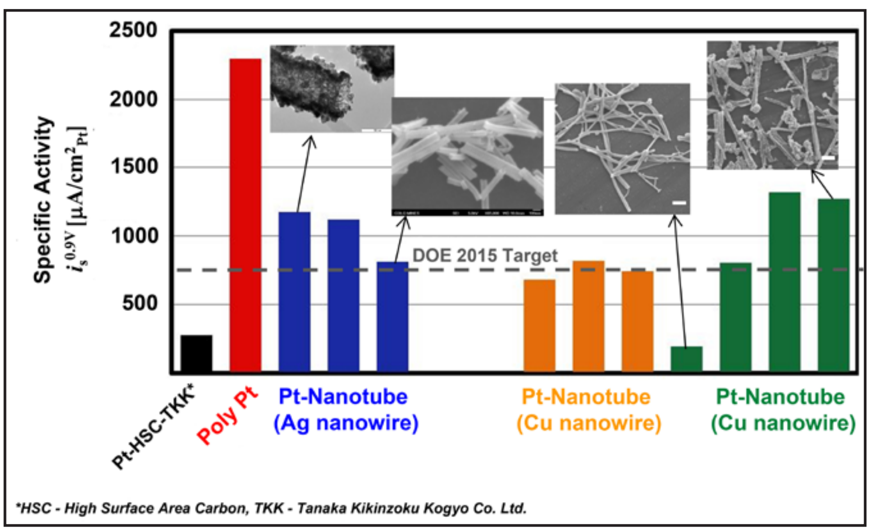
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review09/fcp_09_zhu.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress09/v_j_7_zhu.pdf
[3] For more information: http://www.osti.gov/scitech/biblio/959141

Extended Continuous Pt Nanostructures in Thick, Dispersed Electrodes

Emerging Technology

The National Renewable Energy Laboratory (NREL), with funding from FCTO, has been investigating Pt nanostructured catalysts with extended surfaces in order to address the low specific activities and low durability of traditional Pt catalysts supported on carbon. Using extended structure nanoparticle templates (typically nanowires) of metals (silver, copper, and selenium have been used), Pt extended thin film electrocatalyst structures have been synthesized using spontaneous galvanic displacement (SGD). In the SGD process, Pt ions in solution "steal" electrons from the less noble metal template materials, often resulting in Pt nanotubes being formed from the nanowire templates. The specific activities of several select materials have been examined and all had specific activities above the DOE 2015 target.[1]

These materials have maintained their specific activity advantages when placed into fuel cells. They have also shown enhanced durability to electrochemical cycling with and without the presence of carbon.[1] Current efforts are focused on further increasing the electrochemically available Pt surface area in order to meet DOE mass activity targets. Traditional Pt/C catalysts have ~100 m^2/g_{Pt}; typical extended surface structures have been limited to ~10 m^2/g_{Pt}. This project has attained electro-chemical activation >40 m^2/g_{Pt}. The observed mass activity of this material, 330 milli amps/g_{Pt} (at 900 $mV_{IR\text{-}free}$), approaches the DOE 2015 target of 440 milli amps/g_{Pt} (at 900 $mV_{IR\text{-}free}$).[1]



NREL's Pt Electrode Nanostructured Technology

Technology History

- Developed by NREL with academic and industrial partners.
- Continued work to increase the Pt surface area and deploy in fuel cell electrodes.

Applications

Can be used in polymer electrolyte fuel cells.

Capabilities

Uses galvanic displacement to produce continuous Pt nanostructures.

Benefits

Cost Savings

Uses less Pt material to reduce material cost and the balance of plant cost to process the materials; e.g., the need for compressor and expander equipment is lessened.

Durability

Improves durability against cycling and carbon corrosion.

Performance

Increases fuel cell performance through high specific activity of the material.

Scalability

Uses a wet chemical production process, which is scalable, to produce material quantities required for mass production.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_4_pivovar_2012.pdf

Fuel Cell Membrane Measurement System for Manufacturing

Emerging Technology

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 been issued a U.S. patent (No. 7,652,479) 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.[1] 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.
- Currently offering potential customers a trial prototype unit to solicit feedback on unit performance.

Applications

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

Capabilities

Uses bare, as-manufactured membrane or MEA samples.

Benefits

Cost Effectiveness

Achieves consistent results, thus lowering manufacturing costs through less waste.[1]

Performance

Improves fuel cell membrane manufacturing efficiency by using high throughput testing.[2]

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[1] For more information: http://www.moorebusiness.org/wp-content/uploads/2009/07/Scribner-Associates-DoE-contract-press-release-11-1-07.pdf
[2] For more information: http://www.sciencedirect.com/science/article/pii/S1464285907700949

Fuel-Cell-Based Mobile Lighting

Emerging Technology

Sandia National Laboratories and industry partners, with funding from FCTO, are developing a clean, energy-efficient technology based on fuel cell power for mobile lighting systems. The fuel cell mobile light system employs a 5-kW hydrogen fueled proton exchange membrane (PEM) fuel cell that powers plasma lighting. The fuel cell is a zero-emissions power generation source, releasing only slightly humidified warm air.[1] The combination of fuel cell efficiency with plasma lighting allows an improvement in overall energy efficiency.[2]

The project has focused on designing, building, and deploying five fuel cell mobile lighting systems to replace existing diesel-powered lighting towers commonly seen along highways in road maintenance work. After the fuel cell mobile lights are field tested, Multiquip Inc. plans to commercialize them as the H2LT mobile lighting system.[3]

Sandia's Fuel Cell Based Mobile Lighting System by Multiquip Inc.

Technology History

Developed by Sandia National Laboratories, Altergy Systems, Boeing, California Fuel Cell Partnership, California Department of Transportation (Caltrans), Golden State Energy Corp., Lumenworks Inc., Luxim Corp., Multiquip, Ovonic Hydrogen Systems, Saunders Electric Inc., San Francisco International Airport and Stray Light Optical Technologies.

Applications

Can be used for numerous off-grid lighting applications, e.g. road construction, aviation ground support, entertainment lighting and other temporary lighting applications.

Capabilities

- Produces mobile lighting using eight 23 kilo-lumen plasma lamps.
- Provides 2.5kW of auxiliary AC power.[2]
- Achieves zero emissions at point of use.

Benefits

Efficiency

Provides system efficiency by using a PEM fuel cell and plasma lighting.

Flexibility

Can be used indoors or outdoors.

Safety

Reduces noise and eliminates emissions.

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[1] For more information: http://lighting.com/sandia-fuel-cell-light-award/
[2] For more information: http://www.multiquip.com/multiquip/h2lt.htm
[3] For more information: http://www.hydrogen.energy.gov/pdfs/review11/mt010_klebanoff_2011_p.pdf

GenSys® Blue: High-Temperature CHP Fuel Cell System

Emerging Technology

Plug Power Inc. developed a high-temperature PEM system that provides electricity generation and waste heat. The GenSys Blue uses polybenzimidazole membrane technology that enables fuel cell operation at 160°C-180°C. Heat generated from this system is of sufficient temperature to meet thermal comfort demands,[1] allowing the GenSys Blue to be connected to existing hydronic or forced-air heating systems. The unit is fueled by natural gas and has an autothermal reformer for generating the hydrogen used by the fuel cell. A natural gas burner is integrated into the system to enable a response to increased home heating needs.

With assistance from FCTO (as part of the American Recovery and Reinvestment Act), Plug Power is conducting tests in both laboratory and real-world settings to demonstrate the durability and economic value of the GenSys Blue and to verify its readiness for the commercial marketplace. A fleet of six units has been undergoing long-term testing in Plug Power labs to generate reliability statistics and identify potential engineering improvements to the design. Additional units will be installed and field-tested at residential and light-commercial sites provided by project partners Sempra Energy and the University of California, Irvine.

Plug Power's GenSys Blue Fuel Cell System

Technology History

- Developed by Plug Power Inc. and currently demonstrating units with partners Sempra Energy and the University of California, Irvine.
- Currently running commercial demonstration units at end-user locations in California.

Applications

Can be used to provide electricity, space heating, and hot water for residential and light commercial buildings.

Capabilities

- Provides up to 5 kW of electricity and 28,000 Btu/hr of usable heat.[2]
- Achieves electrical and CHP efficiencies of 30% and 85%, respectively (lower heating value).[3]
- Uses an integrated natural gas burner when a rapid response to home heating needs is required.

Benefits

Compatibility

Integrates with existing hydronic and forced-air heating systems.

Emissions Reductions

Reduces residential CO_2 emissions by 25%-35%.[2]

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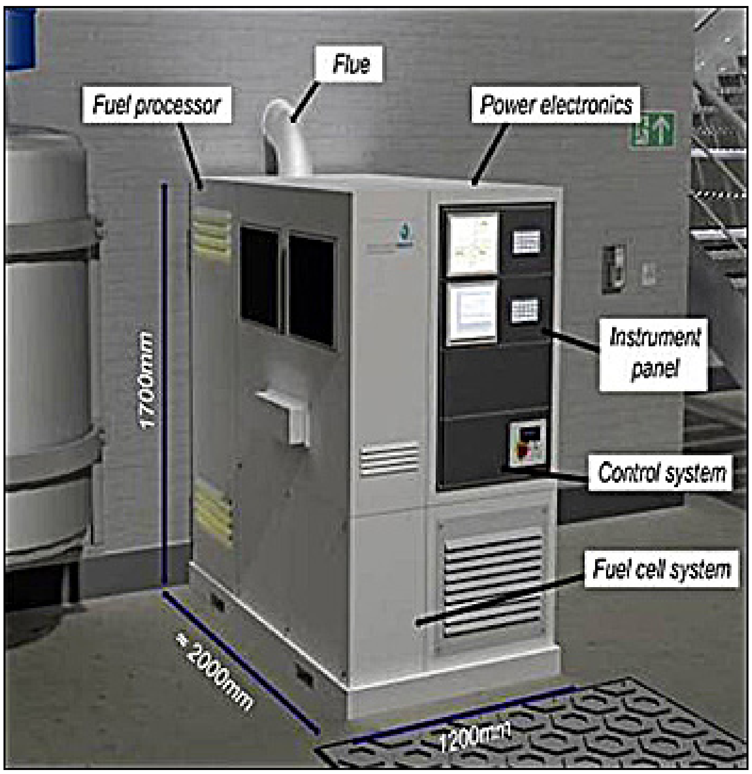
[1] For more information: http://www.plugpower.com/userfiles/GenSys%20HT%20MK.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review11/h2ra003_rohr_2011_o.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/xii_12_rohr_2011.pdf

High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System

Emerging Technology

Intelligent Energy Inc., with funding from FCTO, has developed a high-efficiency polymer electrolyte membrane (PEM) fuel cell combined heat and power (CHP) system. The system works by first converting a hydrocarbon feedstock into pure hydrogen. This clean fuel is then supplied to a fuel cell, where hydrogen and oxygen react to create an electric current. Heat is also released and can be used for space heating, hot water, or various industrial applications.

The CHP system demonstrated its capability as part of the International Partnership for the Hydrogen Economy (IPHE) initiatives in 2011.[1] Extended in-house testing at Intelligent Energy (IE) as well as at customer field test sites are underway.



Intelligent Energy's Series 7 10-kWe CHP System

Technology History

- Developed by Intelligent Energy Inc. in collaboration with Scottish and Southern Energy Ltd.
- The CHP system is undergoing CE certification testing and field testing.

Applications

Can be used to provide electrical and space heating requirements for light-industrial installations or multi-residential dwellings.

Capabilities

- Achieves 35% electrical efficiency, with greater than 70% combined efficiency possible (dependent on application).[2]
- Enables virtually silent operation.

Benefits

Durability

Reduces the frequency of maintenance periods by using local and remote system health monitoring.[2]

Versatility

Can be configured to provide emergency backup power if a grid failure occurs.[3]

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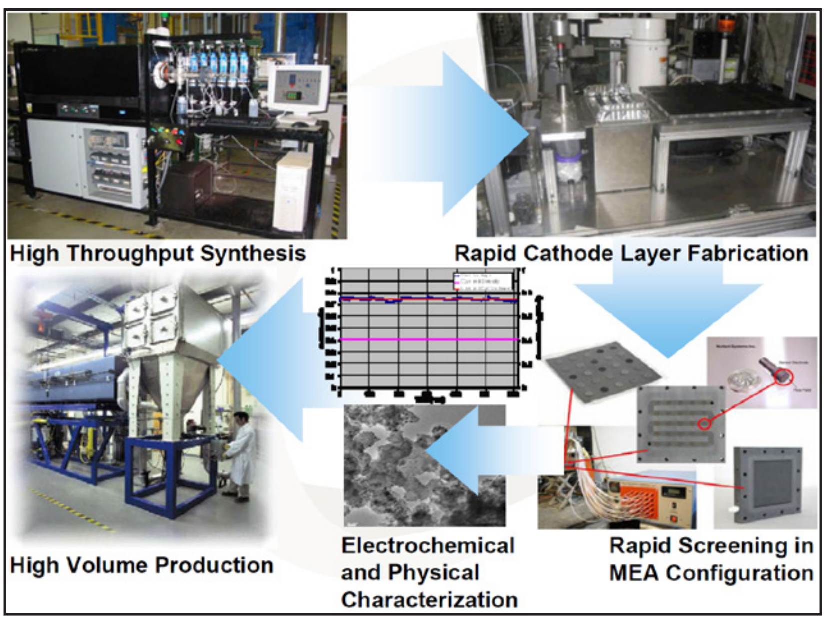
[1] For more information: http://www.iphe.net/docs/Meetings/Germany_11-11/presentations/(2)%20Hayter%20Intel%20Energy.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_j_1_tock_2012.pdf
[3] For more information: http://www.intelligent-energy.com/distributed-power-generation

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

Emerging Technology

Cabot Superior MicroPowders (CSMP) and partners, with funding from FCTO, has developed a complete system for combinatorial discovery of fuel cell electrocatalysts consisting of rapid powder synthesis, primary electrochemical testing screen, automated electrode printing, and 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 an improvement in Pt mass activity compared with that of pure Pt electrocatalysts.[1] 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,[1] 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,[2] exceeding the DOE targets set at the beginning of the project. Selected Pt-alloy compositions also demonstrate improved durability[1] when tested under load cycling protocols. The improved performance of MEAs incorporating Pt-alloy compositions was also validated by testing in short stacks.[1]



Cabot's High Throughput Catalyst Discovery Platform

Technology History

- Developed by Cabot Superior MicroPowders in partnership with DuPont Fuel Cells, CFD Research Corporation, and Hydrogenics Corporation.
- Sending small sample quantities to potential customers and waiting for larger orders.

Applications

Can be used to develop and test new MEAs.

Capabilities

- Provides electrochemical testing.
- Provides a combinatorial electrocatalyst synthesis platform based on spray conversion.[3]
- Allows platinum to be reduced while maintaining performance.

Benefits

Cost Savings

Allows synthesis and testing of electrocatalysts and reduces research costs.[3]

Performance

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

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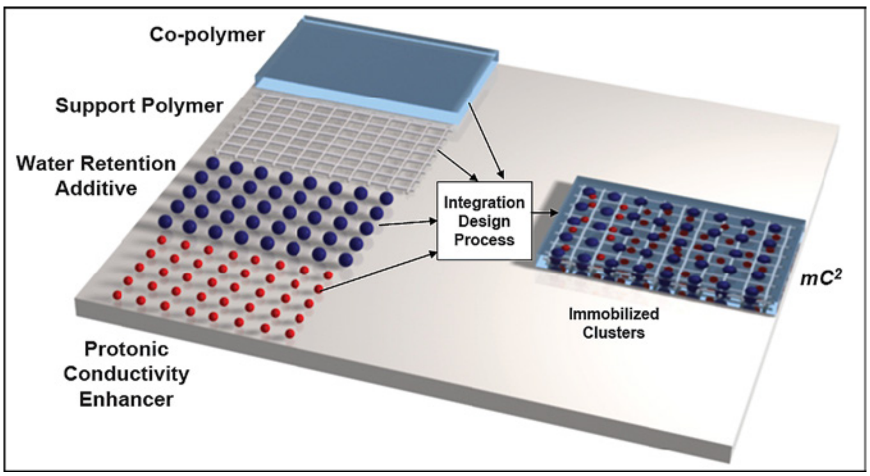
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress05/vii_c_5_atanassova.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review06/fc_16_atanassova.pdf
[3] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/ive5_atanassova.pdf

High-Temperature Membrane with Humidification-Independent Cluster Structure

Emerging Technology

FuelCell Energy, Inc., with FCTO 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.

FuelCell Energy's composite membrane (mC²) 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 a perfluoro sulfonic acid. 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.[1] This path is designed to transport protons at high temperature as well as subfreezing conditions.[1] Moreover, the additives further reinforce the mechanical properties of the composite membrane. Conductivity and durability testing of the mC² is continuing.



FuelCell Energy's Composite Membrane Concept

Technology History

- Developed by FuelCell Energy, Inc., in partnership with the University of Central Florida, Scribner Associates, Inc. and Oak Ridge National Laboratory.
- Improved cathode electrode formulation enabled a fuel cell with mC² membrane to reach performance at rated power of 1247 mW/cm² (DOE 2017 target: 1000 mW/cm²).[2]

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.[1]
- 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.[1]

Durability

Increases mechanical strength.[1]

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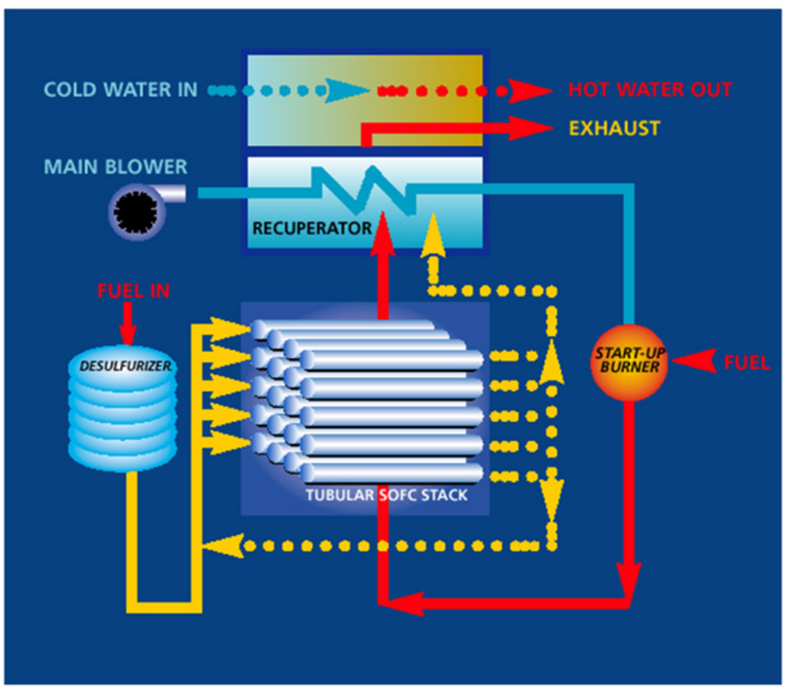
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_c_3_lipp_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review12/fc040_lipp_2012_o.pdf

Low-Cost 3-10 kW Tubular SOFC Power System

Emerging Technology

Acumentrics Corporation, with FCTO funding, is developing an SOFC power system. The Acumentrics design employs discreet tubes bundled in parallel. Several key aspects of the system are being investigated, including improving fuel cell power and stability, reducing the cost of cell manufacturing through increased yield and reduced material consumption, and increasing overall system efficiency by developing simplified controls and balance-of-plant components.[1] Acumentrics has reduced the number of tubes required to generate 1.25 kW of electricity from 126 to 20, reducing weight/volume and saving costs.[2] In addition, a recuperator has been developed to recover waste heat from the fuel cell exhaust stream. The Acumentrics system has demonstrated electrical efficiencies of 35-40% and a CHP efficiency of 85%.[1] On-site simultaneous generation of heat and power will increase efficiency and lower energy costs to consumers.[2]



Flow Diagram of Acumentrics' Tubular SOFC Power System

Technology History

- Developed by Acumentrics Corporation in partnership with Argonne National Laboratory, Ariston Thermo Group, and the Office of Naval Research.
- Continuing work on commercialization and durability by field testing remote power units.

Applications

Can be used to provide electricity and hot water in residential applications. Also looking at remote power and military uses.

Capabilities

- Achieves 85% CHP energy efficiency (1-kWe wall-hung system).
- Operates for more than 5,000 hours with a degradation rate of less than 1% per 1000 hours.[1]
- Adjusts from 10% to 90% of rated power in less than three minutes.[1]

Benefits

Cost Savings

Reduces costs by using an isopressing process for tube manufacturing, which enables high-volume throughput and reduced material waste.[2]

Durability

Handles fuels such as natural gas and propane, without requiring an external reformer to produce hydrogen.

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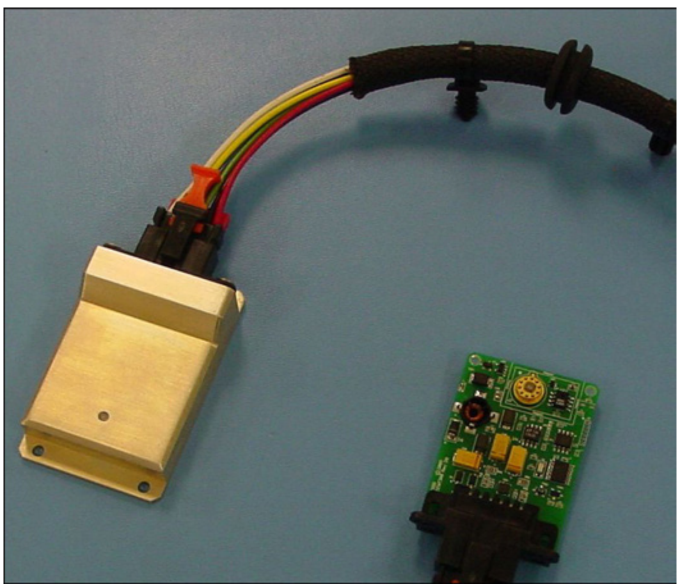
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_k_1_bessette_2011.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review09/fc_28_bessette.pdf

Low-Cost Hydrogen Sensor for Transportation Safety

Emerging Technology

Makel Engineering, Inc., has developed, with funding from FCTO 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.[1] The system was designed around Makel's current 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).[2] 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 monitoring of hydrogen leaks in fuel cell automobiles, stationary power supplies, and other areas where hydrogen leakage poses a safety concern.



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. Actively seeking funding and commercial partnership opportunities.

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.[3]

Safety

Detects hydrogen from 50 ppm up to 100% in oxygen and inert backgrounds.[2]

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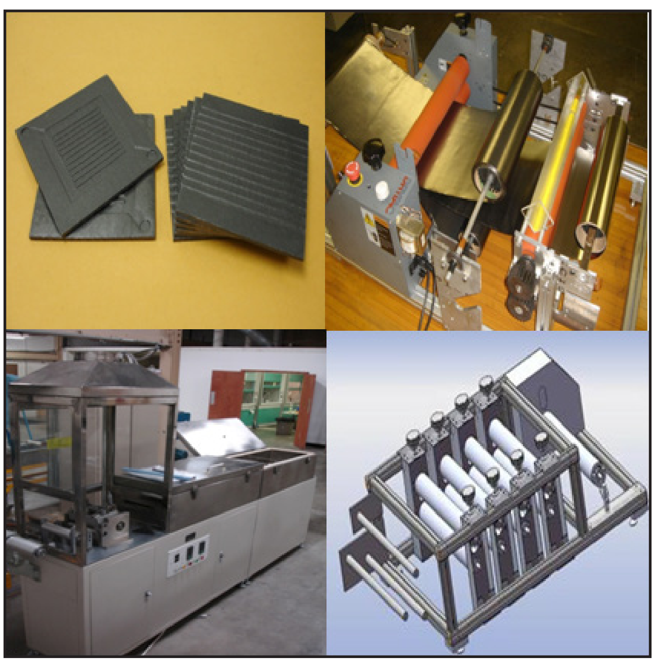
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review10/pd043_martin_2010_p_web.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress07/ii_k_5_martin.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress06/v_h_3_martin.pdf

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

Emerging Technology

Nanotek Instruments Inc., with the help of DOE SBIR grants and in collaboration with the National Composite Center, is developing a class of sheet molding compound (SMC) bipolar plates and related mass-production processes. The composition of the SMC consists of a thin nanocomposite core layer sandwiched between two sheets of flexible graphite (FG). The nanocomposite consists of thermo set resin and conductive nanofiller (graphitic nanofibers) and nano-scaled graphene plates.[1] The nanocomposite lowers material costs and improves electrical, mechanical, and gas permeation resistance properties.[1] These nanocomposite materials can be as thin as 0.125 mm.[1]

The developed FG-SMC bipolar plates meet or exceed DOE targets for conductivity, cost per kilowatt, weight, gas permeation rate, corrosion, strength, and flexibility.[1, 2] Nanotek has demonstrated a roll-to-roll SMC fabrication process, which continuously produces a nanocomposite core laminated on both sides with flexible graphite sheet and partially cured resin.[2] This sheet can then be die-cut, molded into the desired shape, and fully cured. The process can similarly fabricate fluid flow channels using in-line embossing and curing on the outer surfaces of the SMC laminate to produce bipolar plates.[2]



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

Technology History

Developed by Nanotek Instruments, Inc. and industry collaborators.

Applications

Can be used to develop bipolar plates for fuel cells using sheet molding compound manufacturing techniques.

Capabilities

Allows large-scale manufacturing of sheets of bipolar plate material.[2]

Benefits

Productivity

Reduces manufacturing costs through large-scale sheet manufacturing and significantly reduces fuel cell weight, dimensions, and contact resistance.[2]

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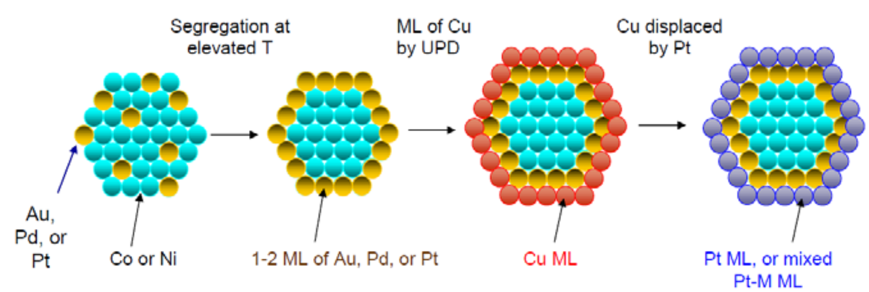
[1] For more information: http://www.freepatentsonline.com/8518603.html
[2] For more information: http://www.docstoc.com/docs/26151070/Manufacturing-of-Integrated-Diffuser-Bipolar-Plates-for-PEM-Fuel---PowerPoint

Low Platinum Loading Fuel Cell Electrocatalysts

Emerging Technology

Brookhaven National Laboratory (BNL), with funding from FCTO, has developed patented anode electrocatalysts having low platinum loading that resist CO poisoning.[1] 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.[1] 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.[1]

For oxygen reduction, BNL is also developing a class of cathode electrocatalysts consisting of platinum monolayers deposited on the surfaces of noble metal/non-noble metal core-shell nanoparticles. These electrocatalysts have been demonstrated to have high activities and a very low platinum mass in the monolayer.[2] The platinum monolayers were electrodeposited on metal or alloy nanoparticles using galvanic displacement of a copper monolayer.



Synthesis Route for BNL's New Class of Cathode Electrocatalysts

[1] For more information: http://www2.egr.uh.edu/~ecnfg/9.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review11/fc009_adzic_2011_o.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_6_adzic_2012.pdf

Technology History

Developed by BNL in collaboration with Los Alamos National Laboratory, Battelle Memorial Institute, 3M Company, Plug Power Inc., and General Motors Company.

Applications

Can be used in fuel cells to enhance their performance by eliminating CO poisoning.

Capabilities

- Survives in a CO environment without degradation.[1]
- Allows the use of less platinum while maintaining performance.[2]

Benefits

Cost Savings

Reduces costs due to lower content of noble metal.[3]

Durability

Resists CO poisoning.

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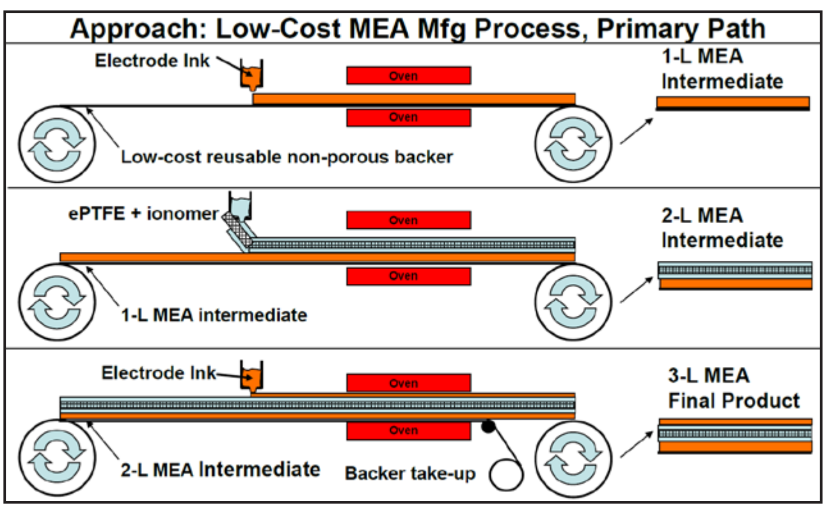
Manufacturing of Low-Cost, Durable Membrane Electrode Assemblies

Emerging Technology

W. L. Gore & Associates, Inc. (Gore), and industry partners, with funding from FCTO, are developing a high-volume manufacturing process to produce low-cost, durable, high-power density three-layer MEAs that require minimal conditioning.[1] The process is scalable to industry MEA volume targets of 500-K systems per annum and is consistent with achieving DOE's 2015 transportation fuel stack cost target of $15/kWe, assuming raw material costs forecast by DTI Energy, Inc., and TIAX LLC.[2] MEA durability is being addressed by optimizing mechanical durability and power density of three- and five-layer designs, which use Gore's expanded polytetrafluoroethylene (ePTFE) membrane reinforcement and perfluorosulfonic acid ionomers. The designs are being further optimized by computer modeling the MEA's mechanical stress as well as thermal and water management.[2]

Durability testing results of MEAs made with Gore's thin, reinforced membranes have reached 9,000 hours of operation in an 80°C automotive duty cycle, exceeding the DOE's 2015 target by 5,000 hours.[1]



Gore's 3-Layer MEA High-Volume Manufacturing Process

Technology History

- Developed by Gore and other industry collaborators.
- Working on scaling-up the manufacturing process.

Applications

Can be used in fuel cell applications for transportation, backup power, and portable power.

Capabilities

- Achieves DOE 2015 targets for high-volume manufacturing and durability.
- Offers scalable high-volume manufacturing process.
- Achieves MEA conditioning times of less than four hours.[2]

Benefits

Cost Savings

Achieves MEA manufacturing consistent with achieving DOE's cost target of $15/kWe.[2]

Environment

Reduces waste material and solvent during processing.[2]

Manufacturability

Produces a product that is compatible with automotive assembly line manufacturing.[2]

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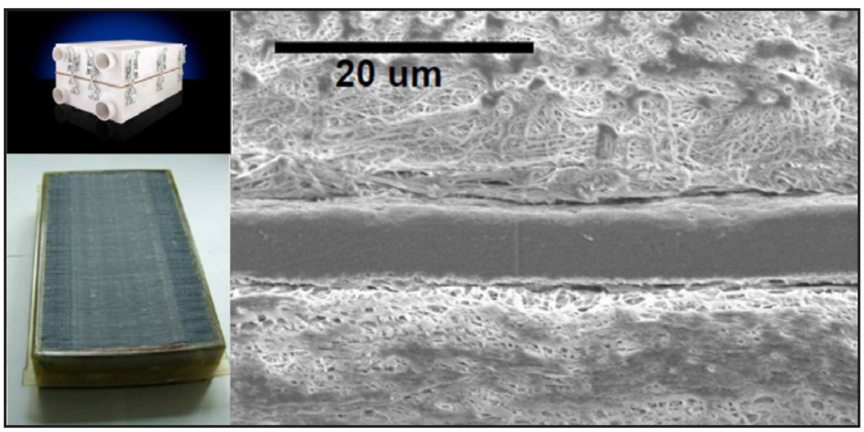
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/vi_2_busby_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review13/mn004_busby_2013_o.pdf

Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers

Emerging Technology

W. L. Gore & Associates, Inc. and industry partners, with funding from FCTO, are developing a composite membrane capable of water transport. The membrane structure consists of an ionomer layer sandwiched between micro porous polymer expanded polytetrafluoroethylene layers.[1] The ionomer layer provides active water transport but is impermeable to prevent gas crossover, which can reduce fuel cell efficiency.[1] The micro porous layers protect the thin ionomer layer from mechanical damage and enhance durability during operation. These layers can provide support for additional layers necessary for ease of handling and assembly, e.g., gas diffusion layers.[1]



W.L. Gore's Membrane and High Transport Rate Modules

Technology History

Developed by W.L. Gore & Associates, Inc. and industry partners.

Applications

Can be used for transportation or stationary applications.

Capabilities

Increases water transport within the cell.

Benefits

Cost Savings

Reduces system costs by using less expensive materials and decreasing overall system size.[1]

Flexibility

Can be used for non-fuel-cell applications that require optimized systems with high water transport rates.[2]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_j_1_johnson_2011.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_i_1_johnson_2012.pdf

Nitrided Metallic Bipolar Plates for PEM Fuel Cells

Emerging Technology

Oak Ridge National Laboratory (ORNL), with funding from FCTO, 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.[1] 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.[2] Low ICR and corrosion resistance have been demonstrated for thermally nitrided Ni-Cr base alloys in PEM fuel cell environments.[2]

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., LANL, and NREL.

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 surface nitride layers.
- Lowers ICR in fuel cells.[3]
- Reduces corrosion in fuel cells.

Benefits

Cost Savings

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

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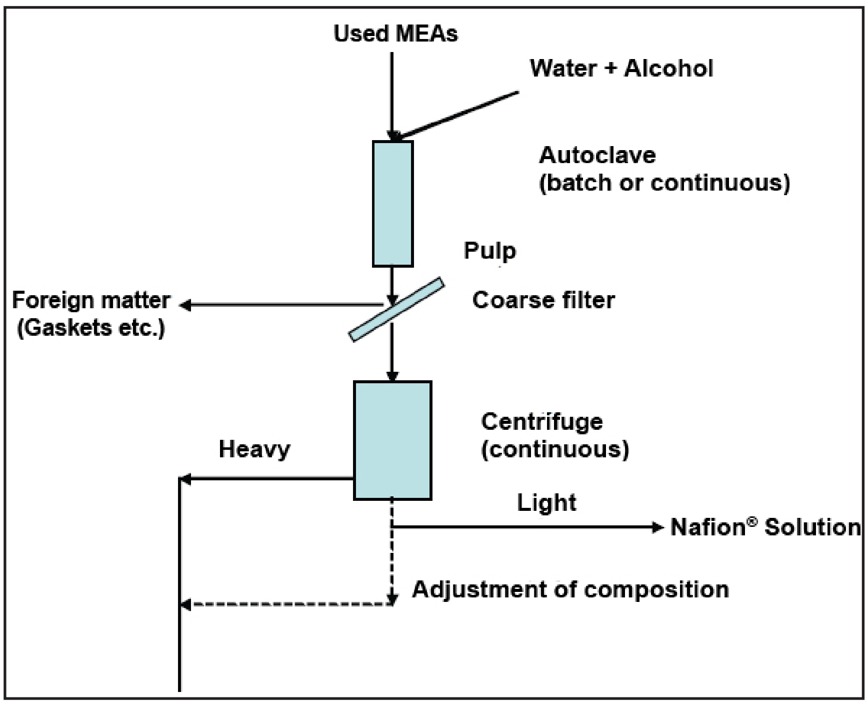
[1] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/merit03/86_ornl_mike_brady.pdf
[2] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/new_fc_tortorelli_ornl.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/v_1_1_brady.pdf

Platinum and Fluoropolymer Recovery from PEM Fuel Cells

Emerging Technology

Ion Power, Inc., has developed and patented, with FCTO 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. The recovered Pt catalyst will be re-deposited on the remanufactured membrane so that a completely remanufactured CCM is the final product.[1] To do this, recovered catalyst and Nafion are characterized to examine the changes of properties and structures during the component's life.



Ion Power's Recycling Process for MEAs

Technology History

Developed by Ion Power, Inc., in conjunction with DuPont Fuel Cells and Delaware State University.

Applications

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

Capabilities

- Allows for recycling of platinum from used fuel cells.
- Prevents the formation of dangerous hydrofluoric acid fumes during recycling.[1]

Benefits

Environmental

Eliminates the emission of hydrofluoric acid to the environment.

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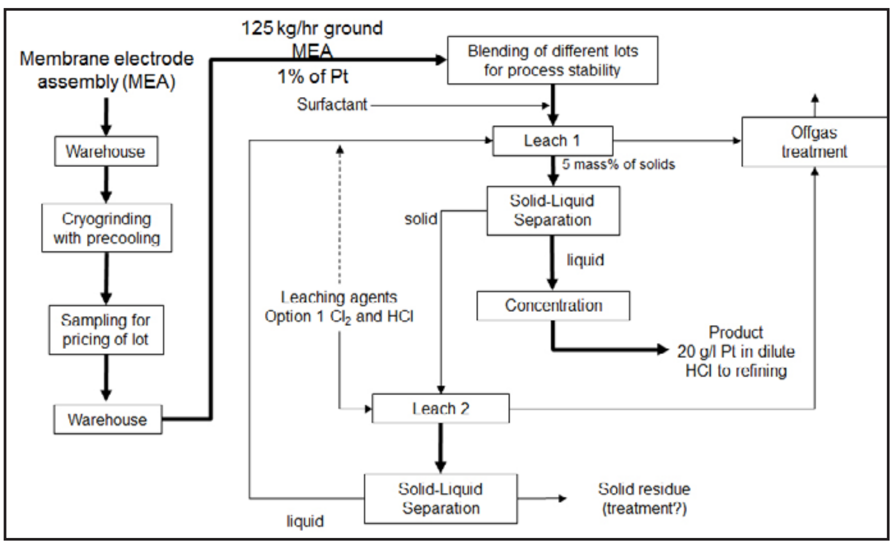
[1] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/iva7_grot.pdf

Platinum-Group-Metal Recycling Technology

Emerging Technology

BASF Catalysts LLC, with FCTO funding, is developing a uniform process to recover and recycle precious metals (primarily Pt) used in constructing PEM fuel cell MEAs. BASF has developed a process that leaches the precious metal from the MEA, eliminating the need for combustion.[1] 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.[2]



BASF's Platinum Recycling Process

Technology History

- Developed by BASF Catalysts LLC, in partnership with Ceralink, Inc.
- Technology is ready for commercialization after a market for precious metal recovery from fuel cells develops.

Applications

Can be used to provide a recycling option for used fuel cells that eliminates the formation of hydrogen fluoride fumes.[3]

Capabilities

- Allows for single process batching of multiple fuel cell types.[1]
- Achieves high process yields independent of MEA aging history, membrane construction, or electrocatalyst composition.[1]

Benefits

Efficiency

Recovers >98% of the platinum in MEAs.[4]

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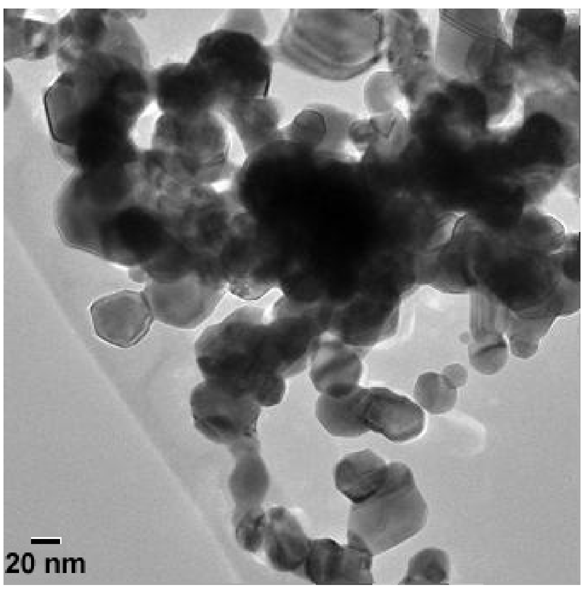
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review07/fc_30_shore.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress08/v_f_1_shore.pdf
[3] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/iva8_robertson.pdf
[4] For more information: http://www.hydrogen.energy.gov/pdfs/review05/fc21_shore.pdf

Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports

Emerging Technology

Brookhaven National Laboratory (BNL), with funding from FCTO, is developing a high-surface-area electrocatalyst using Pt monolayers on suitable metal or alloy nanoparticles. When the oxygen reduction reaction is catalyzed, these catalysts have several times higher activity per mass of Pt than pure Pt nanoparticles.[1] To further improve these catalysts, the atomically thin layers of Pt can be deposited as contiguous metal adlayers on transition metal nanostructures, such as nanorods, nanowires, and nanobars.[1] The electrocatalysts are produced by forming a continuous, atomically thin adlayer of non-noble metal atoms (e.g., copper) on the nanostructured core and then by immersing the coated nanostructures in a solution containing noble metal ions. The high noble-metal mass activity reduces the need to incorporate materials such as Pt, resulting in lower overall costs for the inventive electrocatalysts.[2]

Fifty-gram batches have been produced, and further scale-up work has begun. The electrocatalysts have been tested to investigate the reaction behavior using a rotating disk method. Performance and durability testing also has been performed in prototype fuel cells. Work is ongoing to adapt membrane electrode assemblies to more effectively incorporate the novel electrocatalysts.



BNL's Pt-Coated Palladium Nanostructures

Technology History

- Developed by BNL.
- Continuing testing of prototype electrocatalysts in membrane electrode assemblies and fuel cells.

Applications

Can be used for oxygen reduction such as in fuel cells and as a heterogeneous catalyst.

Capabilities

- Achieves high activity for the oxygen reduction reaction in fuel cells.
- Resists Pt dissolution under cycling conditions.
- Reduces Pt loading.

Benefits

Cost Savings

Reduces costs by reducing Pt loading while maintaining activity for oxygen reduction.[3]

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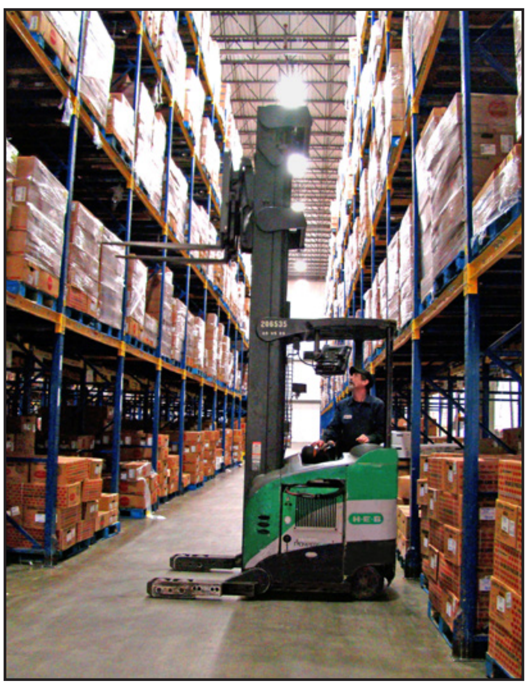
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/v_e_9_adzic.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/v_d_6_adzic_2011.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_6_adzic_2012.pdf

PowerEdge™ Fuel Cell System

Emerging Technology

With assistance from FCTO and the American Recovery and Reinvestment Act, Nuvera Fuel Cells, Inc., is deploying a power source called PowerEdge for forklift fleets. PowerEdge consists of a hydrogen fuel cell, lithium-titanate batteries, a compressed hydrogen storage tank, and other balance-of-plant components, all packaged so as to be interchangeable with standard lead acid batteries.[1] Forklift operators can refuel the system, which stays in the truck, in less than two minutes[2] at a hydrogen dispenser that is similar to using a normal gasoline pump. The hydrogen can be produced on-site using Nuvera's PowerTap™ steam methane reforming technology, or delivered by an industrial gas supplier and compressed, stored, and dispensed using PowerTap refueling equipment.

Conversion of forklift fleets to fuel cells also provides environmental benefits. According to a study performed by Argonne National Laboratory,[3] fuel cells using on-site hydrogen reduce forklift carbon dioxide emissions by 33% compared with national averages for grid-generated electricity used for battery charging.



Class 2 Forklift Powered by Nuvera's PowerEdge Fuel Cell System

Technology History

- Developed by Nuvera Fuel Cells, Inc.
- Currently on fourth generation of product development.

Applications

Can be used as a drop-in replacement for lead acid batteries used to power electric forklifts.

Capabilities

- Provides 10-30 kW of continuous power and 13-36 kW of peak power.[4]
- Provides constant voltage output with no performance degradation.[2]
- Uses a rebuildable fuel cell stack for low lifecycle cost.[2, 5]

Benefits

Emissions Reductions

Reduces carbon dioxide emissions attributable to forklift operation by an average of 33% compared with batteries charged with grid-generated electricity.

Productivity

Eliminates battery changing and charging. Offers full voltage over an entire shift.

Versatility

Available in three different models to meet the needs of Class 1 (counterbalance), Class 2 (reach), and Class 3 (pallet jack) lift trucks.[6]

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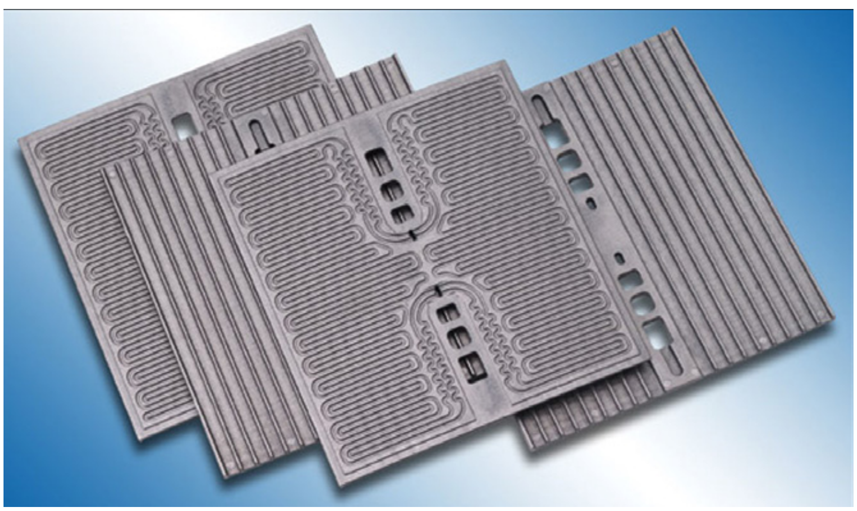
[1] For more information: http://www.nuvera.com/index.php/products-services/orion-fuel-cells
[2] For more information: http://img.directindustry.com/pdf/repository_di/22807/poweredge-r-series-90712_1b.jpg
[3] For more information: http://www.transportation.anl.gov/pdfs/TA/537.pdf
[4] For more information: http://www.nuvera.com/index.php/products-services/orion-fuel-cells-rc/orion-industrial-mobility
[5] For more information: http://www.nuvera.com/index.php/technology
[6] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf

Resin-Impregnated, Expanded-Graphite GRAFCELL Bipolar Plates

Emerging Technology

GrafTech International Ltd., with funding from FCTO, is developing a new generation of GRAFCELL® bipolar flow-field plate technology. This technology uses expanded graphite in conjunction with a 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 requirements of automotive and materials-handling applications.

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.[1] High-temperature resins provide mechanical strength and structural stability and allow continuous operation of the composite bipolar plates at temperatures up to 120°C.[1]



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.

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.

Benefits

Cost Savings

Can be fabricated using high-volume manufacturing processes.

Performance

Operates at temperatures up to 120°C.

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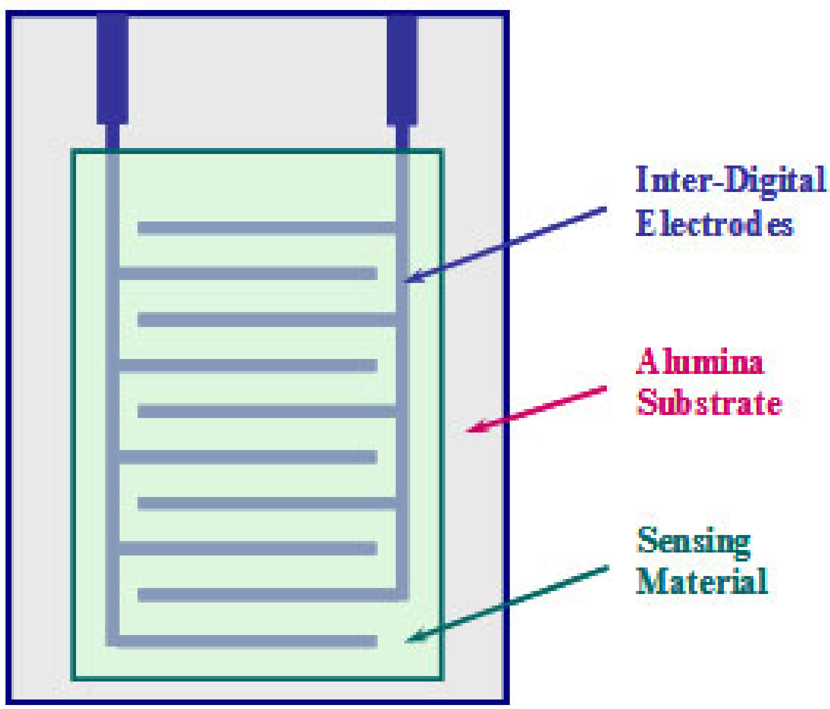
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress08/v_b_2_adrianowycz.pdf

Sensors for Automotive Fuel Cell Systems

Emerging Technology

In an FCTO-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_2S. The 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_2S sensor that can detect extremely low levels of H_2S in a hydrogen-rich gas.[1]

NexTech's H_2S sensor operates by a reversible change in resistance caused by adsorption and desorption of H_2S in a film of an H_2S sensitive material. The patent-pending H_2S 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_2S. The sensing material is deposited as a thick film on a substrate. The sensors can detect H_2S from 25 ppb to 10 ppm, with response times of less than 30 seconds.[1] Application requirements for H_2S sensors in fuel cell systems vary greatly with respect to the type of fuel cell, the level of H_2S detection required, the ambient gas composition and temperature.



NexTech's H_2S Sensor

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress05/vii_h_5_clark.pdf

[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress04/ivh7_clark.pdf

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.

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_2S 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.[2]

Product Quality

Enables fuel cells to stay on-line without frequent changing of fuel cell components due to damage from H_2S.

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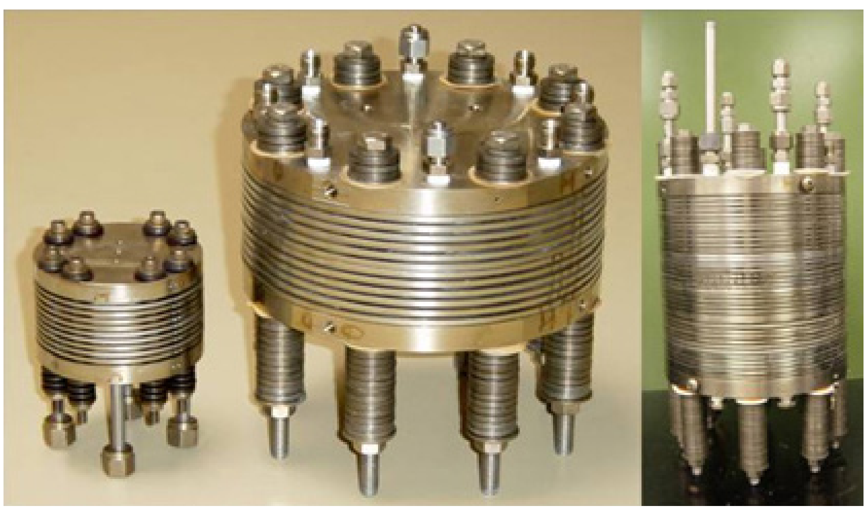
Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications

Emerging Technology

SAFCell, Inc., with funding from FCTO, is developing solid acid fuel cell (SAFC) stacks that generate electricity using hydrogen from a variety of commercial fuel reformate sources. The SAFC stacks will be combined with a proprietary diesel reforming technology, supplied by Nordic Power Systems (NPS), to constitute a complete APU. The core of the SAFCell technology is the use of a solid acid electrolyte (CsH_2PO_4), a solid-state proton conducting material intermediate between normal salts and normal acids. SAFCs operate from 230-280°C, increasing the tolerances of SAFCell stacks to typical fuel impurities (e.g., CO, NH_3, and H_2S), which pose performance problems to other fuel cell technologies operating at lower temperatures (< 200°C).[1]

This capability allows SAFCell stacks to operate on a variety of reformed gas and liquid fuels, including diesel fuels commonly used in the commercial trucking industry.[2] SAFCell is continuing to work with fuel cell system developers to commercialize full SAFC power systems for military and commercial portable power and home distributed power.



SAFCell's 30 W, 250 W, and 800 W SAFC Stacks

Technology History

- Developed by SAFCell, Inc., in partnership with Nordic Power Systems.
- Continuing development of stacks up to 1.5 kW for portable power applications and up to 5 kW for residential power applications.

Applications

Can be used for both mobile and stationary applications requiring auxiliary power generation, including buses, large trucks, mobile homes, boats, and remote residential and premium power (e.g., silent watch) applications.

Capabilities

- Operates on a wide range of reformate from commercially available fuels, including propane, butane, methanol, liquid petroleum gas, diesel/bio-diesel, and kerosene.
- Enhances performance and offers near silent operation, quick start-up time, and ability to handle start-stop cycling.[3]

Benefits

Cost Savings

Enables system simplifications when operating on commercially available reformed fuels.

Emissions Reduction

Reduces emissions by providing a more fuel-efficient alternative to auxiliary power generated from combustion engines.

Manufacturability

Provides low-cost, high-volume manufacturing because of the solid nature of electrolyte and use of metal and polymer stack components.

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[1] For more information: http://www.safcell.com/_press/20131125-LABJ-Innovation-Awards.pdf
[2] For more information: http://www.safcell.com/tech.html
[3] For more information: http://www.safcell.com/_press/20100812-SAFCell-NPS%20PR2.pdf

Solid Oxide Fuel Cell Auxiliary Power Unit

Emerging Technology

Delphi Automotive Systems, LLC, with funding from FCTO and other government agencies, has developed a solid oxide fuel cell (SOFC) APU. This electrochemical generator is designed to provide up to 3 kW of electrical power.

The design is an integrated package that includes a stack design with an increased active area, increased efficiency using an endothermic fuel reformer and high anode recycle flow, reduced pressure drop of components to minimize parasitic loads, high performance insulation thickness to minimize heat loss, and a reformate desulfurizer.[1, 2]

Delphi's Solid Oxide Fuel Cell APU

Technology History

Developed by Delphi Automotive Systems, LLC.

Applications

Can be used to provide auxiliary electrical power for a variety of mobile applications, including heavy-duty trucks, recreational vehicles, boats, truck and trailer refrigeration, and military vehicles.

Capabilities

- Operates on a wide range of commercially available fuels, including natural gas, diesel, bio-diesel, propane, gasoline, coal-derived fuel, and military logistics fuel.
- Reduces noise and pollutants.

Benefits

Emissions Reductions

Achieves Tier 4 emissions standards set by the Environmental Protection Agency for nonroad diesel engines.[2]

Energy Savings

Saves up to 85% of the fuel currently required for operating the main diesel engine during idling.[3]

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review10/ar-rah2002_shaffer_2010_o_web.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review08/fc_44_blake.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/xii_1_hennessy_2012.pdf

Ultra-Low Platinum Alloy Cathode Catalysts for PEM Fuel Cells

Emerging Technology

The University of South Carolina (USC), with FCTO funding, is developing fuel cell components with decreased platinum loading in the cathode electrodes. USC is developing a hybrid cathode catalyst (HCC). The HCC process is a combination of nitrogen-containing carbon composite catalyst (CCC) and platinum for oxygen reduction reaction. To improve performance and reduce costs further, USC is producing HCCs with materials developed from recent synthesis research of Pt-alloy catalysts deposited on activated graphitic carbon supports. The HCCs show higher performance than commercial Pt/C at low loadings (between 0.04 and 0.4 mg cm^{-2}).[1]

USC has demonstrated that the HCC catalyst performance will satisfy 2017 DOE target fuel cell performance metrics; mass activity, durability, electrochemical surface area (ECSA) loss, current density under H_2-air operating conditions.[1]

USC's MEAs in a Prototype Test Fuel Cell Stack (top)
Durability & Performance Evaluation Testing Equipment (bottom)

Technology History

Developed by University of South Carolina in collaboration with Yonsei University (YU), S. Korea and Hyundai Motor Company (HMC).

Applications

Can be used to reduce fuel cell costs and maintaining or exceeding current fuel cell durability and performance specifications.

Capabilities

- Achieves 1.25 - 1.4 A cm^{-2} current densities under H_2-air operating conditions (80°C, 40% RH, 150 kP_{abs} outlet pressure).[1]
- Reduces mass activity loss of 30.3% and 46%- 49.3% after extended operation (30,000 cycles) and ECSA loss of 27.8% for the Pt_1Co_1/CCC catalyst.[1]
- Achieves initial mass activities in the 0.33 - 0.45 Amg_{Pt}^{-1} region.[2]

Benefits

Cost Savings

Reduces precious metal content.

Manufacturability

Catalyst synthesis process is scalable from laboratory scale to high-volume production.

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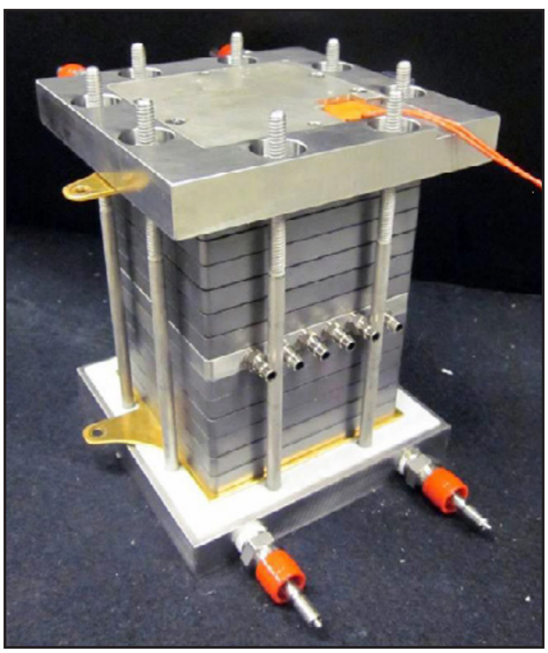
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_13_popov_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review12/fc088_popov_2012_o.pdf

Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture

Emerging Technology

Rensselaer Polytechnic Institute's (RPI's) Center for Automation Technologies and Systems, with FCTO funding, is reducing the unit process cycle time and energy required for PEMFC MEA pressing. RPI's approach uses ultrasonic bonding and minimizes variations in MEA performance. They are developing advanced diagnostics to gain insight into how process conditions and variables affect performance. This will in turn help reduce or eliminate the practice of burn-in testing of fuel cell stacks.

The performance of MEAs made by ultrasonically bonded high-temperature bonding[1] matches MEAs made by traditional thermal pressing. RPI has demonstrated 95% energy and 90% cycle time reductions, and preliminary single-cell testing with low-temperature 10 cm^2 MEAs has shown similar performance results.[2] Cost modeling based on experimental data predicts a 90% reduction.[3] Diagnostic methods are being used to (1) better understand how component (gas diffusion electrode and membrane) variability affects MEA performance, throughput, and yield and (2) determine how to reduce cycle times for downstream processes.



RPI's Test Fuel Cell Stack Using 50 cm^2 MEAs

[1] For more information: http://en.wikipedia.org/wiki/Ultrasonic_welding
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/vi_5_puffer.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/vi_5_walczyk_2011.pdf

Technology History

- Developed by RPI's Center for Automation Technologies and Systems.
- Continuing work includes developing an ultrasonic bonding processes guideline and cost modeling of larger scale manufacturing.

Applications

Can be used for manufacturing various types of high- and low-temperature proton exchange membranes and MEAs for hydrogen fuel cell applications.

Capabilities

- Reduces energy consumption and unit cycle time by >90%.
- Achieves cost reduction of 90% for MEA bonding.
- Offers a scalable process.
- Achieves comparable MEA performance to those made using conventional bonding processes.

Benefits

Cost Savings

Reduces manufacturing costs by reducing cycle time and energy consumption and improves product yield.

Manufacturability

Reduces MEA pressing cycle time and energy consumption using a newly developed robust ultrasonic bonding process.

Product Quality

Improves the uniformity and performance of MEAs using quality control based on advanced diagnostics.

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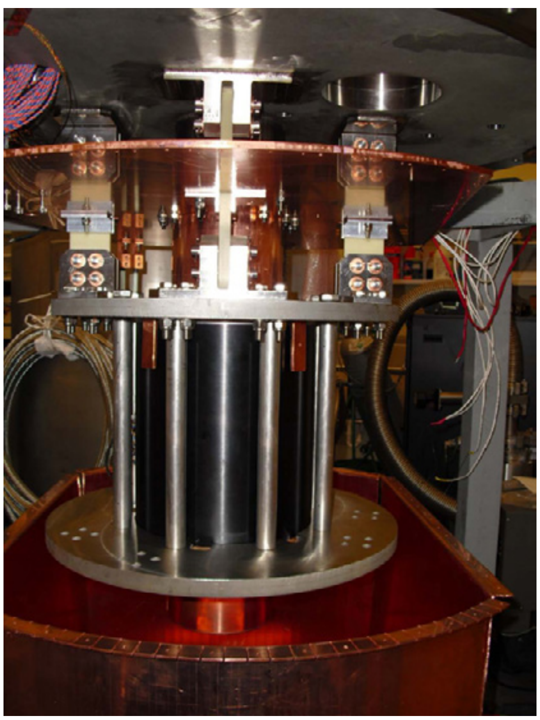
D.2 Production/Delivery Technologies

Active Magnetic Regenerative Liquefier

Emerging Technology

Prometheus Energy Group Inc., with funding from FCTO, developed a hydrogen liquefier using active magnetic regenerative liquefaction (AMRL). AMRL cooling uses magnetic field changes of magnetic refrigerants coupled with a helium heat transfer fluid to complete the regenerative cycle. The magnetic solids are both the working refrigerant, using the magnetocaloric effect, and the regenerator material, which is required to complete the AMRL cycle. AMRL hydrogen liquefiers do not require efficient gas compression.

Recent engineering efforts have focused on non-chlorofluorocarbon refrigeration for a few hundred watts of cooling near room temperature using permanent magnets and also on cryogenic liquefiers with kilowatts of distributed refrigeration to liquefy hydrogen and natural gas. Prometheus Energy Group Inc. has designed, fabricated, and tested a lab-scale AMRL operating between ~290 K and ~240 K with a target of ~290 K to ~120 K.[1] The extended range is made possible using a 7 Tesla superconducting magnet, which is cooled to 4 K by conduction cooling using a Gifford-McMahon cryocooler. The lab-scale prototype results are being used to design an AMRL system that can liquefy hydrogen with a figure of merit (FOM) of ~0.5.[1]



Emerald Energy's Lab-Scale AMRL Prototype

Technology History

- Developed by Prometheus Energy Group Inc. and being commercialized by Emerald Energy NW, LLC.
- Designing scaled-up AMRL prototype system for producing ~25 kg/day LH_2.

Applications

Can be used to produce LH_2 for storage, transport, and delivery to multiple end-users among different energy sectors.

Capabilities

- Produces LH_2 with a projected FOM of ~0.5.
- Achieves a wide operating temperature range that is expected to be between ~290 K to ~20 K.
- Produces ~25 kg per day of LH_2.

Benefits

Efficiency

Can meet DOE's target FOM of 0.6.[1]

Manufacturability

Can be scaled up to provide LH_2 production plant capacity to meet DOE's target of 30,000 kg/day.

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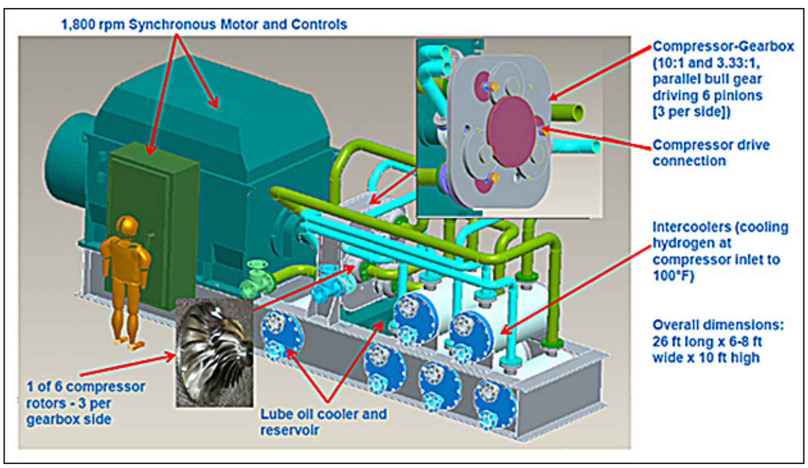
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/iii_17_barclay_2011.pdf

Centrifugal Hydrogen Pipeline Gas Compressor

Emerging Technology

Concepts NREC, with FCTO funding, is developing a centrifugal compressor system for pipeline transport of hydrogen. The design selection utilizes six stages, with each impeller operating at 60,000 rpm with a tip speed of 2,100 ft/s.[1] High impeller tip speeds enable greater pressure ratios to be attained with fewer stages, but also impose increased stresses. For its impeller material, Concepts NREC selected an aluminum alloy that provides a high strength-to-density ratio and resistance to hydrogen embrittlement. Aluminum also helps to reduce the weight of the rotor, which leads to improved rotor dynamic stability at the 60,000 rpm operating speed. The maximum hydrogen compression temperature is maintained at 140°F by providing intercoolers between each of the six stages. The intercoolers cool the hydrogen to 100°F at the inlet to each stage.[1] Additional design features include the use of proven bearings and seal technology to provide isolation of the hydrogen from the lubricating oil and increase system reliability at a competitive cost. The complete modular package can be transported to the installation site as a pre-assembled package. Concepts NREC is currently conducting subsystems modeling and testing of components in the centrifugal compressor design. Future work will focus on assembly of a two-stage compressor, with eventual scale-up and demonstration of the six-stage system.



Concepts NREC's Centrifugal Hydrogen Pipeline Gas Compressor

Technology History

- Developed by Concepts NREC, in partnership with Praxair, Texas A&M University, and HyGen Industries.
- Continuing work with assembly field testing and evaluation of a two-stage centrifugal compressor.

Applications

Can be used to support existing hydrogen pipeline infrastructure in the industrial sector, and for future pipeline transport of high-pressure hydrogen from production sites to vehicle fueling stations.

Capabilities

Delivers hydrogen at a rate of 240,000 kg/day at a discharge pressure of 1285 psig.[1]

Benefits

Product Quality

Eliminates lubricant contamination in the hydrogen supply line through use of proven seal and bearing technology.[1]

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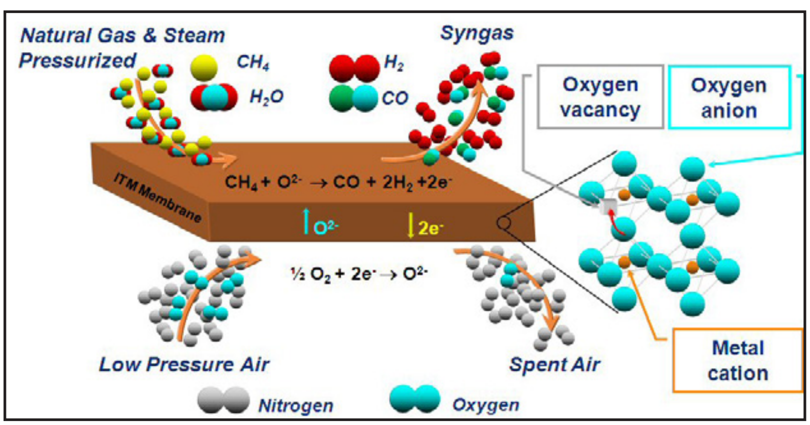
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/iii_7_dibella_2012.pdf

Ceramic Membrane Reactor Systems for Converting Natural Gas to Hydrogen and Synthesis Gas (ITM Syngas)

Emerging Technology

The Ion Transport Membrane (ITM) is a technology using ceramic membranes for gas separation being developed by a team led by Air Products and Chemicals, Inc., with FCTO funding. ITM membranes are fabricated from nonporous, multi-component metallic oxides. The membranes work by transporting an ionized gas through oxygen vacancies in the crystalline ceramic. ITM syngas membranes combine air separation and methane partial oxidation into a single-unit operation. Oxygen from low-pressure air permeates through the ceramic membrane and reacts with natural gas in a partial oxidation process, creating a chemical driving force that pulls oxygen ions across the membrane. The resulting product is a high-pressure hydrogen and carbon monoxide synthesis gas mixture, which can be used to manufacture synthetic ultraclean liquid fuels, hydrogen, and/or chemicals. The ITM syngas process is also readily configured for carbon capture from the high-pressure syngas product.

An ITM syngas module is assembled by stacking wafers vertically, with ceramic spacers placed between the individual wafers to create channels for the flow of natural gas and synthesis gas between wafers.



ITM Syngas Process

Technology History

Being developed by an Air Products led team consisting of Chevron, Sasol, Ceramatec, and others.

Applications

Can be used to generate syngas, which is used to manufacture synthetic ultraclean liquid fuels, hydrogen, and chemicals.

Capabilities

Extracts oxygen from low-pressure air.

Benefits

Capital Cost

Offers a projected 30% lower capital cost and has a 1% to 2.5% improvement in plant thermal efficiency.

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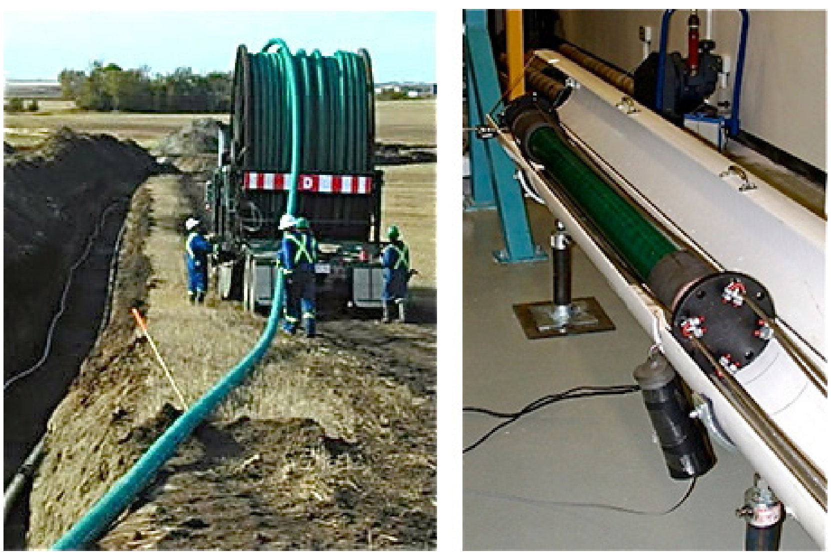
Composite Pipeline Technology for Hydrogen Delivery

Emerging Technology

Oak Ridge National Laboratory (ORNL), with FCTO funding, is evaluating fiber-reinforced polymer (FRP) pipelines to verify that the technology can achieve the FCT Program technical targets for hydrogen delivery. The pipeline architecture consists of multiple layers of fiber-reinforced epoxy matrix encasing a liner that transports a pressurized gas or liquid or both. Thousands of feet of continuous pipe can be unspooled and trenched, and adjoining segments of pipeline can be joined in the trench using connection techniques without welding.[1] FRP pipe can be manufactured with fiber optics, electrical signal wires, power cables, or capillary tubes integrated within its layered construction.



Emplacement of FRP Pipeline (left) and Pipeline Testing at ORNL (right)

Technology History

- Commercially available technology being evaluated by ORNL for hydrogen delivery.
- Ongoing work includes continuous improvement initiatives, determination of integrated sensing and data transmission needs.

Applications

Can be used for delivery of hydrogen fuel for fuel-cell-powered vehicles.

Capabilities

Achieves 2020 DOE hydrogen pipeline leakage target of <780 kg/mi/y.[1]

Benefits

Cost Savings

Reduces pipeline installation costs by eliminating pipeline welding.[1] Eliminates the need for anodic protection against corrosion.

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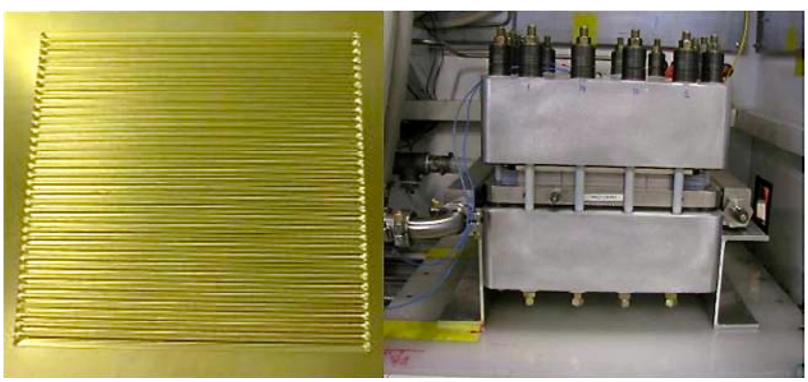
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/iii_10_smith_2012.pdf

Efficient, Low-Cost Hydrogen Generation from Renewable Energy

Emerging Technology

Proton Energy Systems, Inc., with FCTO funding, is developing electrolysis cell materials, components, and manufacturing methods to reduce commercial production cost and improve electrical efficiency for a large-area electrolysis cell platform. Proton is developing a cell design that integrates the function of several bipolar plate assembly components into a single component.

Proton has assembled and tested a 0.1 ft^2 electrolysis cell stack and projects a 41% reduction in stack cost calculated from the bill of materials for a 0.6 ft^2 design.[1] Using the hydrogen analysis (H2A) model, this capital cost savings translates to an overall cell stack capital cost of <$0.50/kg for the new large format design. The cell stacks contribute over 50% of Proton's commercial system costs, leading to an overall system cost of >20% with these design improvements.[1] Combined with Proton's parallel efforts in efficiency improvements and system scale up, the cost of hydrogen production based on the H2A model is $3.64/kg, at an electricity cost of $0.05/kWh.[1] The new stack design, using consolidated components, is currently in preproduction and represents a drop-in to Proton's existing commercial platform.



Proton's Consolidated Bipolar Plate and 0.6 ft^2 Electrolysis Stack (right)

Technology History

- Developed by Proton Energy Systems, Inc.
- Technology transfer to manufacturing nearing completion and final design testing underway.

Applications

Can be used to improve cost and efficiency in hydrogen production applications.

Capabilities

- Reduces fuel cell stack cost by >40% and overall electrolyzer system cost by >20%.
- Reduces precious metal content by >50%.
- Achieves an H2A model production cost of $3.64/kg at an electricity cost of $0.05/kWh.

Benefits

Manufacturability

Offers compatibility with high-volume manufacturing by consolidating components and simplifying assembly.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ii_d_2_ayers_2012.pdf

Efficient Solid-State Electrochemical Hydrogen Compressor

Emerging Technology

FuelCell Energy, Inc., in collaboration with Sustainable Innovations, LLC, is developing a solid-state electrochemical hydrogen compressor (EHC) with funding from DOE SBIR grants and FCTO. The EHC contains no moving parts and has a modular architecture. The modular architecture allows the capacity to be increased by adding more EHCs.[1] The EHC achieves ≥ 95% hydrogen recovery efficiency. The compression capability has been increased from 3000 psi to up to 12,000 psi.[1] The specific energy consumption has been decreased from >32 kWh/kg to <4 kWh/kg. The compressor uses proton conducting membranes for solid-state compression of hydrogen.[1]

FuelCell Energy's EHC Pre-Prototype Stack

Technology History

- Developed by FuelCell Energy, Inc., in collaboration with Sustainable Innovations LLC.
- Continuing development to demonstrate a full-scale fueling station system.

Applications

Can be used to compress or co-produce hydrogen in fueling industrial or smart grid applications.

Capabilities

- Produces hydrogen fuel at pressures up to 12,000 psi using multi-stage compression.
- Produces 1–2 kg per day (1–2 gasoline gallon equivalent).
- Achieves a single-step compression ratio of 300:1.

Benefits

Durability

Achieves operation using a solid-state EHC design with no moving parts.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/iii_9_lipp_2012.pdf

HRS-100™ Hydrogen Recycling System

Emerging Technology

H2Pump, LLC, developed, with assistance from a DOE SBIR grant, an electrochemical hydrogen recovery system that separates hydrogen from a mixed gas stream (e.g., furnace exhaust), purifies it, and pumps it back into the feed stream of an industrial process. The hydrogen separation and pumping process occurs in an electrochemical cell stack. Hydrogen and other gaseous impurities (e.g., CO, CO_2, and CH_4) enter the anode chamber of a cell, where each hydrogen molecule is oxidized to two protons and two electrons. A direct current power supply provides the electrical potential to drive the electrons and protons to the cathode through an external wire and a proton exchange membrane, respectively. The electrons and protons recombine at the cathode to produce pure hydrogen. The gaseous impurities, which do not pass through the membrane, are directed out of the system as a waste stream. The system operates at high efficiency[1] by avoiding the large heat losses associated with mechanical hydrogen compression, and can be easily scaled to provide a wide range of hydrogen flowrates.

H2Pump's 100 kg/day Hydrogen Recycling System

Technology History

- Developed by H2Pump, LLC, with support from NYSERDA and an SBIR Phase II grant.
- Currently field testing a number of units to evaluate performance and increase customer acceptance.

Applications

Can be used to recover byproduct or unconsumed hydrogen from industrial process exhaust streams and recycle purified, pressurized hydrogen back to the process feed stream.

Capabilities

- Recycles up to 100 kg of hydrogen per day (1,600 standard cubic feet per hour).[1]
- Recovers up to 90% of the hydrogen present in the exhaust stream.[1]
- Compresses hydrogen to hundreds of psig.[1]
- Achieves >80% pumping efficiency.[1]
- Purifies hydrogen to >99.999% (exact purity value depends on exhaust gas stream composition).[1]

Benefits

Cost Savings

Reduces operating expenses by recovering previously wasted hydrogen at a lower cost than would be required for a new supply.

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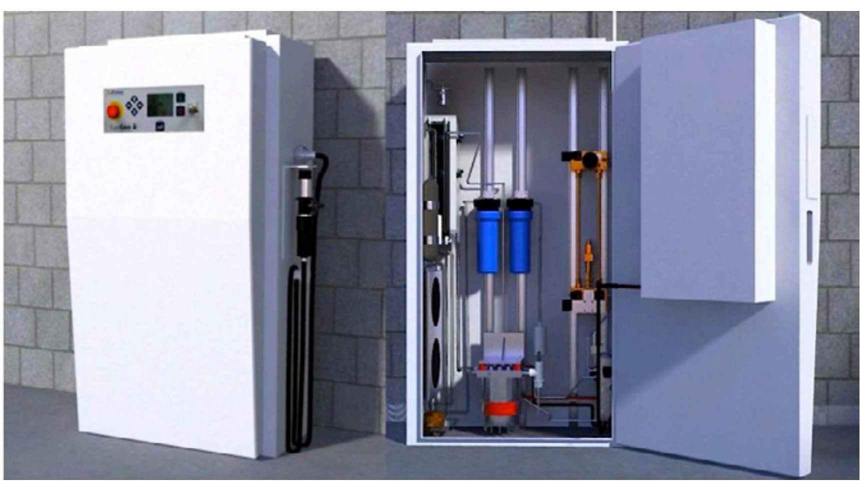
[1] For more information: http://h2pumpllc.com/userfiles/files/Spec_Sheet03_23_11(1).pdf

Hydrogen by Wire — Home Fueling System

Emerging Technology

Proton Energy Systems Inc., with funding from DOE SBIR grants and FCTO, is developing a 350-bar hydrogen home fueling system. Proton will use its PEM electrolysis technology to generate hydrogen for this application. The system effort involved designing the gas-liquid phase separator, dryer, and programmable logic control. In parallel with system design, a prototype PEM stack was developed, using Proton's electrolysis cell stack technology development, to meet the 350-bar pressure requirements.

After the prototype was fabricated and assembled, basic sensor calibrations and acceptance testing were completed, including leak, ground continuity, and hi-pot testing. Upon completion of the prototype PEM stack design, detailed design verification inspection and component testing were performed. Nonoperational stacks were built to verify sealing to proof pressure and proper distribution of load through the components. Flow tests were conducted on single- and multiple-cell stacks. Finally, an operational electrolysis cell stack was fabricated, assembled, and checked through standard acceptance criteria. The stack was integrated with the system and operated for a demonstration of 350-bar electrolysis technology.[1]



Rendering of Proton's Home Fueling System

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/pd067_dalton_2013_p.pdf

Technology History

- Developed by Proton Energy Systems, Inc.
- Phase II SBIR completed, exploring potential early applications and markets.

Applications

Can be used for refueling hydrogen-powered vehicles or stationary or portable power devices.

Capabilities

- Produces hydrogen at <$4.00/gasoline gallon equivalent, including capital cost.[1]
- Produces up to 2 kg/day of hydrogen fuel at 350 bar.[1]
- Eliminates mechanical compression.

Benefits

Convenience

Generates fuel in the end user's home.

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Hydrogen Gas Sensing System

Emerging Technology

Intelligent Optical Systems, Inc. (IOS), with FCTO funding, is developing the H_2-dTECT™ gas sensing system, a sensor that detects hydrogen leaks in a broad range of operating environments from home garages to pipelines. At the heart of the IOS technology is a proprietary chemical formulation that changes color in the presence of hydrogen. The chemical hydrogen indicator is immobilized on a porous glass substrate that can be used either in remote fiber optic sensor networks or in compact (handheld or wall-mountable) sensor units.

IOS has designed and fabricated an optoelectronic sensor prototype, which features an integrated user interface, audio and visual alarms, and a microcontroller with digital signal processing capabilities.[1, 2] The prototype supports four channels (signal, reference, temperature, and humidity) and includes both USB and RS-232 serial communication. The device has been tested by the National Renewable Energy Laboratory (NREL) and is available for field trials in operational environments.[1, 2]

IOS's Prototype H_2-dTECT Hydrogen Sensor

Technology History

- Developed by IOS in partnership with NREL.
- Currently developing other chemical detection applications of the technology.

Applications

Can be used to detect hydrogen leaks in operating environments.

Capabilities

- Detects hydrogen at concentrations from 10% to 100% hydrogen-in-air with a response time of less than 5 seconds and can detect concentrations down to 100 ppm hydrogen in air.[1, 2]
- Operates over a wide range of conditions, including temperatures of 10-55°C and 0-90% relative humidity.[1, 2]

Benefits

Cost Savings

Identifies points at which high-purity hydrogen is being lost via leaks along the delivery, storage, and refueling infrastructure for fuel cell vehicles.

Safety

Alerts users to hydrogen leaks, reducing the risk of hydrogen-related flammability, explosive, or asphyxiation incidents.

Versatility

Can be handheld, wall mounted, or deployed for remote monitoring of multiple locations where a potential hydrogen leak is expected.

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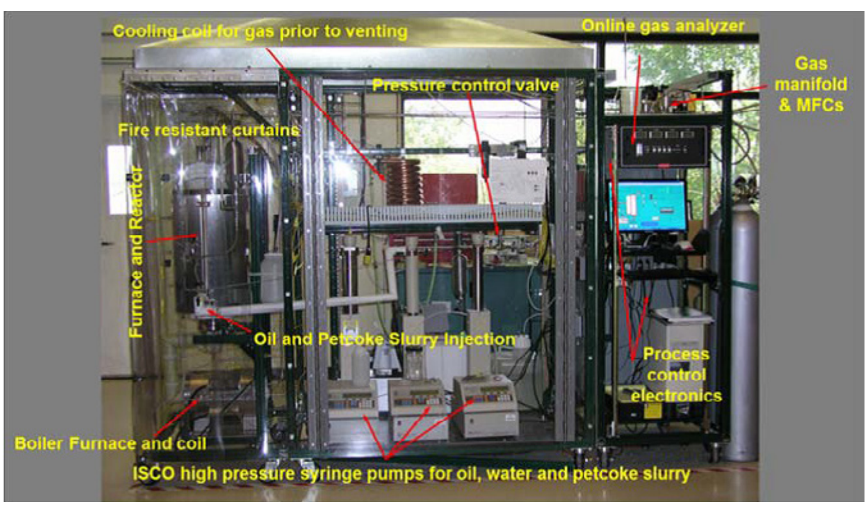
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/viii_14_lieberman_2011.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review10/scs014_lieberman_2010_o_web.pdf

Hydrogen Production for Refineries

Emerging Technology

With assistance from DOE SBIR grants, TDA Research, Inc. (TDA) is developing a technology that will allow hydrogen to be produced in refineries. This technology converts "bottom of the barrel" materials into hydrogen, which facilitates producing more distillate fuels from each barrel of oil, especially from less expensive heavy crudes that are available in great quantity.[1] TDA's process converts heavy oil and residuum to a hydrogen-rich syngas, using a conventional nickel steam-reforming catalyst. The process uses a fluidized-bed reactor, and has a reforming reactor and a catalyst regeneration reactor in a loop. The catalyst flows around the reactor-regenerator loop with minimal contact with the feed. The catalyst returns to the reactor as inactive nickel oxide, but is quickly reduced back to catalytically active Ni metal by the hydrocarbons in the feed.[1]

The process has been demonstrated using both atmospheric tower bottoms (ATBs), vacuum tower bottoms (VTBs) and oil sands bitumen as feedstocks.[1] TDA is now working with industry partners on a preliminary scale-up design for eventual pilot plant testing.



TDA's Lab-Scale Test Apparatus for Hydrogen Production

[1] For more information: http://www.allriskengineering.com/library_files/AIChe_conferences/AIChe_2012/data/papers/P245516.pdf

Technology History

- Developed by TDA Research, Inc.
- Continuing work with industry partners to develop scaled-up design for pilot-plant testing.

Applications

Can be used to produce H_2 from heavy feedstocks in refineries as well as oil sands bitumen.

Capabilities

- Enables steam reforming heavy feedstocks without catalyst deactivation.
- Allows use of proved nickel-based steam reforming catalysts because periodic catalyst regeneration burns off any coke/carbonaceous deposits.
- PConverts heavy oil, residuum and bitumen to a H_2-rich syngas.[1]

Benefits

Energy Savings

Process operates at lower temperatures than steam methane reforming and gasifiers.

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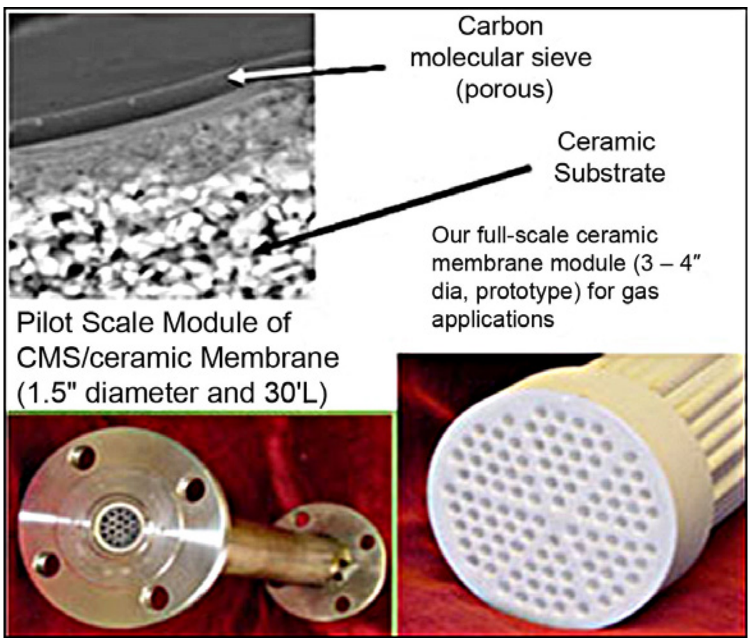
Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor

Emerging Technology

Media and Process Technology (M&P), Inc., with FCTO funding, has developed a carbon molecular sieve (CMS) membrane. M&P's 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 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.
- Performance specification testing of portable power product application and investigating commercial opportunities.

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 in one step.

Benefits

Versatility

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

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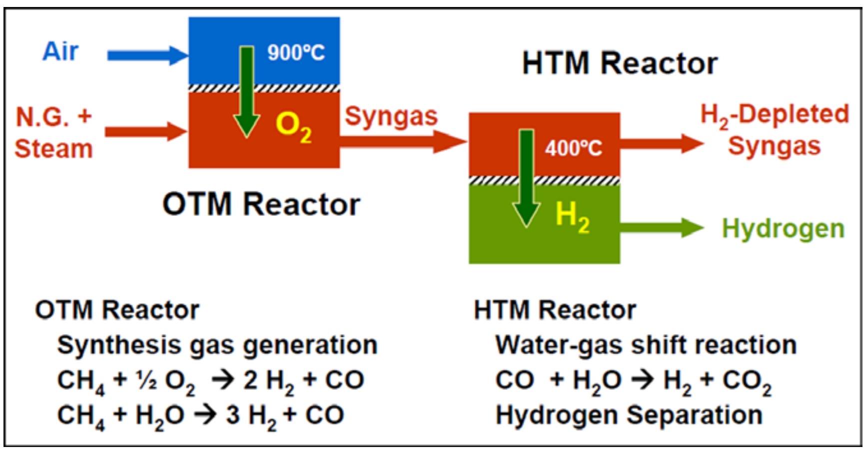
Integrated Ceramic Membrane System for Hydrogen Production

Emerging Technology

Praxair, Inc., with funding from FCTO, 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 produces hydrogen. 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, 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.[1]
- Achieves strength with porosity through ceramic substrate technology.[1]
- Increases production of high-purity hydrogen from syngas.[1]

Benefits

Performance

Produces hydrogen at sufficient purity for PEM fuel cells without further purification.[1]

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.

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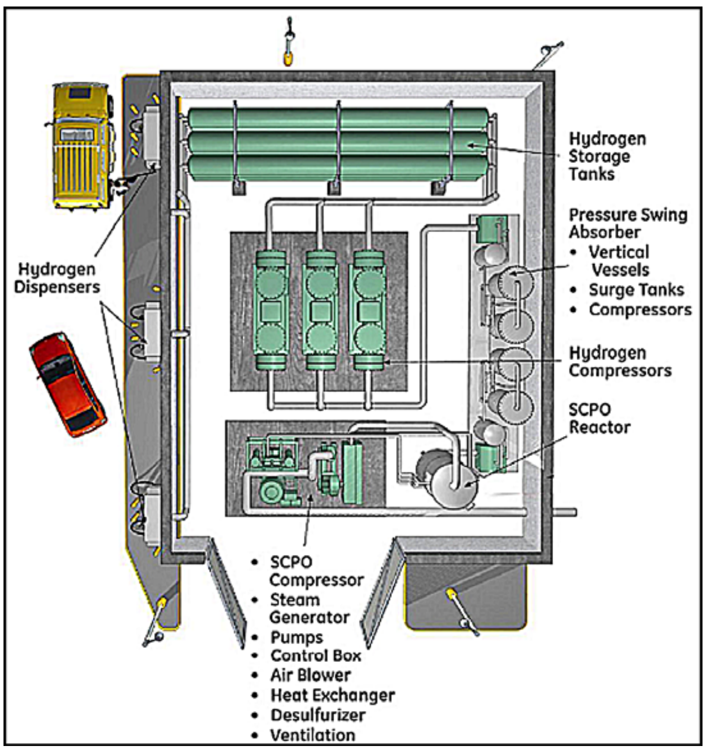
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/ii_d_1_schwartz_2011.pdf

Integrated Short Contact Time Hydrogen Generator

Emerging Technology

GE Global Research Center, with funding from FCTO, is developing a 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 system allows for greater reformer compactness. The 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.[1] The project has demonstrated that it is a potential technology for H_2 production from natural gas and with minor modifications may allow the use of biofuels, gasoline, or diesel as feedstock.[1]



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.

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°C to allow the use of low cost stainless steel.[1]

Benefits

Cost Effectiveness

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

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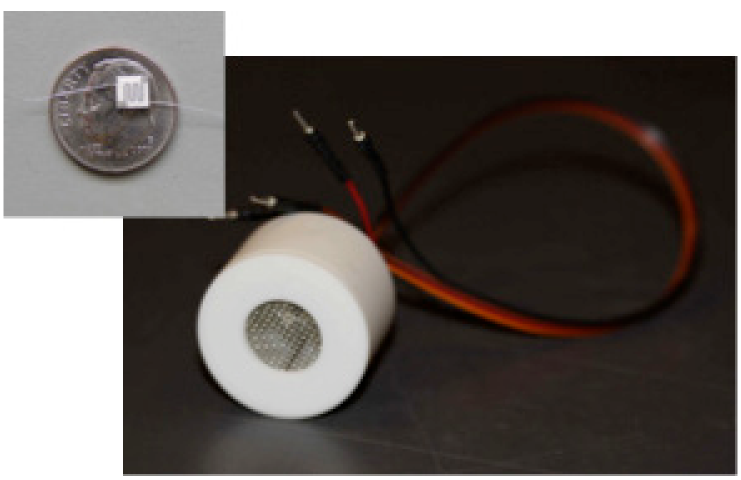
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress07/ii_a_4_liu.pdf

Leak Detection and Hydrogen Sensor Development

Emerging Technology

Los Alamo National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL), with funding from FCTO, are working together to develop and test inexpensive, zirconia-based, electrochemical (mixed-potential) sensors for H_2 detection in air. Mixed potential sensors are a class of electrochemical devices that develop a voltage in response to differences in the electrode electro-catalytic properties and the different redox reaction rates of various gases at each electrode/electrolyte/gas interface. Although zirconia-based mixed potential sensors have been investigated for other applications for several decades, issues with signal stability and device-to-device reproducibility have kept them out of the commercial mainstream. Work in the fundamental understanding of the mixed potential phenomena at LANL and LLNL has led to new materials, methods, and designs for this important class of sensor. Sensor designs facilitate a reproducible device response resulting from stable electrochemical interfaces. In addition, higher mixed potential signals result because gas diffusion is through the less catalytically active electrolyte than the electrode.

The sensors have shown good response time, stability, and resistance to aging and degradation from thermal cycling. LANL and LLNL are now working to demonstrate the technology in H_2 applications and to enable commercialization through cost-conscious, reproducible manufacturing methods. Cross-validation and eventual field testing of prototypes is being undertaken with other DOE labs and commercial parties.



Packaged Electrochemical H_2 Safety Sensor

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/viii_8_brosha_2012.pdf

Technology History

- Developed by LANL and LLNL.
- Currently testing a robust zirconia-based, electrochemical sensor technology for vehicular and stationary H_2 safety applications. Exploring avenues for commercialization.

Applications

Can be used for on-vehicle leak detection and refueling and for production and storage applications for hydrogen safety.

Capabilities

- Exceeds targets for minimum detection threshold of 1% H_2 in air (10,000 ppm) and response time of ≤1 minute.[1]
- Measures hydrogen from 0.04 - 4%, with an accuracy of ± 1%.[1]
- Shows minimal cross-sensitivity to common gas interferences such as CO_2, CO, and CH_4 and is relatively insensitive to changes in ambient humidity and barometric pressure.[1]

Benefits

Cost Savings

Provides a H_2 safety sensor for vehicle and infrastructure applications.

Durability

Provides durability and stability of response using similar automotive oxygen lambda sensor design and ceramic materials.

Flexibility

Provides a low-power, compact fit sensor with direct voltage readout, circumventing the need for any additional conditioning circuitry.

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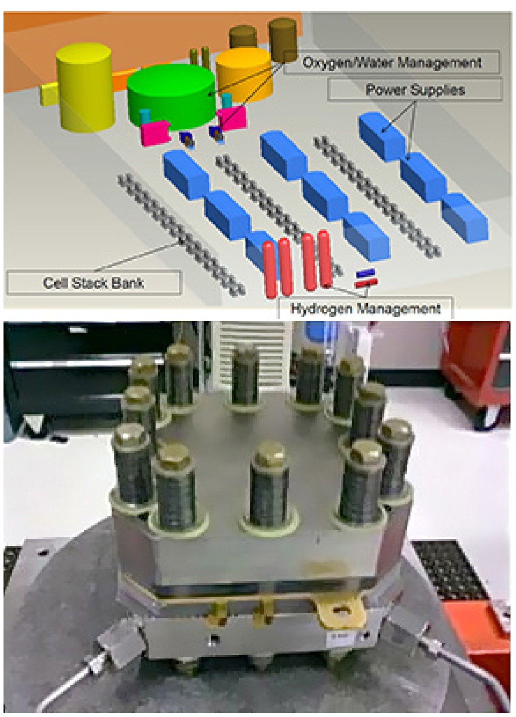
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage

Emerging Technology

Proton Energy Systems, Inc. has commercialized PEM water electrolysis for distributed production of hydrogen. Through funding from DOE SBIR grants and the FCTO, Proton aims to reduce production and capital costs as well as improve system (electrolyzer) efficiency. To meet DOE's 50,000 kg/day capacity target, Proton is working to advance the performance and capability of key components and establish new system design parameters. A system operating efficiency of 69%[1] will be required by developing new catalyst and membrane materials to reduce efficiency losses arising from oxygen evolution over-potential and membrane ionic resistance. For large-scale installations the use of expensive precious metals also needs to be minimized. Fuel cell materials research can be applied to enable these required advancements.

Proton is investigating two catalysts with tri-metallic composition for long-term stability and scale up. New catalyst application processes for reduced catalyst loading are being transferred to Proton's manufacturing group. Proton is expecting further reductions by incorporating a next-generation metal oxide ink. Thinner, reinforced membranes have been fabricated into assemblies for performance testing, and stack testing has been initiated. A 50,000 kg/day hydrogen installation has been modeled, with a predicted system capital cost of \$0.49/kg of hydrogen.[1] The feasibility modeling of the installation will be complete once the new membrane performance parameters have been determined. Environmental impact will also be estimated.



Proton's 50,000Kg/day Concept and Advanced Fuel Stack (right)

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ii_d_5_ayers_2012.pdf

Technology History

- Developed by Proton Energy Systems, Inc.
- Technology transfer to manufacturing nearing completion and final design testing underderway.

Applications

Can be used to improve cost and efficiency in hydrogen production applications.

Capabilities

- Reduces catalyst precious metal loading by 50%.[1]
- Reduces ionic resistance by >50% and increases catalyst activity by a factor of 10.[1]
- Achieves a capital cost of \$0.49/kg hydrogen in a 50,000 kg/day Greenfield facility.[1]

Benefits

Cost Savings

Reduces membrane electrode assembly cost using less expensive materials and an improved manufacturing process.

Environmental

Works with renewable energy sources and achieves zero or near zero greenhouse gas emissions.

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Materials Solutions for Hydrogen Delivery in Pipelines

Emerging Technology

Secat, Inc., with FCTO funding, is developing methods to identify steel compositions and associated welding filler wires and processes that would be suitable for construction of new pipeline infrastructure. Secat is investigating the embrittlement of existing commercial pipeline steels under high-pressure hydrogen. Several phenomena are being examined. Firstly, steel microstructure behavior since this is known to contribute to overall performance. Secondly, mechanical property testing including; testing to the National Association of Corrosion Engineers hydrogen induced cracking infraction standard (NACE TM0284 HIC) and tensile, fracture and fatigue in the presence of gaseous hydrogen under various pressures (800 – 3000 psi). Secat has found that all the steel types investigated exhibit performance degradation but certain steel microstructure performance stabilizes with increasing hydrogen pressure and could perform adequately (safely) for hydrogen gas service applications.[1] There is the possibility that parts of the existing steel transmission pipeline infrastructure in North American could be suitable for hydrogen transportation. Secat is currently sharing and incorporating the results of their research in the development of hydrogen safety codes and standards and working with industry partners to develop suitable steel pipelines.

Test Sample Failures (LHS Cup & Cone RHS Faceted Surface) and High Pressure Test Equipment

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/pd047_stalheim_2011_p.pdf

Technology History

- Developed by Secat, Inc., in collaboration with industry partners.
- Future work includes development of barrier coatings to minimize hydrogen permeation in pipelines, a barrier coating deposition process and cost analysis of the existing pipeline infrastructure with new or modified pipelines.

Applications

Can be used to select steel compositions that would be suitable for safe transmission of hydrogen at high pressures (800 – 3000 psi).[1]

Capabilities

- Enables pipeline construction for transmission of hydrogen at pressures ranging from 800 – 3000 psi.[1]
- Allows failure detection and performance characterization of the mechanical properties of pipeline steel compositions.

Benefits

Cost Savings

Potentially reduces pipeline infrastructure "hydrogen readiness" costs by identifying suitable existing pipelines and avoiding the replacement cost.

Safety

Provides technical information and understanding of pipeline steel fracture and fatigue enabling further development of hydrogen related American Society of Mechanical Engineers codes and standards.

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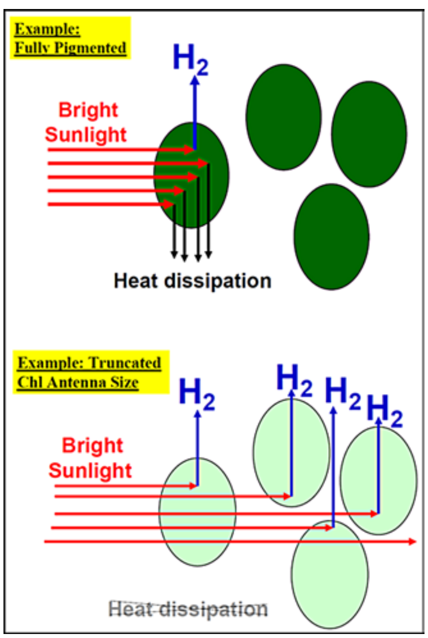
Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures

Emerging Technology

The University of California (UC)-Berkeley is developing, with funding from FCTO, a simple, low energy technology that uses natural materials and does not produce unwanted byproducts 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%.[1]



UC-Berkeley's Production of Hydrogen from Truncated Antenna Algae Cells

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 slow 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%.[1]

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.

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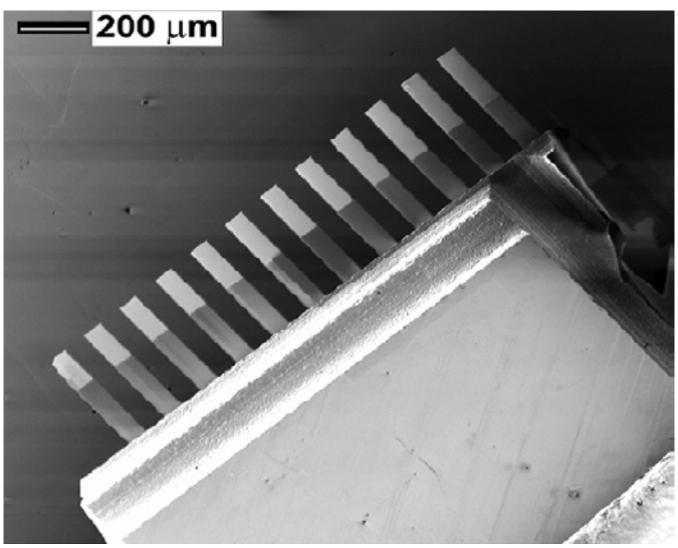
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ii_g_4_melis_2012.pdf

MEMS Hydrogen Sensor for Leak Detection

Emerging Technology

Oak Ridge National Laboratory (ORNL), with FCTO funding, is developing an H_2 detection device based on nanostructured thin-film palladium microcantilever arrays–a microelectomechanical system (MEMS). The sensor has shown performance improvements over existing and recently developed sensors.[1] When gas-phase molecules are adsorbed onto the thin film surface, changes in surface stress cause the cantilever structure to bend. In the MEMS, this response can be detected using piezoresistive, capacitive, and optical techniques, providing potential sub-part-per-billion sensitivity, wide dynamic range, and fast response time.[1] Optically read microcantilever sensors are advantageous in combustible or explosive gases and vapors (e.g., H_2) compared with heated or electrically operated sensors that could cause vapor ignition. Other advantages of this sensing technique include its very low power consumption and its applicability to distributed wide-area sensor networks, allowing multiple low-cost chemical sensors to be located at storage or processing facilities (e.g., in the H_2 fuel economy) or on H_2-powered transportation vehicles.[1]

The key technological finding in ORNL's sensor technology is a nanostructured palladium/argon alloy that was developed specifically for H_2-sensing applications.



ORNL's Cantilever Array Prior to Alloy Coating

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/viii_16_smith_2011.pdf

Technology History

- Developed by ORNL and the University of Tennessee-Knoxville.
- Working on prototypes for third-party evaluation and exploring technology licensing and commercialization opportunities.

Applications

Can be used for hazardous condition detection in H_2 fuel-powered applications.

Capabilities

- Achieves DOE targets for response and recovery times (<10 s).[1]
- Operates in ambient atmospheric conditions and is immune to interferents (e.g., H_2O, CO_2, CH_4, H_2S and CO).[1]
- Provides a measurement range of 0.1%–10% H2 over a wide temperature range (-22°F to 176°F).[1]
- Provides H_2 gas detection in air at concentrations significantly below the flammability threshold.[1]

Benefits

Cost Savings

Uses alloy-coated microcantilever sensor design to provide nearly ideal attributes required for distributed low-cost sensing of hydrogen leaks in many applications.

Durability

Provides projected 10-year operating lifetime without sensitivity, specificity, response, and recovery time degradation.[1]

Safety

Provides protection for human health and safety and property damage.

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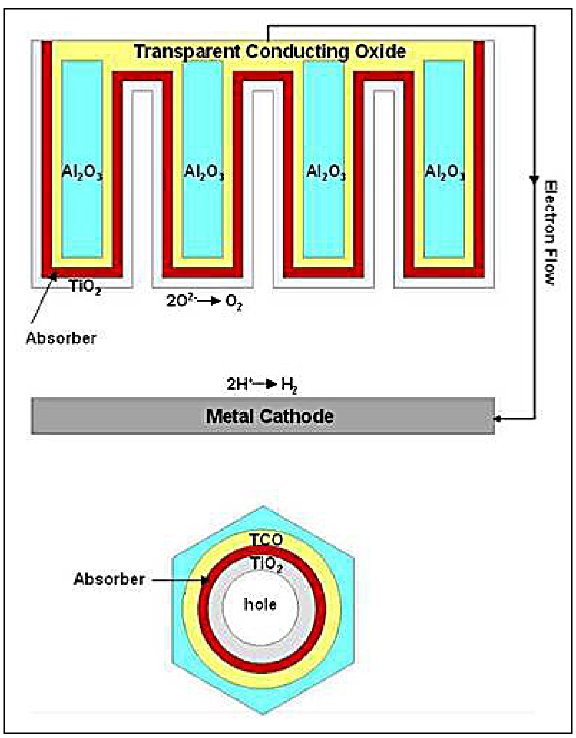
Nanotube Array Photocatalysts

Emerging Technology

Synkera Technologies, Inc., with the assistance of DOE SBIR grants, is developing highly-efficient, long-lifetime, and cost-effective photocatalysts to address the current shortcomings associated with photoelectrochemical hydrogen production. Synkera's approach is based on high-density arrays of nanotubes with coaxial architecture. These nanotubes integrate a conductive layer, a semiconductor absorber with a vertically integrated bandgap, and chemically robust electrochemical interface coating. This approach enables several photocatalyst designs and takes advantage of a new templated process for nanoarray synthesis developed by Synkera.[1] The ability to reliably and consistently fabricate a device with such complex architecture is key to developing competitive photocatalysts.

Synkera demonstrated the feasibility of its approach using doped titanium oxide (TiO_2) nanotube arrays with a coaxial conductor. Improvements in photoelectrochemical performance were observed compared with planar structures, including increased photocurrent density and increased stability in 0.1 M potassium hydroxide.[2] Spectral sensitivity and conversion efficiency measurements are currently in progress, and Synkera is seeking product development and commercialization partners.



Schematic of Synkera's Nanotube Array with Integrated Absorber

Technology History

- Developed by Synkera Technologies, Inc.
- Currently applying technology to other applications as well as exploring partnerships and funding opportunities.

Applications

Can be used to produce hydrogen from solar energy.

Capabilities

- Enhances light harvesting through a large absorption cross-section and a high surface area to promote catalytic chemistry.[2]
- Minimizes recombination losses through rapid and efficient charge separation in a very thin absorber.[2]
- Increases efficiency through broadband light absorption and a vertically graded bandgap.

Benefits

Cost Savings

Is scalable to large size and high volumes and lowers costs compared with traditional technologies.

Durability

Achieves long lifetime by using corrosion-resistant conformal layers of titania as electrochemical interface.

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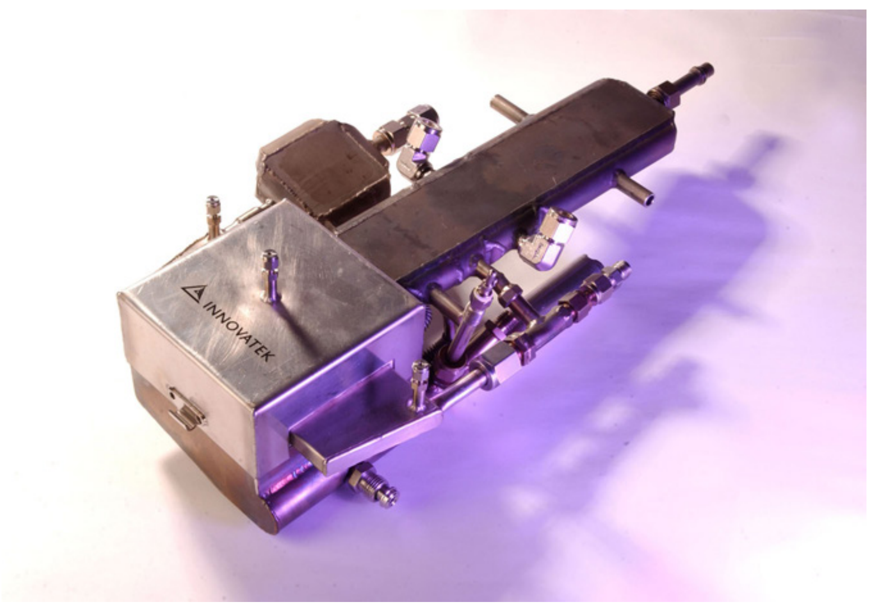
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/pd062_wind_2011_p.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/ii_g_13_wind_2011.pdf

Novel Catalytic Fuel Reforming

Emerging Technology

InnovaTek, Inc., with FCTO funding, has developed a hydrogen generator that reforms multiple fuel types (natural gas, gasoline, diesel, and biodiesel) to produce pure hydrogen by integrating microreactor and microchannel heat exchanger technology with 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 liters per minute of hydrogen that can fuel a 1- to 5-kW polymer electrolyte membrane (PEM) fuel cell, or other auxiliary power unit.[1] 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.
- Developing a "go-to-market" strategy and continuing with long term testing to validate system efficiency and reliability

Applications

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

Capabilities

- Produces 60 grams per hour of hydrogen.[1]
- 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% for natural gas reforming.[2]

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[1] For more information: http://www.innovatek.com/files/InnovaGen.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress04/iia5_irving.pdf

Oil Free Hydrogen Compressor

Emerging Technology

Mohawk Innovative Technology, Inc., with FCTO and DOE SBIR grant funding, is developing an oil free, high-speed centrifugal compressor that addresses the limitations of current compression technologies. Using compliant foil gas bearings and seals, engineered coatings, in conjunction with high-speed drives, this centrifugal compressor approach offers a potential 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.[1]

Full Scale Mockup of MiTi Hydrogen Compressor Presented at 2012 ARPA-E Energy Summit

Technology History

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

Applications

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

Capabilities

- Centrifugal compressor with foil bearings eliminates the need for oil lubrication.
- Provides flow rates up to one million kilograms of hydrogen per day with output pressures of 1,200 psi.[1]
- Provides improved compressor reliability and efficiency.[1]

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.

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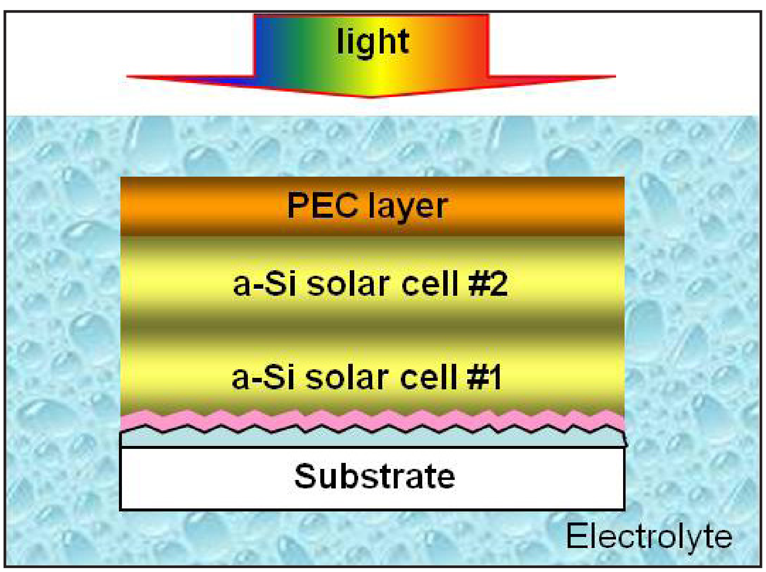
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/iii_8_heshmat_2012.pdf

Photoelectrochemical Hydrogen Production

Emerging Technology

MVSystems, Inc., with funding from FCTO and in partnership with Hawaii Natural Energy Institute, is developing materials to meet current photoelectrochemical (PEC) hydrogen production challenges in efficiency, stability, and cost in converting sunlight directly to hydrogen. Three classes of materials have been identified: amorphous silicon carbide-based, tungsten oxide-based, and copper chalcopyrite-based films. MVSystems, Inc. has conducted extensive studies of these materials classes to understand and improve PEC behavior, specifically by applying theoretical, synthesis, and analytical techniques to identify relevant aspects of structural, optoelectronic, and electrochemical properties.

Laboratory scale hybrid devices fabricated have shown encouraging results. Further improvement of solar-to-hydrogen (STH) efficiency will involve three main elements: (1) treating the surface of the photoelectrodes to improve interface interaction, (2) identifying suitable alloying to increase photocurrent density, and (3) modifying and edge positions to improve light absorption and electron recombination interaction. The long-term goal for the technology is to transfer the fabrication process to manufacturing scale for commercialization.



MVS' Monolithic Hybrid PEC Device Powered By a Tandem Solar Cell

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress13/ii_c_2_hu_2013.pdf

Technology History

- Developed by MVSystems, Inc., in partnership with the University of Hawaii.
- Continuing development work to improve PEC performance and durability.

Applications

Can be used to produce "solar fuels" such as hydrogen and methanol from solar energy.

Capabilities

- Achieves 5% STH conversion efficiency and operational life up to 500 hours.[1]
- Uses durable thin-film-based PEC devices which lower the cost compared with traditional PEC cells based on photovoltaics/electrolyzer and crystalline material.[1]

Benefits

Cost Savings

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

Performance

Achieves increased conversion efficiency when converting solar energy to hydrogen.

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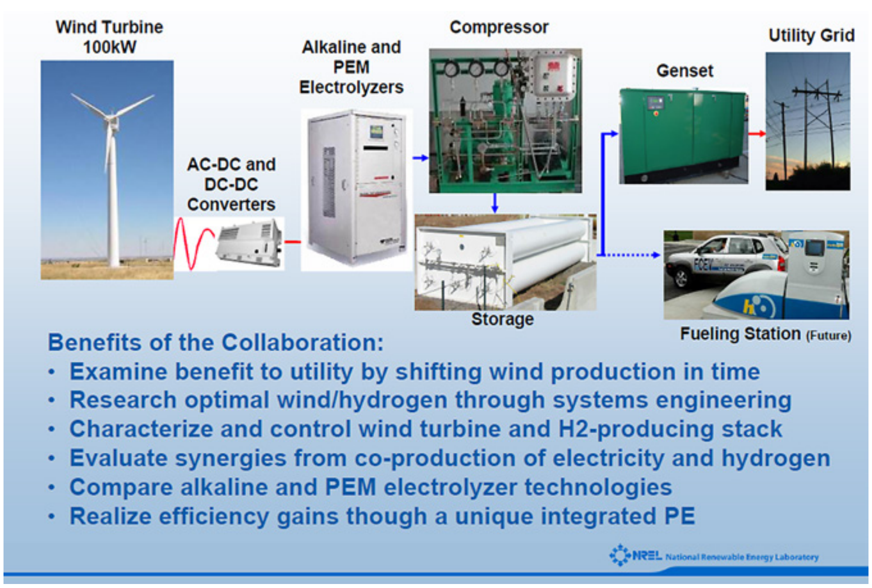
Renewable Electrolysis Integrated System Development and Testing

Emerging Technology

The National Renewable Energy Laboratory (NREL), with FCTO 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.



NREL's Wind2H2 Project Collaboration

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.

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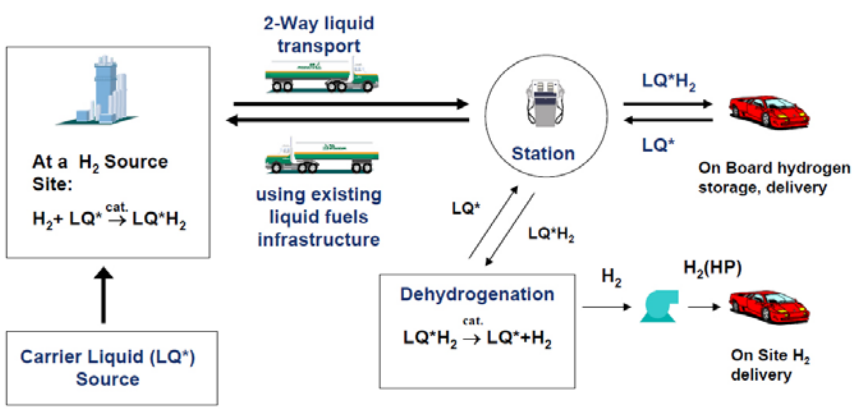
Reversible Liquid Carriers

Emerging Technology

Air Products and Chemicals, Inc., with FCTO funding, developed 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 were evaluated.



Air Products' Reversible Liquid Carrier System

Technology History

- Developed by Air Products and Chemicals, Inc., in partnership with United Technologies Research Corporation, Pacific Northwest National Laboratory, and BMW AG.
- Project completed at the end of 2010 and currently investigating commercial opportunities. Technology developed is a 0.1-1 kW prototype microchannel dehydrogenation reactor with 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

- 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.

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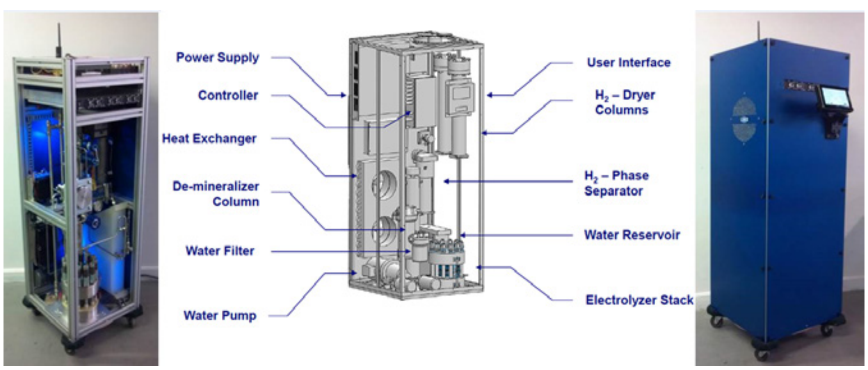
Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi

Emerging Technology

Giner, Inc., with FCTO funding, is developing a low-cost electrolyzer stack and balance of plant (BOP) components. Giner has used their proton exchange membrane (PEM)-based electrolyzer technology for producing hydrogen at moderate to high pressure directly in the electrolyzer stack. The current focus is to reduce commercial electrolyzer costs while simultaneously raising the efficiencies of the PEM-based water electrolyzer units that operate at 400 psi. Giner plans to further extend this technology to operate at 5,000 psi pressures by modifying the electrolyzer stack, providing the ability to safely operate in a differential hydrogen/oxygen pressure mode.

Giner's new electrolyzer stack concept and recent advancement in producing high strength membranes has accelerated progress towards achieving a viable 5,000 psi PEM-based water electrolyzer system for home refueling applications. Giner has found that high-pressure hydrogen can be generated in low-cost moderate-pressure electrolyzer stacks by reinforcement of the individual cell frames. External reinforcement eliminates bulky and costly stack parts and enables safe operation at higher pressure.[1] In addition, a reduction of major system components and system cost is realized. Giner has been testing a 5,000 psi home refueling appliance (HRA) prototype with preliminary cost analysis and commercialization planning underway.



Giner's Prototype Electrolyzer (HRA) System

Technology History

- Developed by Giner, Inc. in collaboration with industry partners.
- Continuing prototype development, system cost reduction and commercialization planning.

Applications

Can be used as a hydrogen refueling device for residential and a wide range of other applications that require pressurized hydrogen.

Capabilities

- Provides home refueling using a PEM-based electrolyzer system that produces hydrogen up to 6,000 psi.[1, 2]
- Provides remote system monitoring and operation via Bluetooth™ connection up to 30 ft. away.[1, 2]
- Provides hydrogen at a cost per kilogram that is rapidly approaching DOE progam 2020 targets of less than $4.00/kg.[1, 2]

Benefits

Cost Savings

Reduces overall refueling system cost by eliminating the need for hydrogen storage and compression at user end site.

Safety

Provides safe operation by providing adequate system safety features to meet current and future agency certification standards.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ii_h_1_norman_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review13/pd065_norman_2013_p.pdf

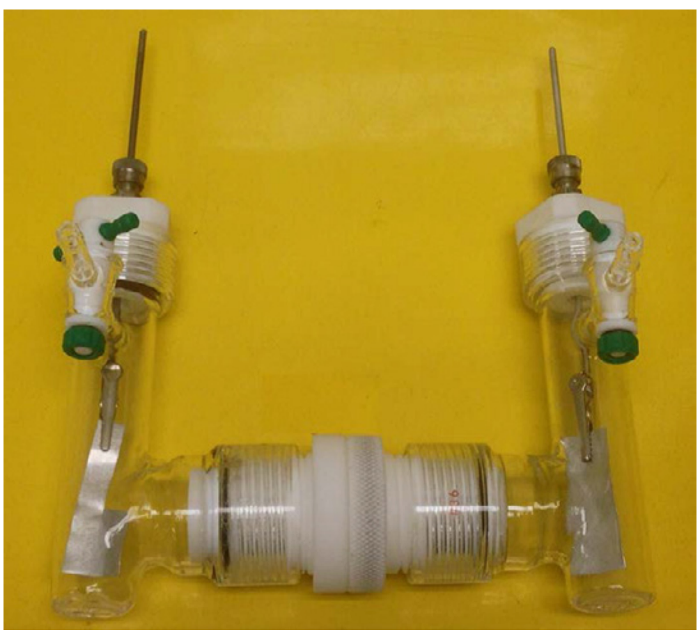
D.3 Storage Technologies

Electrochemical Reversible Formation of Alane

Emerging Technology

Savannah River National Laboratory (SRNL), with FCTO funding, is developing a low-cost rechargeable hydrogen storage material, aluminum hydride (alane - AlH_3), with high hydrogen capacity, favorable thermodynamics and kinetics fulfilling many of DOE onboard hydrogen transportation goals. SRNL's material will avoid using high pressures needed to form AlH_3 and the normal chemical reaction route that leads to the formation of alkali halide salts such as LiCl or NaCl. This will be achieved by using an electrochemical synthesis process for alane originally developed at SRNL and has since been improved for higher efficiency and increased production rate.[1] These improvements were achieved by using $LiAlH_4$ etherates (e.g. Et_2O and DME) and a hydrogen-pressurized electrochemical cell. Aluminum from the dehydrogenated aluminum hydride (spent aluminum) was used to form the alane and regenerate the starting electrolyte.

SRNL are also developing simple passivation methods to make the alane safe to handle. Surface passivation, which reduces H_2 capacity by less than 1%, prevents the material from igniting in air or water and is safer to handle than complex hydrides. Electrochemical generation represents a different but very promising method for AlH_3 production.



SRNL's Nafion® Film Electrochemical Cell for Producing Alane

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/iv_a_7_zidan_2011.pdf

Technology History

- Developed by Savannah River National Laboratory in collaboration with industry partners.
- Continuing work with industrial partners to lower production costs and improve energy efficiency for use as high energy density storage material.

Applications

Can be used to produce low-cost hydrogen storage materials for portable or stationary fuel cell applications.

Capabilities

- Enables efficient and practical production of aluminum hydride (alane - AlH_3).
- Provides gravimetric capacity of 10 wt.% and volumetric capacity of 149 g/L H_2, desorption temperature range of ~60°C to 175°C (particle size and catalyst dependent).[1]
- Provides desorption performance that approaches 2015 DOE onboard system targets.

Benefits

Cost Savings
Manufacturability

Increases alane production by using more efficient electrochemical reactions.

Safety

Avoids hazardous (flammable in air and water) material handling problems by surface passivation which has minimal effect on material hydrogen storage capacity.

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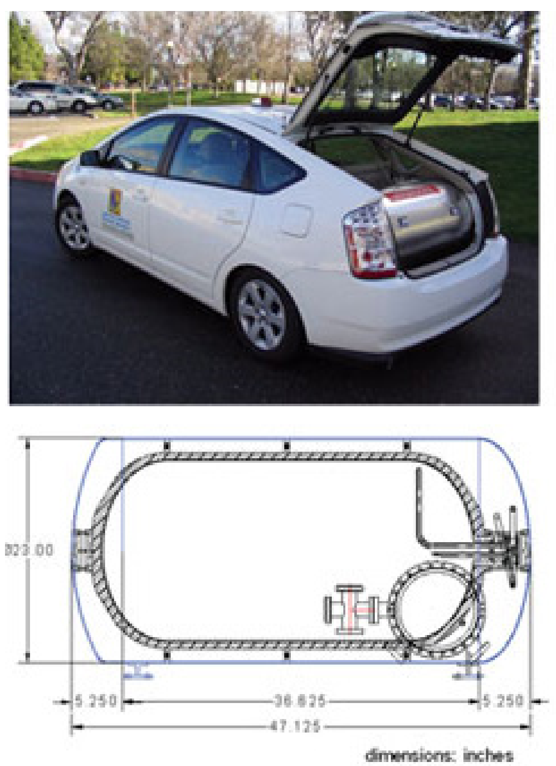
Hydrogen Storage in Cryo-Compressed Vessels

Emerging Technology

Lawrence Livermore National Laboratory (LLNL), with funding from FCTO, developed cryogenic capable hydrogen storage pressure vessels. The cryo-compressed storage tanks present several potential advantages over ambient compressed hydrogen tanks, including higher hydrogen volumetric and grarimetric capacity, reduced cost, safety advantages, and fuel flexibility for both liquid and gas fuel sources. The cryogenic pressure vessel developed 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 is continuing research and development that focuses on increasing the cryo-compressed system pressure as well as scaling down the existing system and targeting aggressive reductions in the cost, weight, and volume characteristics of the vessel. LLNL is effectively collaborating with industry and benchmarking the cryogenic pressure vessel against other physical hydrogen storage systems such as 700 bar high pressure ambient storage 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

The cryo-compressed hydrogen storage systems have achieved a storage density of 43g H_2/L; weight fraction of 7.3%; and cost of $11.3/kWh.[1]

Versatility

Can be used with either compressed or liquid hydrogen.

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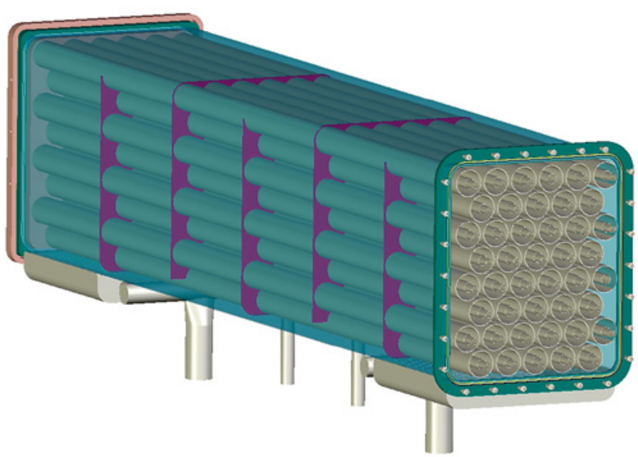
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/iii_11_aceves_2012.pdf

Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications

Emerging Technology

To demonstrate the practical viability of a metal hydride solid-state (MHSS) fuel system, Hawaii Hydrogen Carriers, LLC (HHC), in collaboration with Sandia National Laboratories and industry partners and with funding from DOE SBIR grants and FCTO, is developing an MHSS system that is optimized to operate with PEMFC-powered forklifts. HHC will optimize its AB5 alloy-based storage solution design, whose feasibility has already been demonstrated, and will integrate it with a PEMFC to provide a market-ready conversion kit for HP- and BP-powered forklifts. Once the engineering and manufacturability analysis has been completed, HHC will fabricate a prototype MHSS system and install it on an existing forklift platform. Performance will then be verified and compared with an equivalent HP system and agency certification will be sought for public use (NFPA, OSHA, and ANSI). Once certified, HHC will beta test the MHSS PEMFC system in a representative operational environment.



HHC's MHSS System

Technology History

- Developed by HHC in collaboration with Sandia National Laboratories.
- Currently working on finalizing and optimizing a MHSS PEMFC prototype for fabrication and demonstration.

Applications

Can be used to fuel a PEMFC-powered forklift or other similar low-speed operations support vehicles.

Capabilities

- Provides increased energy storage, 35%, and consistent versus decreasing power compared with BP systems.[1]
- Reduces refueling times, 10 minutes, compared with 24 hours for BP.[1]
- Provides capability to refuel using low pressures, 7 bar compared with 44 bar required in HP systems.[1]

Benefits

Cost Savings

Reduces hydrogen system costs by eliminating the need for HP hydrogen refueling and compressor infrastructure.

Environment

Reduces emissions and eliminates acid battery handling and disposal precautions and procedures.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/st095_jensen_2011._p.pdf

Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)

Emerging Technology

Oak Ridge National Laboratory (ORNL) with FCTO funding, is developing lower cost carbon fiber precursors to reduce the cost of carbon fiber for hydrogen storage tanks. One of ORNL's solutions is a spun textile grade polyacrylonitrile with methyl acrylate (PAN-MA) precursor with strengths potentially in the range of 650-750 Klbs/in^2 (KSI).[1] The textile-based PAN precursor technology will use a higher performance formulation, developed from the technical feasibility stage. The optimized polymer formulation and conversion process (time-temperature-tension profiles) to produce carbon fiber will use existing textile PAN precursor fiber plants and existing precursor conversion plants.

Currently, ORNL is investigating fiber to fiber consistency during precursor spinning. The carbon fibers produced will be tested in a fiber composite with an epoxy resin; fibers with a 650 KSI strength and 35 Mlbs/in^2 (MSI) modulus are targeted. Once these material metrics have been achieved work will begin transferring the technology over to a carbon fiber manufacturer to incorporate this precursor into a production facility and optimize surface treatment and sizing protocols. ORNL expects that once the technology transfer is completed the fiber(s) developed will be ready for commercialization within two to three years to meet DOE program targets.

New Precursor Before Processing into Carbon Fiber

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/st099_warren_2013_0.pdf

[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress13/iv_f_3_warren_2013.pdf

Technology History

- Developed by Oak Ridge National Laboratory and industry partners, SGL Carbon Fibers and FISIPE.
- Continuing work includes optimizing conversion protocols and process parameters to improve fiber-to-fiber consistency and production throughput.

Applications

Can be used to improve strength-to-weight ratio of carbon fiber composite materials for a wide range of applications including high-pressure hydrogen storage tanks.

Capabilities

- Targets fiber strengths > 650 KSI for high pressure applications. (~ 575KSI currently).
- Targets $10-$12 per pound compared with $15-$20 per pound to meet DOE 2015 program goals.

Benefits

Cost Savings

Reduces carbon fiber costs from current market cost of $15-$20/lb to $10-$12/lb by using a readily available methyl-acrylate based PAN precursor manufactured using high throughput textile processes.[2]

Manufacturability

Carbon fiber can be manufactured using existing high volume textile production processes rather than highly specialized processes and materials.

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Manufacturing Technologies for Low-Cost Hydrogen Storage Vessels

Emerging Technology

Quantum Technologies is demonstrating, with FCTO funding, new methods for manufacturing Type IV pressure vessels for hydrogen storage with the objective of lowering the overall product cost with funding from FCTO. Quantum is optimizing composite usage through a hybrid manufacturing method that combines traditional filament winding (FW) and advanced fiber placement (AFP) technologies, exploring the usage of lower-strength, higher modulus fibers on the outer layers of FW, and building economic and analytical models capable of evaluating FW and AFP processes including manufacturing process variables and their impact on vessel mass savings, material cost savings, processing time, manufacturing energy consumption, labor and structural benefits.

The AFP method places fiber where it is needed and does not place fiber in the cylinder section when trying to reinforce the domes. After AFP layers are applied, a FW process step then completes the vessel construction by reinforcing the cylinder section and further reinforcing the domes to bring the vessel up to the required strength. By removing the parasitic fiber, the cost and weight of the pressure vessel are reduced. A vessel constructed using the AFP manufacturing concept recently demonstrated a 15% reduction in both weight and cost while meeting the required burst pressure.[1] Additional testing is currently underway to perform cycle testing, drop tests, extreme temperature cycle tests, and accelerated stress rupture tests to validate process/material changes critical to hybrid vessel design. In addition, the cost models will be updated with the cost and amount of fiber used in the final hybrid design.

Quantum's Hybrid Manufacturing Technology for Pressure Vessels

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/mn008_leavitt_2013_p.pdf

Technology History

Developed by Quantum Technologies and the Boeing Company.

Applications

Can be used to manufacture high-pressure vessels for fuel storage at lower weight and cost.

Capabilities

- Produces pressure vessels using less carbon fiber.
- Reduces weight without compromising pressure rating.
- Enables hydrogen and compressed natural gas vehicles to be more cost competitive.
- Reduced the cost and weight of hydrogen storage composite tanks by more than 15% using AFP manufacturing techniques.

Benefits

Cost Savings

Eliminates parasitic fiber in FW to reduce carbon fiber material cost.

Manufacturability

Separates AFP end-cap manufacturing from the FW process, enabling parallel processing.

Weight Savings

Optimizes carbon fiber placement for reduced pressure vessel weight without compromising vessel structure integrity.

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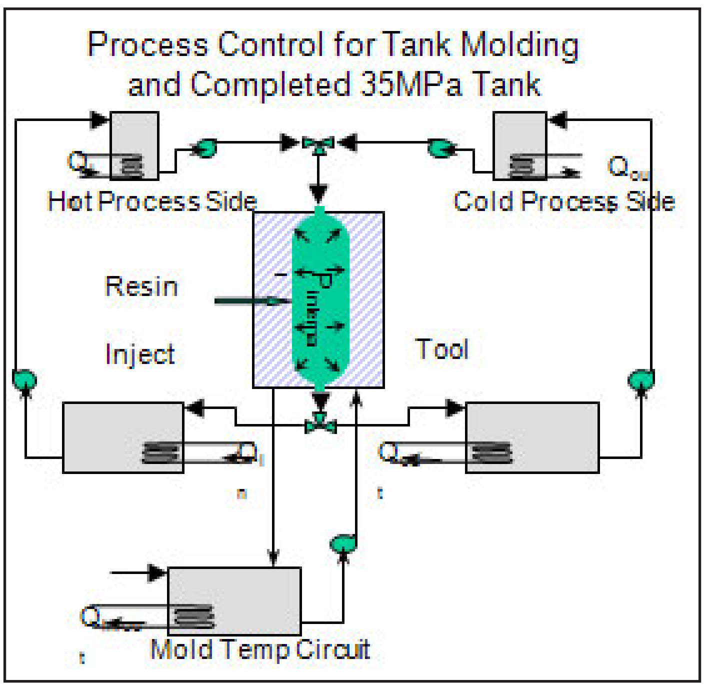
Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders

Emerging Technology

To support the commercial introduction of hydrogen vehicles, a more efficient 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 FCTO 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.[1] The technology will be used to manufacture gas cylinders to store 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 fewer parallel tooling lines are required.



Profile Composites' Hydrogen Tank Fabrication Process

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review08/mf_4_wood.pdf

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.
- Planning to commercialize a 5,000 psi cylinder and begin developing a 10,000 psi cylinder. Awaiting certification of the tank so commercialization can start.

Applications

Can be used to manufacture gas cylinders for storing hydrogen, methane, and natural gas.

Capabilities

- Allows fabrication of high-pressure hydrogen storage tanks in under 20 minutes total cycle time.[1]
- 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.

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Appendix E:
Directory of Technology Developers

Commercially Available Fuel Cell Technologies

Commercially Available Production/Delivery Technologies

Commercially Available Storage Technologies

Emerging Fuel Cell Technologies

Emerging Production/Delivery Technologies

Emerging Storage Technologies

Prepared by Pacific Northwest National Laboratory
for the U.S. Department of Energy Fuel Cell Technologies Office

PNNL-22832 | April 2014

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www.eere.energy.gov/informationcenter