U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY & RENEWABLE ENERGY

Pathways to Commercial Success:

Technologies and Innovations Enabled by the U.S. Department of Energy Fuel Cell Technologies Office

October 2017

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 annual report is to identify and document the research and development (R&D) innovations and technologies that resulted from U.S. Department of Energy (DOE) support through the Fuel Cell Technologies Office (FCTO) in the Office of Energy Efficiency and Renewable Energy (EERE). In addition to hydrogen and fuel cell related U.S. patents as an indicator of innovation, the report also tracks technologies that were subsequently commercialized by industry and those that are projected to be commercialized in the next 3 to 5 years. These results document the impact of FCTO's applied R&D funding sustained over a number of years. FCTO directed Pacific Northwest National Laboratory (PNNL) to undertake the analysis based on the lab's previous expertise, existing databases, and familiarity with the program through years of similar analysis. PNNL conducted two tasks 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 or innovations documented in the patent. The second effort was to identify FCTO-funded innovations by contacting the principal investigators or points of contact and FCTO personnel. PNNL also reviewed FCTO program annual reports, and examined 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 650 patents associated with research supported by FCTO dating back to 1977, with 522 of those patents since 2003 and 395 since 2008. The 650 FCTO patents include: 330 fuel cell patents, 235 hydrogen production/delivery patents, and 85 hydrogen storage patents. In the FY 2015 report, 589 total patents including 299 in fuel cells, 213 in hydrogen production/delivery, and 77 in hydrogen storage, were reported. Three types of organizations received the patents: national laboratories (244 patents), private companies (303 patents), and universities (103 patents). Private companies received the greatest number of patent awards in the fuel cell and production/delivery areas, accounting for 53% of the fuel cell patents and 48% 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 31 patents are currently used in R&D innovations and 39 are part of research now taking place on emerging technologies. In addition, 374 awarded patents are still being used via continuing research and/or active attempts to license the patents. Of all the patents reviewed, 68% are still actively being pursued through use in continuing research, emerging technologies, or commercially available products developed by industry.

In addition, PNNL identified 50 technologies that have been commercialized over time by industry. From 2000 through 2006, an average of 1.5 technologies entered the market per year as a result of industry building upon the early funding by FCTO. From 2007 through 2015, an average of 4.0 technologies per year entered the market. For 2016, two technologies are known to have entered the market thus far. The innovations that subsequently became commercialized also supported the creation/retention of 534 direct jobs in fiscal year 2016. This effort also identified 76 emerging technologies that are anticipated to be commercially available in 3 to 5 years as a result of anticipated development by industry based on their feedback. Of the 76 emerging technologies, 45% are in the fuel cell area, 43% are in the production/delivery area, and 12% are in the storage area.

This report documents the methodology and results of this study, including the specific patents and innovations that resulted from FCTO funding as well as commercial and emerging technologies that were developed by industry and can be attributed to the impact of early FCTO R&D funding.

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1.0 Introduction

This report documents the methodology and results of an effort to identify and characterize R&D innovations and technologies that resulted from DOE support through EERE's Fuel Cell Technologies Office. In addition to hydrogen and fuel cell related U.S. patents as an indicator of innovation, the report also tracks technologies that were subsequently commercialized by industry and those that are projected to be commercialized in the next 3 to 5 years. These results document the impact of FCTO's applied R&D funding sustained over a number of years.[1,2] Pacific Northwest National Laboratory (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 and include input and resources from FCTO.

This chapter presents a brief overview of FCTO-funded R&D that is leading to innovations, and a summary of the contents of this report.

1.1 Overview of the DOE Fuel Cell Technologies Office

FCTO has been 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. FCTO is currently conducting applied research, technology development, and learning demonstrations, as well as safety research, systems analysis, and public outreach and education activities. The research involved in solving critical technological barriers is often high risk, and can benefit from leveraging resources and skills. Therefore, 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.

FCTO focuses primarily on transportation (fuel cell vehicles and hydrogen refueling infrastructure, as well as forklifts and range extenders for medium/heavy duty vehicles). Additional applications include stationary power (including backup emergency power and residential electric power generation), and portable power (including consumer electronics such as cellular phones and laptop computers) that can enable economies of scale and pave the way for transportation applications. 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 as they are most likely to result in technology innovations. Manufacturing R&D is a relatively new subprogram that is likely to lead to R&D innovations in the future or may result in manufacturing processes that will enable lower cost and robust components or systems that enable innovations of hydrogen and fuel cell systems.

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, with a focus on renewables. The subprogram objectives include lowering the cost of distributed production (at the pump) of hydrogen from electrolysis and biomass; developing high-temperature thermochemical cycles; and developing advanced renewable photo-electrochemical and biological hydrogen generation technologies. Hydrogen separation is a key technology that cross-cuts hydrogen production options,

[1] Technologies commercialized by industry are defined as those available for purchase and that have been sold to at least one party. Emerging technologies as defined in this report, are innovations/technologies that are projected to be commercialized within the next 3 to 5 years, based on the opinion of the innovation/technology developer.

[2] Formerly the Hydrogen, Fuel Cells & Infrastructure Technologies Program, 2002-2009, and the Fuel Cell Technologies Program, 2009-2012.

and various separation membranes have been developed as part of distributed and central hydrogen production systems. In addition, work in the subprogram includes developing better catalysts and coordinating with the Office of Science on basic research, such as hydrogen production from algae and other biological systems. The subprogram has also coordinated 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. More recently, the subprogram has been coordinating with DOE's Joint Center for Artificial Photosynthesis (JCAP) funded by DOE's Office of Science which has recently shifted away from hydrogen production and to electrochemical carbon dioxide reduction.

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 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 the efficiencies of hydrogen liquefaction.

Hydrogen Storage. The goal of the Hydrogen Storage subprogram is to develop and demonstrate viable hydrogen storage technologies primarily for transportation applications, though some early market applications, such as forklifts and portable power, have also been under consideration. Various research activities are being pursued, including lightweight composite tanks for high-pressure storage; conformability; high-capacity metal hydrides, including boron-based materials, adsorbent-based and nanostructured materials; chemical carriers; and other promising materials for low or medium pressure hydrogen storage. Coordination with the Office of Science is also noteworthy, particularly in developing a fundamental understanding of hydrogen-material interactions. More recently, the subprogram has been coordinating with the Advanced Research Projects Agency-Energy (ARPA-E) which has funded innovative materials and tank R&D for natural gas storage. Synergies between hydrogen and natural gas storage are being explored. Within the last couple of years, the subprogram has coordinated efforts with EERE's Advanced Manufacturing Office (AMO) and Vehicle Technologies Office (VTO) on carbon fiber cost reduction.

Fuel Cells. The goal of the Fuel Cells subprogram is to develop and demonstrate fuel cell technologies primarily for transportation applications though synergies exist with stationary and early market applications. The subprogram emphasizes polymer electrolyte membrane or proton exchange 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 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. The subprogram had included small-scale solid oxide fuel cell (SOFC) R&D for several years to complement the FE's Solid Oxide Fuel Cells Program[1] on megawatt-scale SOFC power systems; however recently FCTO has shifted away from SOFC R&D. The FCTO portfolio includes diverse non-SOFC fuel-cell technology such as alkaline fuel cells, and only includes solid oxide approaches as they relate to hydrogen production/ electrolysis. Work on fundamental catalysis is coordinated with the Office of Science. Coordination with ARPA-E has also been initiated, particularly in innovative areas such as alkaline exchange membranes.

More information about program goals, objectives, research thrusts, and activities can be found in the FCTO Multi-Year Research, Development, and Demonstration Plan (https://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development office-multi-year-research-development).
The objectives of, and R&D activities funded by, 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 R&D innovations over the history of hydrogen and fuel cell research within EERE, the patents and the resultant and potential R&D innovations described in the remainder of this report may be broader than one would expect from examining the current FCTO efforts.

[1] FE's Solid Oxide Fuel Cells Program is supporting the development of large-scale SOFCs that can be mass-produced in modular form at $400/kW. The objective of the Solid Oxide Fuel Cells Program is to put reliable fuel cells into a more modular and affordable design to allow widespread penetration into stationary and utility-scale markets.

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 details related to the data-gathering techniques and descriptions of each of the R&D innovations and technologies that were identified during the study, as well as the list of patents resulting from the R&D efforts undertaken by FCTO and its predecessor program. 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 fiscal year (FY) 2011 is an estimate of 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 become available.

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2.0 Approach

Two efforts were undertaken by PNNL, initiated 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 developed by industry that may have used the technology documented in the patent. The second effort was a series of interviews and document reviews conducted to identify and characterize commercial and emerging technologies developed by industry that directly benefited as a result of funding from 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 has subsequently produced an annual update to this report from FY 2010 through FY 2015. The approach taken for these efforts is summarized in Sections 2.1 and 2.2 below.

2.1 Patent Search and Analysis

Initially, PNNL conducted several patent searches using the United States Patent and Trademark Office (USPTO) database. The searches included key words related to the hydrogen program and focused exclusively on patents for which DOE had a "Government Interest." [1,2] 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 the 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 and included them in the patent list.[3] The list was sent to FCTO 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 its 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 FCTO or EERE (or its predecessors) funded the research resulting in the patent. Patents not related to 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 by industry 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. Note that while FCTO does not fund the development of a commercial product, early-stage R&D which resulted in innovations with ultimate commercialization potential, are tracked by documenting the products or technologies subsequently developed by industry. As PNNL gathered technology data, additional patents associated with FCTO/EERE funding and found through other sources, were also identified and added to the list. Figure 2.1 depicts the initial patent analysis process for the hydrogen and fuel cell technologies.

[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

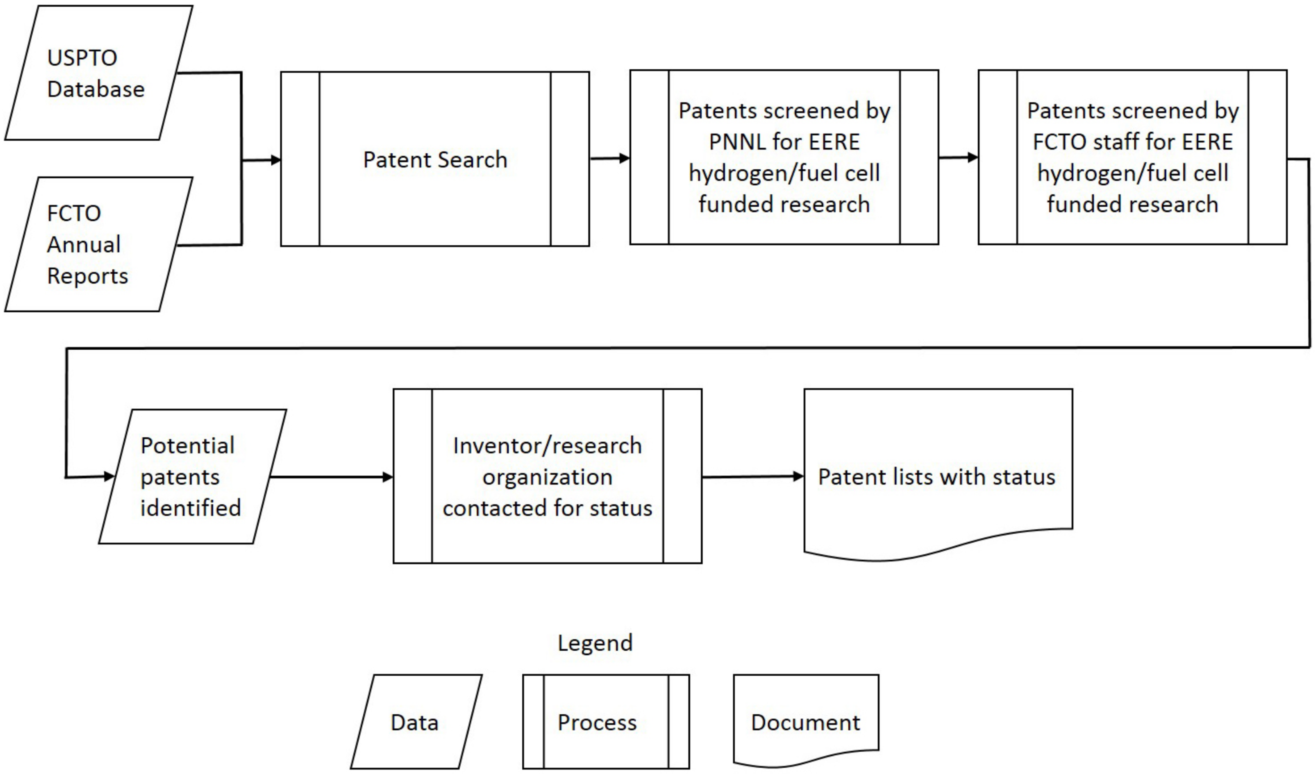

Figure 2.1 Initial Patent Analysis Process for Hydrogen and Fuel Cell Technologies

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 R&D work. In June 2010, EERE launched a Technology Commercialization Portal on its 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 that employed screening strategies similar 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 by industry or that are soon to be commercialized. The section below describes the effort, conducted in parallel with the patent analysis, to identify and describe technologies commercialized by industry and emerging technologies. Chapter 3 provides information about these innovations and the patents related to them.

2.2 Technology Tracking Methodology

The PNNL team also identified FCTO-funded projects that may have resulted in or potentially led to R&D innovations and subsequent industry-commercialized technologies. To accomplish this, a series of one-on-one meetings was first held with current and former FCTO personnel during which the lists of all FCTO-funded projects, obtained from the Hydrogen and Fuel Cells Program Annual Progress Reports for 2002 through 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 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 their status 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 regarding the status.

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 \$100K to \$150K), and Phase 2 grants focus on principal R&D and are funded at a higher level (typically up to \$500K, and more recently \$1 million). 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 associated PIs to determine the status of the innovations being developed under these grants. Any innovations identified as commercial or emerging were added to the technology tracking list. In FY 2013 and FY 2014, FCTO piloted a SBIR/STTR Technology Transfer Opportunity (TTO) Funding Opportunity Announcement (FOA). This was the first TTO FOA conducted by DOE through EERE and entailed offering specific national laboratory patents to small businesses for commercialization.

Data gathered about the technologies were then entered into a FCTO Technology Tracking 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.

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 used 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.

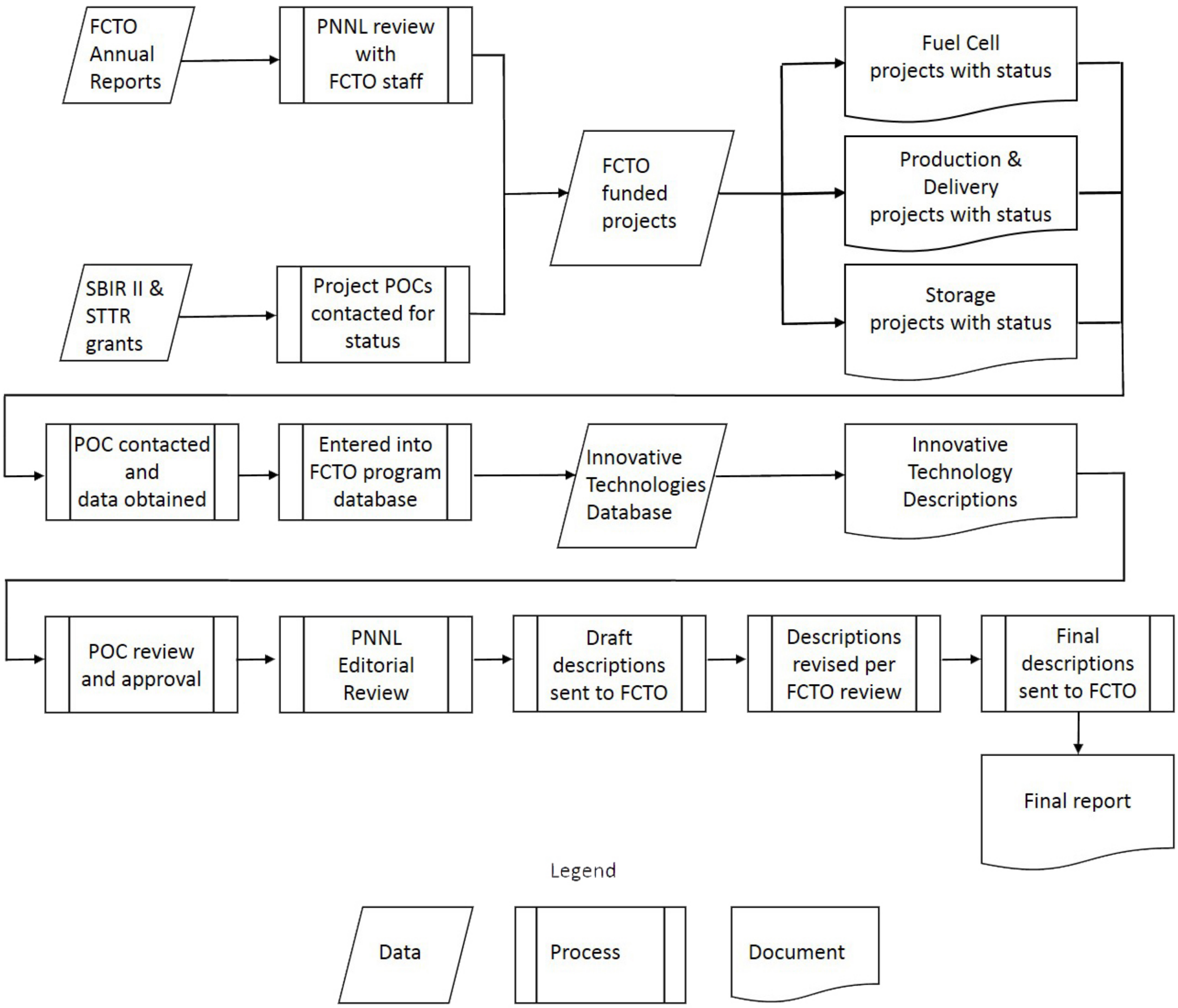

Figure 2.2 Technology Tracking Process for Hydrogen and Fuel Cell Technologies

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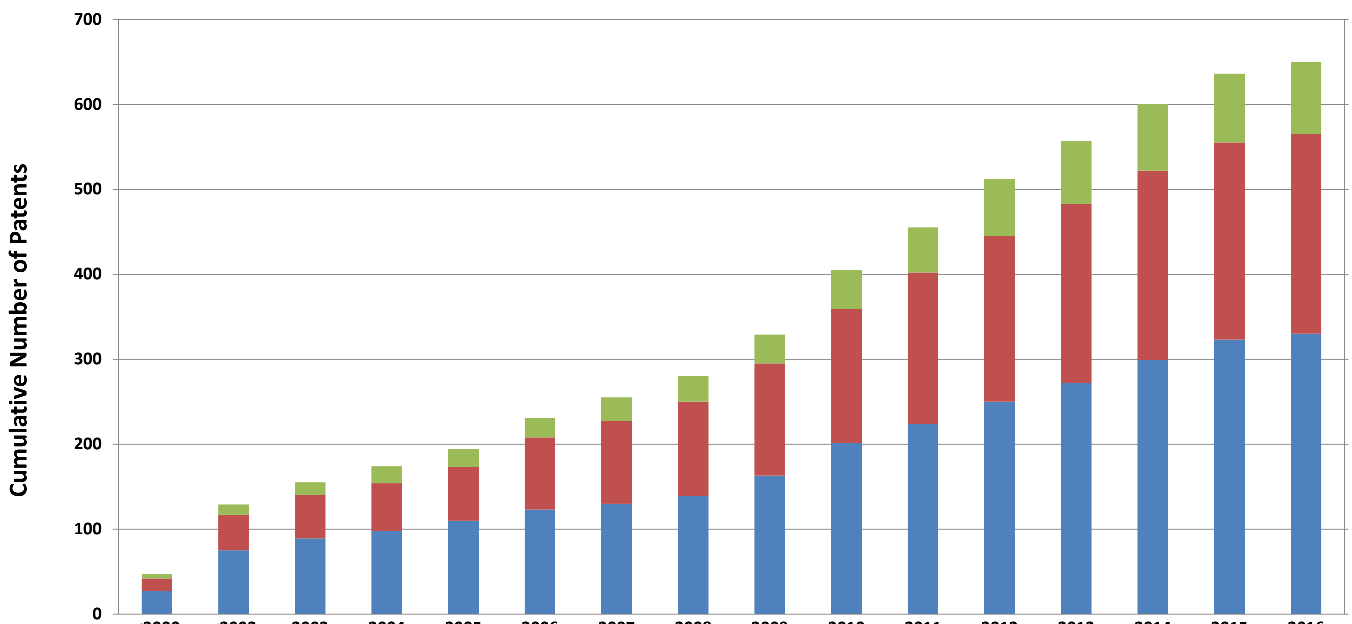
3.0 Results

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 330 fuel cell patents are listed in Appendix B.1, the 235 hydrogen production/delivery patents are listed in Appendix B.2, and the 85 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.

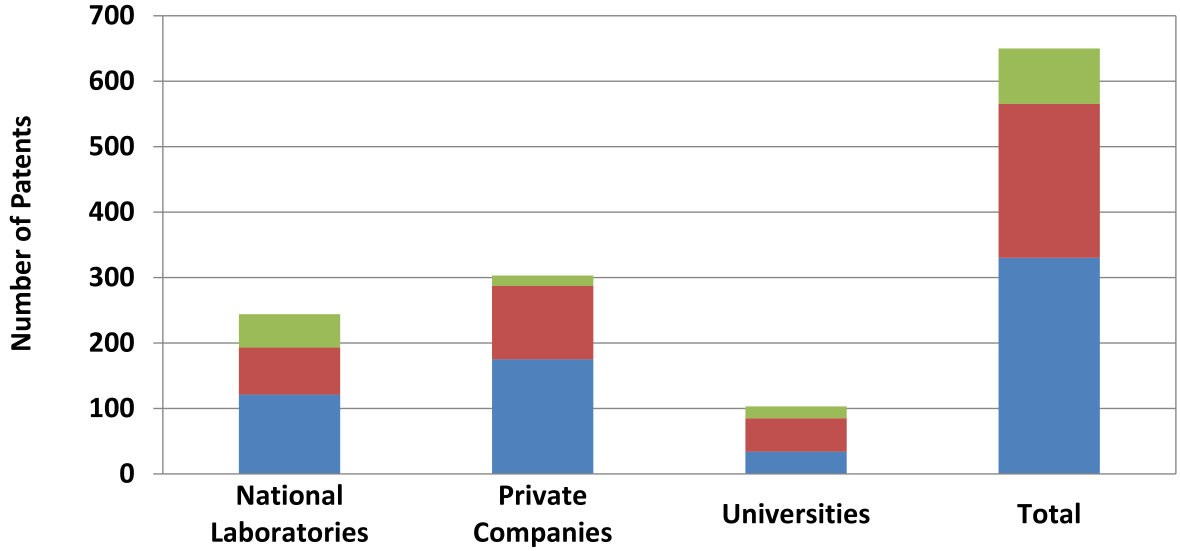
Figure 3.1 shows the cumulative number of patents awarded over time through 2016 (at the time of this report, data for 2016 were only partially available). From 2007 through 2016, an average of 44 patents per year were awarded. During the same time frame, fuel cell, production/delivery, and storage patents were awarded at an average rate of 22, 15, 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: 38 fuel cell patents, 26 production/delivery patents, and 12 storage patents.



	<2000	<2003	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Storage	5	12	15	20	21	23	28	30	34	46	53	67	74	78	81	85
Production/Delivery	15	42	51	56	63	85	97	111	132	158	178	195	211	223	232	235
Fuel Cell	27	75	89	98	110	123	130	139	163	201	224	250	272	299	323	330
Total	47	129	155	174	194	231	255	280	329	405	455	512	557	600	636	650

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 (244 patents), private companies (303 patents), and universities (103 patents). National laboratories and private companies account for 90% of all patents awarded for fuel cell technologies; private companies receive 53% of the awards. Private companies had more patent awards in the production/delivery area (48%) than national laboratories (31%), while universities had 22% of the production/delivery patents. National laboratories account for 60% of the storage patents, followed by universities with 21% and private companies with 19%.



	National Laboratories	Private Companies	Universities	Total
Storage	51	16	18	85
Production/Delivery	72	112	51	235
Fuel Cell	121	175	34	330
Total	244	303	103	650

Figure 3.2 Types of Organization Receiving Patent Awards

Figure 3.3 shows the patent award status by use. As the figure shows, 31 patents are used in resultant technology innovations. Twenty-seven (27) of the 31 patents are awarded to private companies/universities and are associated with the following 12 commercialized technologies:

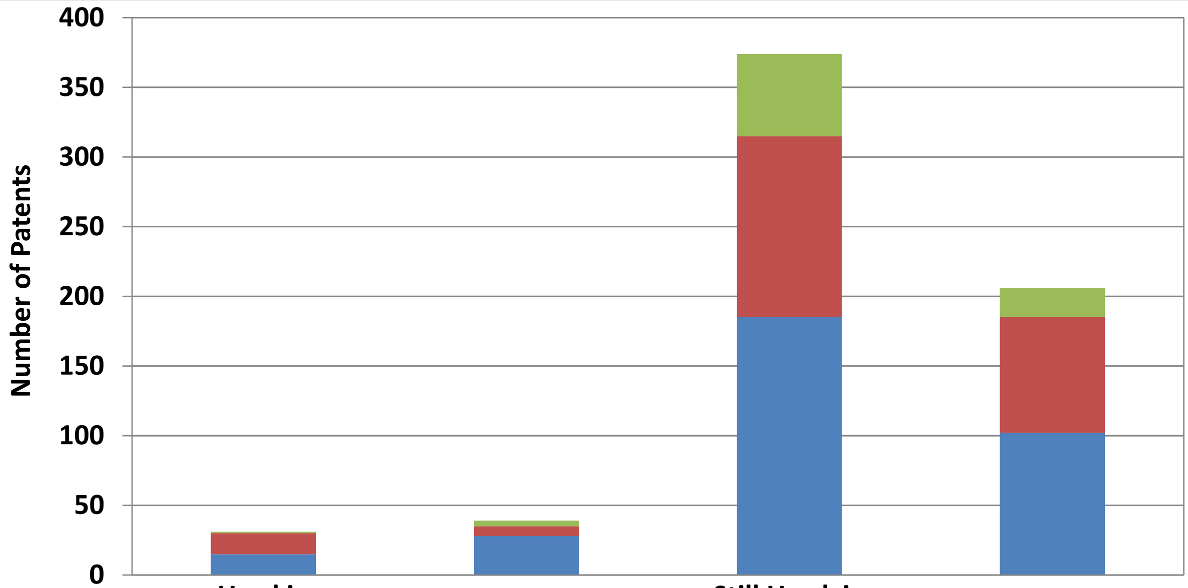
- Cathode Catalysts and Supports for PEM Fuel Cells, 3M Company – Patent number 8,227,140 (2012)
- Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells, Dynalene, Inc. – Patent number 7,138,199 (2006)
- FARADAYIC® ElectroEtching of Stainless Steel Bipolar Plates, Faraday Technology, Inc. – Patent number 8,329,006 (2012)
- H2 ProGen: A Total Supply Solution for Hydrogen Vehicles, Gas Technology Institute – Patent number 7,059,364 (2006)
- HRS-100™ Hydrogen Recycling System, H2Pump, LLC – Patent numbers 8,734,632 (2014) and 8,663,448 (2014) [1]
- Hydrogen Composite Tanks, Quantum Fuel Systems, LLC 8,517,206 (2013) [2]
- Hydrogen Generation from PEM Electrolysis, Proton OnSite – Patent numbers 7,850,838 (2010), 7,744,733 (2010), 7,678,251 (2010) [3]
- Intellipigment™: Visible Hydrogen Gas Leak Detection Material, University of Central Florida – Patent numbers 8,703,642 (2014), 8,652,993 (2014), 8,623,662 (2014), 8,591,818 (2013), 8,268,392 (2012), 8,048,384 (2011), 8,003,055 (2011)
- Low-Cost 3-10 kW Tubular SOFC Power System, Atrex Energy, Inc. – Patent numbers 8,586,252 (2013), 8,628,891(2014) [4]
- Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions, 3M Company – Patent numbers 8,481,227 (2013), 8,323,809 (2012), 7,838,138 (2010), 7,572,534 (2009), 7,517,604 (2009)
- Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production, Catacel Corporation – Patent numbers 8,721,973 (2014), 7,906,079 (2011) [5]
- Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi, Giner, Inc. – Patent number 8,349,151 (2013)

[1] Technology acquired by Sustainable Innovations, Inc.
[2] Formerly Quantum Fuel Systems Technologies Worldwide, Inc.
[3] Formerly Proton Energy Systems, Inc.
[4] Formerly Acumentrics, Inc.
[5] Acquired by Johnson Matthey.

The remaining four patents are based on national lab intellectual property and resulted in the following four commercialized technologies:

- Conductive Compound for Molding Fuel Cell Bipolar Plates, Los Alamos National Laboratory – Patent number 6,248,467 (2001)
- Corrosion Test Cell for PEM Bipolar Plate Materials, Los Alamos National Laboratory – Patent number 6,454,922 (2002)
- DetecTape™: Early Warning Visual Hydrogen Leak Detector, National Renewable Energy Laboratory – Patent number 7,910,373 (2011)
- Portable Reformed Methanol Fuel Cells, Lawrence Livermore National Laboratory – Patent number 6,960,235 (2005)

Thirty-nine patents are part of research now taking place on emerging technologies identified in the technology tracking list in Appendix A. In addition, 374 awarded patents are still being used via continuing research and/or active attempts to license the patent. Of all the patents reviewed, 68% are still actively being pursued through use in continuing research, emerging technologies, or commercially available products.

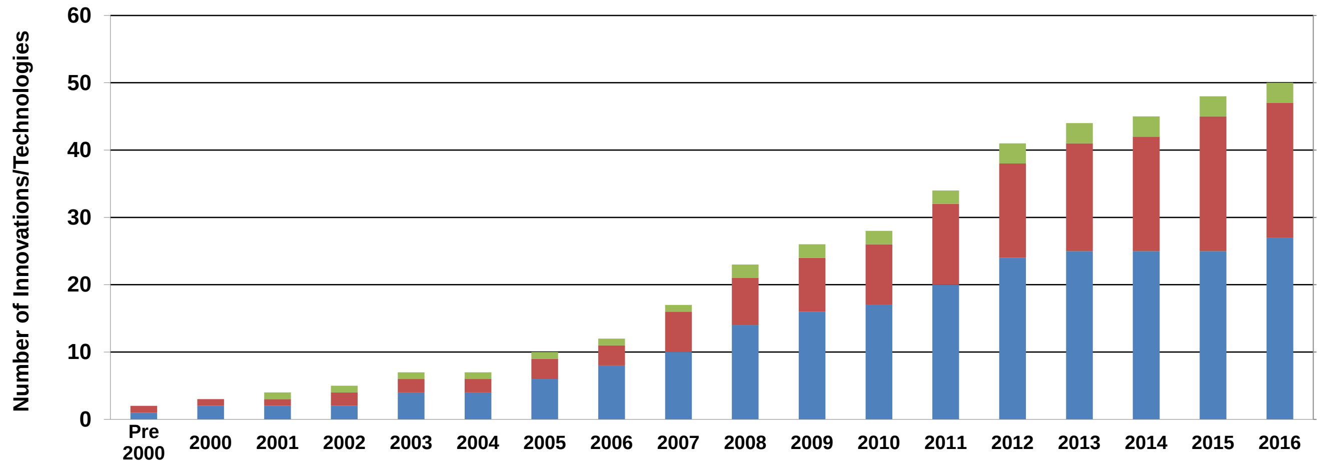


	Used in Commercial Product	Part of Emerging Technology	Still Used in Research and/or Seeking to License	No Longer Being Pursued
Storage	1	4	59	21
Production/Delivery	15	7	130	83
Fuel Cell	15	28	185	102
Total	31	39	374	206

Figure 3.3 Status of Awarded Patents

3.2 Innovation and Technology Identification and Tracking Results

The FCTO Innovation and Technology Tracking Database is updated annually and currently contain 35 R&D technology innovations, all of which are described in the appendices. Because some patents or innovations may no longer be in use in out years, the number of active innovations/technologies may change from year to year. These descriptions were reviewed and approved by the industry POC for each innovation. Figure 3.4 shows the cumulative number of resultant R&D innovations entering the market. Of the 50 innovations, 13 of them are no longer commercially available and two companies decided not to continue to participate in the innovation tracking effort. From 2000 through 2015, three innovations per year have entered the market. The years 2000 through 2006 showed a steady addition of 1.5 innovations entering the market per year. For 2007 through 2015, an average of four innovations per year entered the market. In 2016, two innovations have entered the market to date.



	Pre 2000	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Storage	0	0	1	1	1	1	1	1	1	2	2	2	2	3	3	3	3	3
Production/Delivery	1	1	1	2	2	2	3	3	6	7	8	9	12	14	16	17	20	20
Fuel Cell	1	2	2	2	4	4	6	8	10	14	16	17	20	24	25	25	25	27
Cumulative	2	3	4	5	7	7	10	12	17	23	26	28	34	41	44	45	48	50

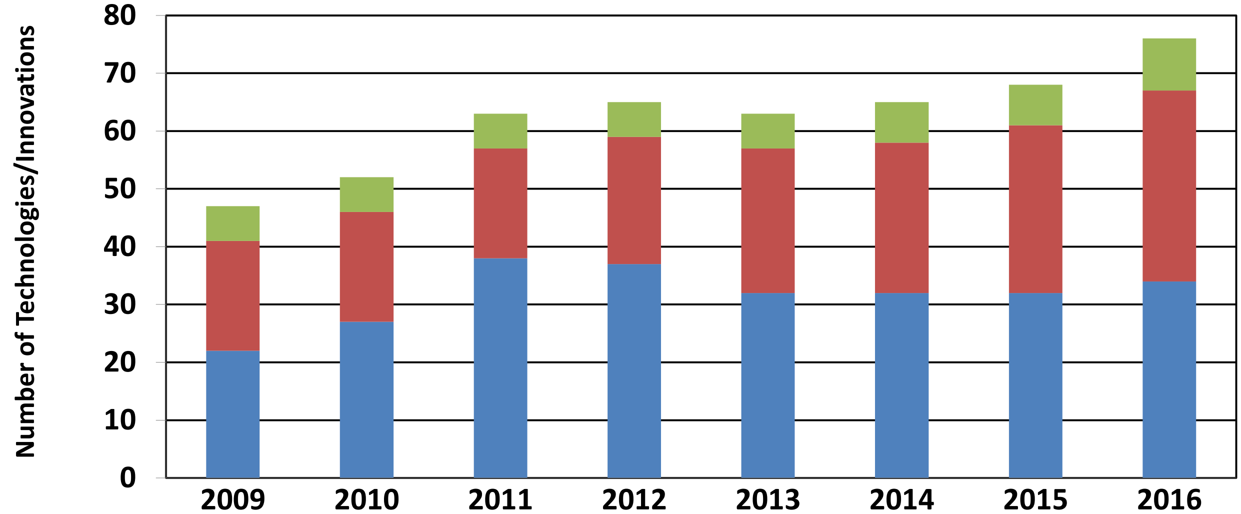
Figure 3.4 Cumulative Number of R&D Innovations

Table 3.1 briefly describes each of the 20 fuel cell innovations that entered the market, and their benefits. All tables are included at the end of this chapter. 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 14 production/delivery innovations that entered the market, and their benefits. These innovations include improved catalysts, hydrogen generation systems for fueling vehicles, and innovations for providing high-purity hydrogen.

Table 3.3 briefly describes the one storage innovation developed by industry which entered the market, and its benefits.

FCTO's Multi-Year Research, Development, and Demonstration Plan, which was last updated in FY 2015/2016, was examined to see how the R&D innovations align with program's objectives and goals. The plan lists challenges, tasks, and technology pathway items for the research areas funded by FCTO. The fuel cell area listed seven tasks. The 20 resultant innovations in Table 3.1 are aligned with six of these tasks, as shown in Table 3.4. Similarly, the 14 resultant production/delivery innovations in Table 3.2 were found to align with four of the 11 challenges/items in that area, as shown in Table 3.5. The resultant storage innovations in Table 3.3 was found to align with one of the three storage challenges, as shown in Table 3.6.

The innovation and technology tracking database currently contains 76 emerging technologies or potential innovations. These were reviewed and approved by the industry POC for each technology. Figure 3.5 shows the number of emerging technologies/innovations in each FCTO research area over the past eight years of the tracking effort. Since 2009, the number of emerging technologies/innovations in the fuel cell area has been about half of the total, with emerging storage innovations making up a very small percentage. Figure 3.6 shows the FY 2016 distribution of the emerging technologies/innovations in the three FCTO research areas.



	2009	2010	2011	2012	2013	2014	2015	2016
Storage	6	6	6	6	6	7	7	9
Production/Delivery	19	19	19	22	25	26	29	33
Fuel Cell	22	27	38	37	32	32	32	34
Total	47	52	63	65	63	65	68	76

Figure 3.5 Number of Emerging Technology/Innovations from FCTO Funding

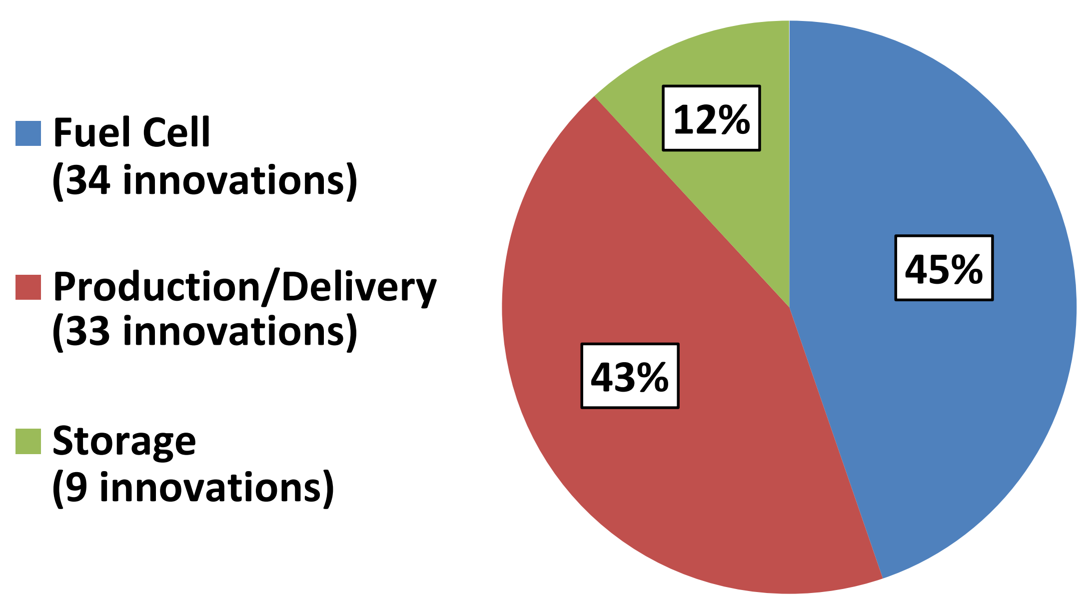


Figure 3.6 Distribution of Emerging Technology/Innovations in FY 2016

Table 3.7 briefly describes each of the 34 emerging fuel cell technologies/innovations and their benefits. These innovations 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 33 emerging production/delivery technologies/innovations and their benefits. These innovations include improved membranes, reformers, and compressors, as well as novel methods and fuels to produce hydrogen.

Table 3.9 briefly describes each of the nine emerging storage innovations/technologies and their benefits. These innovations include improved tanks or cylinders, as well as new approaches for storing hydrogen.

The 34 emerging fuel cell innovations/technologies in Table 3.7 are aligned with five of the seven fuel cell tasks in the FCTO Program Plan, as shown in Table 3.10. Also, one topic in the manufacturing research area of the plan for PEM fuel cells is aligned with four emerging fuel cell innovations. Similarly, the 33 emerging production/delivery innovations/technologies in Table 3.8 are aligned with nine of the 11 production and delivery items or challenges in the plan, as shown in Table 3.11. The nine emerging storage innovations/technologies in Table 3.9 are aligned with two of the four challenges in the storage area, as shown in Table 3.12.

An alphabetized directory of the organizations that developed the technologies that subsequently entered the market and emerging innovations/technologies described are also provided in the appendices.

3.3 Jobs Created or Retained as a Result of the R&D Innovations and Technologies Tracked

Beginning in FY 2011, the PNNL team asked R&D innovation/technology POCs to estimate the number of jobs created or retained as a result of FCTO-funded innovation that ultimately resulted in technologies entering the market. The types of jobs reported by the POCs include R&D, engineering, manufacturing, and marketing/sales within their organizations. Figure 3.7 shows the number of jobs created or retained in FY 2011 through FY 2016 based on the responses from the POCs.[4] 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 2016 distribution of jobs created or retained in the three FCTO research areas.

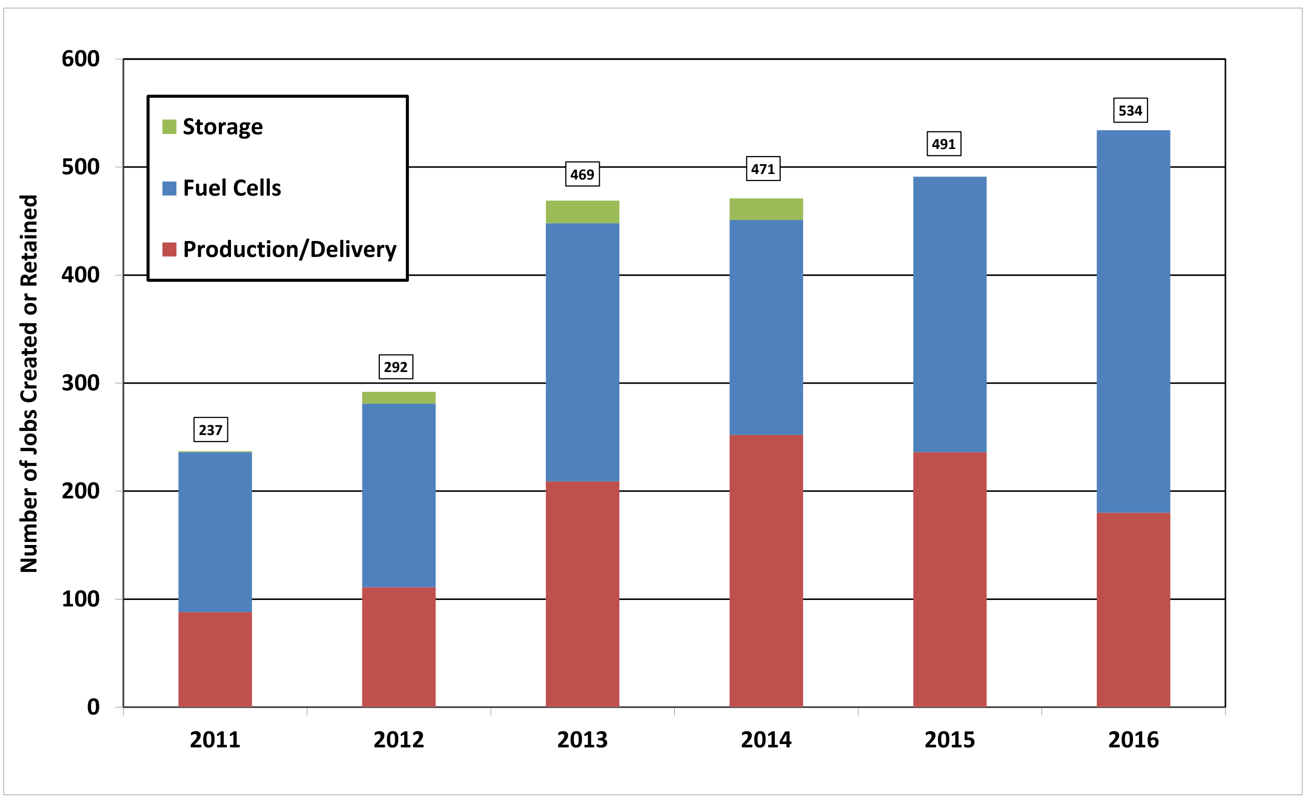


Figure 3.7 Jobs Created or Retained as a Direct Result of FCTO-funded R&D Innovations

[4] Some POCs declined to provide an estimate of the number of jobs created/retained due to business confidentiality. Therefore, the results reported here represent conservative estimates.

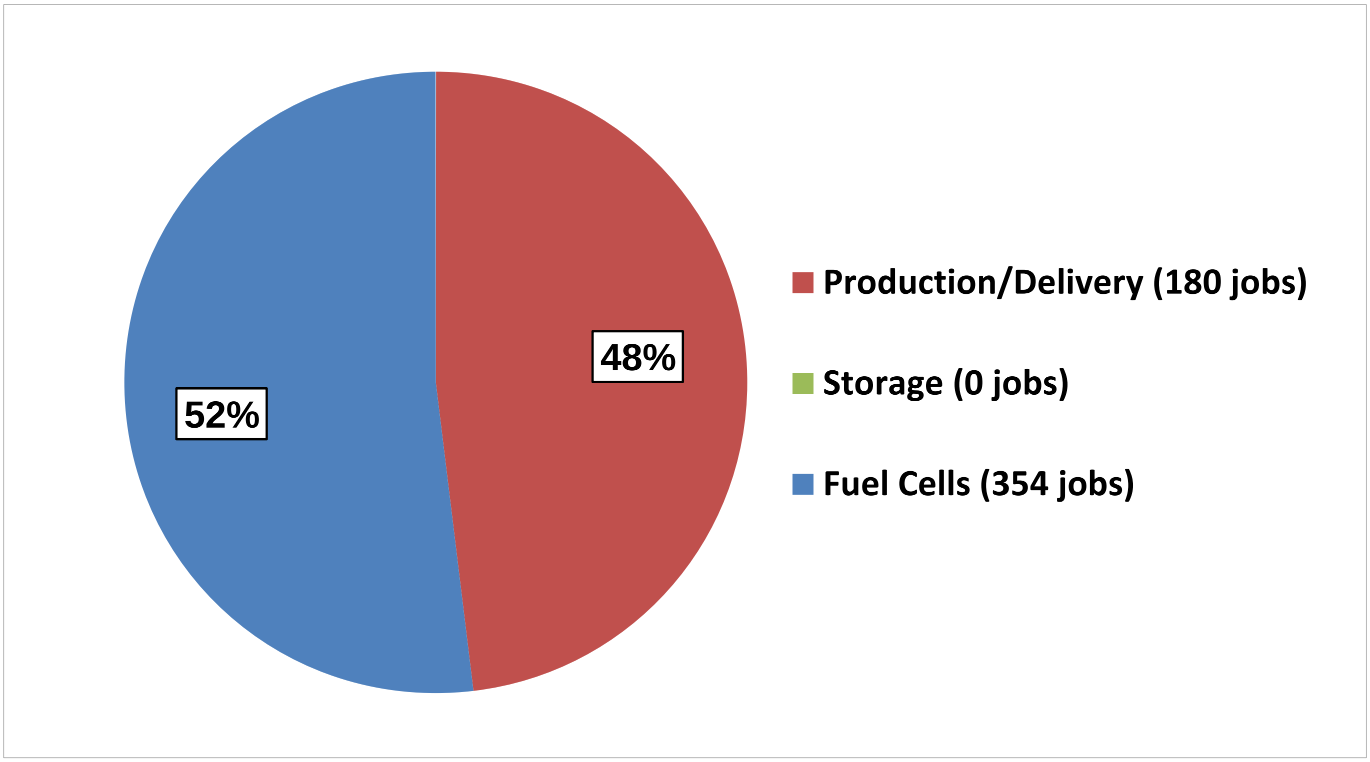


Figure 3.8 Distribution of Jobs Created or Retained in FY 2016

Table 3.1 R&D Innovation and Technology Summary – Fuel Cells

Innovation	Organization	Description	Benefits	Status
Bio-Fueled 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.	Entered the market in 2011.
Cathode Catalysts and Supports for PEM Fuel Cells	3M Company	The membrane electrode assembly (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, manufacturing costs, and smaller fuel cell size. It can operate at higher temperatures and lower humidity.	Entered the market 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 onsite 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.	Entered the market 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.	Entered the market 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.	Entered the market 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 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.	Entered the market in 2008.
Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)	Nuvera Fuel Cells, Inc.[1]	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.	Entered the market 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 BPPs 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 BPPs through use of a high-volume batch process with low capital equipment and tooling costs.	Entered the market in 2012 and a patent awarded in December 2012.

[1] Note: Acquired by Hyster-Yale

Table 3.1 R&D Innovation and Technology Summary – Fuel Cells

Innovation	Organization	Description	Benefits	Status
Fuel Cell Turbocompressor	Honeywell International, Inc.	Two-stage turbocompressor provides much higher air pressures to support small footprint, high-power-density fuel cell stacks.	The turbocompressor provides a low-cost, lightweight, and compact solution using proven and reliable aerospace grade technology. Its modular design enables integration to multiple end user applications.	Entered the market in 2016.
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 (American Recovery and Reinvestment Act [ARRA] Project)	Plug Power Inc.	A fuel-cell-based power source for electric forklift fleets that increases fleet productivity and improves forklift performance compared to conventional lead-acid batteries.	The system can be refueled with hydrogen in less than 3 minutes (compared to 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 10,000 units are currently in use.
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 entered the market in 2006 and the parallel array fuel cell in 2007.
Low-Cost 3-10 kW Tubular SOFC Power System	Atrex Energy, Inc.[1]	The system is a natural-gas-based SOFC that 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. Onsite simultaneous generation of heat and power will increase efficiency and lower energy costs to consumers.	Entered the market in 2016.
Low-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.	A low-cost fabrication process produces durable, low-contact resistance metallic BPPs 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.	Entered the market in 2011.

[1] Note: Formerly Acumentrics, Inc.

Table 3.1 R&D Innovation and Technology Summary – Fuel Cells

Innovation	Organization	Description	Benefits	Status
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.	Entered the market 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.	Entered the market 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[1]	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 100 M250- CX and M300-CX systems since 2010.
Nuvera® 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 to conventional lead-acid batteries.	The system can be refueled with hydrogen in less than 2 minutes (compared to 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.	Entered the market in 2016.
Orion™: Fuel Cell Technology for Hybrid Power Applications	Nuvera Fuel Cells, Inc.	A fuel cell stack design that improves fuel cell performance under subfreezing conditions. The ORION™ uses 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.	The new fuel cell improves startup performance in applications involving subfreezing conditions, such as automobiles, forklifts, and auxiliary power units. The stack achieves 50% of rated power in 28 seconds from a startup temperature of -20°C.	Entered the market in 2013.
Portable Reformed Methanol Fuel Cells	UltraCell Corporation	The XX25 fuel cell, using methanol as a fuel source, is a self- contained, 25-W 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.	Entered the market in 2007.

[1] Acquired by Ballard Power Systems

Table 3.1 R&D Innovation and Technology Summary – Fuel Cells

Innovation	Organization	Description	Benefits	Status
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 AvCarb.

Table 3.2 R&D Innovation and Technology Summary – Production/Delivery

Innovation	Organization	Description	Benefits	Status
California Hydrogen Refueling Stations	Air Products and Chemicals, Inc.	Stationary and mobile refueling stations with differing hydrogen supply methods that were developed to demonstrate hydrogen delivery infrastructure and improve hydrogen fueling station technologies through consumer feedback.	The stations demonstrate the ability to deliver hydrogen using a variety of methods (over-the-road, pipeline, and a connection to a nearby source of anaerobic digester gas). The mobile delivery trailer can provide liquid hydrogen and high- pressure gaseous hydrogen.	Market production and delivery of hydrogen under contract began in 2013.
DetecTape™: Early Warning Visual Hydrogen Leak Detector	Element One, Inc.	The tape is a passive, color changing self-fusing silicone wrap designed to detect hydrogen gas leaks in fuel cells and hydrogen production/transmission/storage facilities. It is based on chemo-chromic technology and can be applied easily to suspected leak areas.	The DetecTape™ identifies hydrogen leaks quickly (response times of less than 20 seconds with 100% Hydrogen gas) at the exact leak location. The fast, accurate leak detection improves workplace safety and reduces the time/costs associated with leak detection and lost hydrogen gas.	Entered the market in 2015.
H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	Atlas Copco	The integrated, onsite 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.	Entered the market in 2007, with one fuel station in use at the University of Texas in Austin.
HRS-100™ Hydrogen Recycling System (SBIR Project)	Sustainable Innovations, 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.	Entered the market in 2014.
Hydrogen Generation from PEM Electrolysis	Proton OnSite	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.	The HOGEN S series entered the market in 1999, selling units in the U.S. and internationally. The HOGEN H series entered the market in 2004 and the HOGEN C series in 2011. A MW scale version, M series entered the market in 2016.

Table 3.2 R&D Innovation and Technology Summary – Production/Delivery

Innovation	Organization	Description	Benefits	Status
Hydrogen Safety Sensor for Energy Applications	Nexceris, LLC[1]	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 humidity 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.	Entered the market in 2010.
Intellipigment™: Visible Hydrogen Gas Leak Detection Material	HySense Technology, LLC	A palladium oxide pigment that changes color in the presence of hydrogen and can be used to identify hydrogen gas leaks in industrial settings. The pigment is used in a tape form that can easily be wrapped around pipes, flanges, valves, and other leak- prone locations.	The Intellipigment™ tape identifies hydrogen leaks quickly (response times of 20 seconds with 100% H_2 gas and less than 3 minutes with 1% H_2 gas) at the exact leak location. The fast, accurate leak detection improves workplace safety and reduces the time/costs associated with leak detection and lost hydrogen gas.	Entered the market in 2013.
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/day at pressures up to 40 psig.	The generator produces very high purity independent of backpressure 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.	Entered the market in 2002.
Nanoscale Water Gas Shift Catalysts	Nexceris, LLC	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.	Entered the market in 2005.
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.	Entered the market in 2015.
PEM Electrolyzer Incorporating a Low-Cost Membrane	Giner Electrochemical Systems, LLC (GES)	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.	Entered the market in 2011. GES has delivered several stacks and continues to scale up output.

[1] Formerly NexTech Materials, Ltd.

Table 3.2 R&D Innovation and Technology Summary – Production/Delivery

Innovation	Organization	Description	Benefits	Status
Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.[1]	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.	Entered the market in 2012 with one international sale and one domestic unit being installed.
TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Hexagon Lincoln[2]	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 to conventional tube trailers, while meeting strength, environmental, and durability targets.	Entered the market in 2011.
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.	Entered the market in 2015.

[1] Note: Acquired by Johnson Matthey.
[2] Note: Formerly Lincoln Composites, Inc.

Table 3.3 R&D Innovation and Technology Summary – Storage

Innovation	Organization	Description	Benefits	Status
Hydrogen Composite Tanks	Quantum Fuel Systems, LLC	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.	Entered the market in 2001.

Table 3.4 Fuel Cell Tasks and Related R&D Innovations/Technologies

Tasks*	Innovation	Organization
Balance of Plant Components	Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells	Dynalene, Inc.
	Fuel Cell Turbocompressor	Honeywell International, Inc.
	Orion™: Fuel Cell Technology for Hybrid Power Applications	Nuvera Fuel Cells, Inc.[1]
Catalysts/Electrodes	Cathode Catalysts and Supports for PEM Fuel Cells	3M Company
	Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems, Inc.
Fuel Cell Systems	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.
	GenDrive™ Fuel Cell Power System	Plug Power, Inc.
	Low-Cost 3-10 kW Tubular SOFC Power System	Atrex Energy, Inc.[2]
	Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation[3]
	Portable Reformed Methanol Fuel Cells	UltraCell Corporation
	Nuvera® Fuel Cell System	Nuvera Fuel Cells, Inc.
Membrane Electrode Assemblies, Cells, and Other Stack Components	Conductive Compound for Molding Fuel Cell Bipolar Plates	Bulk Molding Compounds, Inc.
	Corrosion Test Cell for PEM Bipolar Plate Materials	Fuel Cell Technologies, Inc.
	FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates	Faraday Technology, Inc.
	Low-Cost PEM Fuel Cell Metal Bipolar Plates	TreadStone Technologies, Inc.
	Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
	Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC
Membranes/Electrolytes	Membranes and Membrane Electrode Assemblies for Dry, Hot Operating Conditions	3M Company
Testing and Technical Assessment	GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory

* Note: The fuel cell tasks are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf

[1] Note: Acquired by Hyster-Yale
[2] Note: Formerly Acumentrics, Inc.
[3] Note: acquired by Ballard Power Systems

Table 3.5 Production/Delivery Technology Pathway Challenges and Related R&D Innovations/Technologies

Tasks*	Innovation	Organization
Containment	TITAN™: High-Pressure Hydrogen Storage Tank for Gaseous Truck Delivery	Hexagon Lincoln[1]
Electrolysis	California Hydrogen Refueling Stations	Air Products and Chemicals, Inc.
	Hydrogen Generation from PEM Electrolysis	Proton OnSite
	PEM Electrolyzer Incorporating a Low-Cost Membrane	Giner Electrochemical Systems, LLC
Reforming of renewable, bio-derived feedstocks	H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	Atlas Copco
	ME100 Methanol Reforming Hydrogen Generator	REB Research & Consulting
	Nanoscale Water Gas Shift Catalysts	Nexceris, LLC[2]
	Novel Catalytic Fuel Reforming	InnovaTek, Inc.
	Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production	Catacel Corp.[3]
Separation and purification systems	DetecTape™: Early Warning Visual Hydrogen Leak Detector	Element One, Inc.
	HRS-100™ Hydrogen Recycling System	Sustainable Innovations, LLC
	Hydrogen Safety Sensor for Energy Applications	Nexceris, LLC
	Intellipigment™: Visible Hydrogen Gas Leak Detection Material	HySense Technology, LLC

* Note: These production technology pathway items are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf and for delivery challenges at http://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf.

[1] Note: Formerly Lincoln Composites, Inc.
[2] Note: Formerly NexTech Materials, Ltd.
[3] Note: Acquired by Johnson Matthey.

Table 3.6 Storage Challenges and Related R&D Innovations/Technologies

Tasks*	Innovation	Organization
Physical Storage	Hydrogen Composite Tanks	Quantum Fuel Systems, LLC

* Note: The storage challenges are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf

Table 3.7 Emerging Innovations/Technologies Summary – Fuel Cells

Innovation	Organization	Description	Benefits
Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells	Redox Power Systems	A bilayer electrolyte cell that maintains high power density at intermediate temperatures for distributed generation and combined heat and power applications is being tested.	Improvements in cell performance/ efficiency results in lower costs, higher efficiency, and superior durability.
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.
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 (ARRA Project)	MeOH Power	The Mobion® 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 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	OneD Material, LLC	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.
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 to 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 to traditional Pt/C catalysts and reduce material costs by using less Pt.

Table 3.7 Emerging Innovations/Technologies Summary – Fuel Cells

Innovation	Organization	Description	Benefits
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 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 to 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.
Ground Support Equipment Demonstration	Plug Power, Inc.	A hydrogen-fuel-cell-based alternative to internal-combustion-engine-powered baggage tow tractors at airports.	The fuel-cell-powered tow tractors will reduce carbon emissions compared to existing diesel-fueled vehicles.
High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System	Intelligent Energy, Inc.	The combined heat and power (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, Durable, Low Cost MEAs for Transportation Applications	3M Company	A fuel cell membrane electrode assembly (MEA) with increased durability for use in vehicles. The MEA is based on 3M's nanostructured thin-film (NSTF) catalyst technology.	The new MEA improves fuel cell cold-start performance through changes to the anode gas diffusion layer structure and composition. The design decreases MEA costs by reducing the platinum group metal content of the NSTF catalyst.
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-Performance Water Vapor Membrane for Improved Fuel Cell Balance of Plant (SBIR Project)	Tetramer Technologies	A low-cost water vapor membrane for cathode humidification modules in PEM fuel cells was developed and is undergoing long-term testing.	The membrane will result in lower costs, improved durability, and performance improvement.
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 humidity 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 Innovations/Technologies Summary – Fuel Cells

Innovation	Organization	Description	Benefits
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 BPPs 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 BPPs 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.
Maritime Fuel Cell Generator Project	Sandia National Laboratories	A containerized hydrogen PEM fuel cell generator was developed and deployed at a port to replace a diesel generator.	This demonstration reduces the risk of future port fuel cell deployments and details the benefits to the port of using hydrogen fuel cells.
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.
Nano Structured Metal Bipolar Plates for Low- Cost Fuel Cell Stacks	TreadStone Technologies, Inc.	A new method of coating stainless steel bipolar plates using titanium alloys. The new coating is undergoing durability testing and is meeting corrosion resistance targets.	The new bipolar plates reduce fuel cell stack cost by using less expensive materials while meeting performance targets.
New Fuel Cell Membranes with Improved Durability and Performance	3M Company	Membranes with new ionomers and nanofiber supports were developed and are being tested. These membranes have improved mechanical properties, low area specific resistance, and excellent chemical stability.	The new membranes will result in improved performance, increased durability, and reduced costs.
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.
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.

Table 3.7 Emerging Innovations/Technologies Summary – Fuel Cells

Innovation	Organization	Description	Benefits
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.
Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International, Ltd.	The BPP 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.
Roots Air Management System with Integrated Expander	Eaton Corporation	To enable the use of PEM fuel cells in vehicles a new air management system was developed and tested that will improve costs and reliability.	The air management system improves system performance, operates at a lower speed, reduces the number of parts and uses a plastic expander thus reducing overall cost.
Sensors for Automotive Fuel Cell Systems	Nexceris, LLC[1]	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 startup time, and the ability to handle start-stop cycling.	The technology can operate reliably on a variety of gas and liquid fuel reformates 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.
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.

[1] Note: Formerly NexTech Materials, Ltd.

Table 3.8 Emerging Innovations/Technologies Summary – Production/Delivery

Innovation	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.
Advanced Barrier Coatings for Harsh Environments	GVD Corporation	New barrier coatings for O-rings and other high pressure hydrogen seals to mitigate hydrogen permeability and reduce seal wear due to friction.	The new seals have a longer lifetime and reduce the cost of hydrogen compression, storage, and dispensing.
Catalysts/Electrodes for Hydrogen Production by Water Electrolysis	Proton OnSite	Catalyst structures that reduce the amount of platinum group metals used in electrolyzer stack electrodes.	The less expensive catalyst materials reduce the cost of hydrogen production via electrolysis.
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 1,285 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.
Composite Membrane for High Temperature Hydrogen Separation	Bettergy Corporation	A robust, high temperature hydrogen separation membrane has high hydrogen selectivity and permeability, excellent hydrothermal and chemical stability, and durability in harsh operating conditions.	The membrane system has low energy consumption, the possibility of continuous operation, ease of operation and is cost effective.
Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory	Extensive testing of fiber-reinforced polymer pipelines is 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.
Economical Production of Hydrogen using High-Efficiency Electrocatalysts for Alkaline Membrane Electrolysis	Proton OnSite	An anion exchange membrane is being developed and tested that uses an alkaline membrane enabling the use of lower cost stainless steel plates and less-expensive catalysts.	The new membrane reduces electrolyzer stack costs by using non-noble metal catalysts and stainless steel flow field plates.
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%.
Flexhose: Cryogenically Flexible, Low Permeability Thoraeus Rubber Hydrogen Dispenser Hose	NanoSonic, Inc.	This new hose is cryogenically flexible, has low permeability, and delivers high pressure hydrogen at hydrogen fueling stations.	The hose reduces hydrogen losses to evaporation during fueling and maintains hose integrity even when bent to 180° with no hydrogen embrittlement.
High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis	Giner, Inc.	New catalysts are being developed for water electrolysis that use less costly materials and improve the efficiency and lifetime of proton exchange membranes. These new catalysts are undergoing extended durability testing in harsh conditions to optimize their performance.	The new catalysts will increase electrolyzer system efficiency using nanotechnology by enhancing performance and durability while using less costly materials.
High-Pressure PEM Electrolyzer and Composite Tube Hydrogen Storage	Proton OnSite	A packaged system that includes hydrogen production, storage, and dispensing equipment in an intermodal transport International Organization for Standardization (ISO) container.	The system provides a modular, manufactured hydrogen-fueling infrastructure that is scalable and can be deployed quickly.

Table 3.8 Emerging Innovations/Technologies Summary – Production/Delivery

Innovation	Organization	Description	Benefits
High-Temperature, High Pressure Electrolysis	Giner Electrochemical Systems, LLC	A new non-perfluorinated-ionomer PEM is being developed to increase the efficiency of the electrolysis process while providing hydrogen at a pressure of 350 bar.	The new membrane will operate at high pressures and temperatures to achieve the DOE goal of 77% Lower Heating Value (LHV) by 2020.
Hydrogen by Wire - Home Fueling System (SBIR Project)	Proton OnSite	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 onsite system enables widespread adoption of hydrogen-powered transportation without a well-developed hydrogen supply infrastructure.
Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)	Southwest Research Institute	An advanced compression system, the LMRC, is being developed that utilizes a novel and patented concept of driving a permanent magnet piston inside a hermetically sealed compressor cylinder through electromagnetic windings.	The LMRC has improved compression efficiency and reduced capital and maintenance costs compared to conventional reciprocating compressors.
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.
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.
Hydrogen Station Equipment Performance (HyStEP) Device	Sandia National Laboratories	A new device to test and certify new hydrogen fueling stations is being developed and field tested using a trailer-mounted platform.	The mobile device will validate hydrogen refueling stations more efficiently thus reducing testing costs.
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, onsite hydrogen generators, such those located at fueling stations.
Integrated Hydrogen Energy Station	Air Products and Chemicals, Inc.	A fuel-cell-based power plant that co-produces electricity and hydrogen using a high-temperature fuel cell that internally reforms methane.	The co-production of hydrogen and electricity improves the economics of a standalone hydrogen fueling facility. The system can use methane from renewable sources like digester gas or landfill gas.
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.

Table 3.8 Emerging Innovations/Technologies Summary – Production/Delivery

Innovation	Organization	Description	Benefits
Low-Cost Hydrogen Generation from Renewable Energy	Proton OnSite	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.
Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap	Wiretough Cylinders, LLC	A new low cost, high pressure hydrogen storage system for use in hydrogen refueling is being tested. The vessels consist of a commercial metal gas storage cylinder that is then wrapped with steel wire.	The vessel can be used to store gaseous hydrogen at high pressure for a relatively low cost.
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage (SBIR Project)	Proton OnSite	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 (800–3,000 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.
Nanotube Array Photocatalysts (SBIR Project)	Synkera Technologies, Inc.[1]	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 increase efficiency through broadband light absorption and a vertically graded bandgap. The system is scalable to large size and high volumes and lowers costs compared to traditional technologies.
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.
Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen	FuelCell Energy, Inc.	The REP combines reforming and electrolyzer components into one unit. The REP is being constructed and tested to measure its performance.	The REP is more efficient, reduces operating costs, and reduces emissions associated with typical hydrogen production from natural gas and electrolysis.
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 direct current (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.

[1] Note: Acquired by Integrated Device Technology, Inc. (IDT)

Table 3.8 Emerging Innovations/Technologies Summary – Production/Delivery

Innovation	Organization	Description	Benefits
Reversible Liquid Carriers	Air Products and Chemicals, Inc.	This technology deploys a fully reversible liquid carrier that can be readily hydrogenated, transported to a distribution center, and then catalytically dehydrogenated to provide hydrogen gas to an end use such as fuel cells.	The technology increases catalyst efficiency and allows thermodynamically favorable liquid carriers to be deployed.

Table 3.9 Emerging Innovations/Technologies Summary – Storage

Innovation	Organization	Description	Benefits
Achieving Hydrogen Storage Goals through High-Strength Fiber Glass	PPG Industries, Inc.	A composite overwrapped pressure vessel reinforced exclusively with glass fiber is being developed and demonstrated. New high-strength fibers were developed using a novel manufacturing process.	The new fiber exceeds the strength requirements and can be produced at reduced cost.
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.
Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks	Pacific Northwest National Laboratory	The onboard vehicle tank is formed with polyvinyl ester resins that are less costly and reduce tank mass. The tank is undergoing evaluation and testing.	The tank can be used at cryogenic temperatures to increase hydrogen storage capacity while also reducing costs by using lower cost resins.
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%.
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.
Ultra-Lightweight High Pressure Hydrogen Fuel Tanks Reinforced with Carbon Nanotubes	Applied Nanotech, Inc.	Methods for reducing the amount of carbon fiber used in the construction of carbon-fiber-reinforced polymer (CFRP) tanks used for hydrogen storage. Carbon nanotubes are used to improve the mechanical properties of the tanks.	The hydrogen storage tanks produced using these methods weigh less and cost less than conventional CFRP tanks.
Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage	Oak Ridge National Laboratory	A modular steel/concrete composite vessel for stationary high-pressure gaseous hydrogen storage. The vessels are now undergoing testing.	The new vessels have improved safety and reduced cost by using combined steel/concrete designs.

Table 3.10 Fuel Cell Tasks and Related Emerging Technologies/Innovations

Tasks*	Innovation	Organization
Balance of Plant Components	High Performance Water Vapor Membranes to Improve Fuel Cell Balance of Plant Efficiency and Lower Costs	Tetramer Technologies
	Low-Cost Hydrogen Sensor for Transportation Safety	Makel Engineering, Inc.
	Materials and Modules for Low-Cost, High-Performance Fuel Cell Humidifiers	W.L. Gore and Associates, Inc.
	Nano Structured Metal Bipolar Plates for Low-Cost Fuel Cell Stacks	TreadStone Technologies, Inc.
	Roots Air Management System with Integrated Expander	Eaton Corporation
	Sensors for Automotive Fuel Cell Systems	Nexceris, LLC[1]
Catalysts/Electrodes	Alternative and Durable High-Performance Cathode Supports for PEM Fuel Cells	Pacific Northwest National 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
Fuel Cell MEA Manufacturing R&D	Direct-Write Inkjet Printing for Fabricating Hydrogen Sensors	InnoSense, LLC
	Fuel Cell Membrane Measurement System for Manufacturing	Scribner Associates, Inc.
	Low-Cost Manufacturing of Sheet Molding Compound Bipolar Plates for PEM Fuel Cells	Nanotek Instruments, Inc.
	Ultrasonics and Diagnostics for High-Temperature PEM MEA Manufacture	Rensselaer Polytechnic Institute
Fuel Cell Systems	Direct Methanol Fuel Cell (DMFC) Anode Catalysts	National Renewable Energy Laboratory
	Direct Methanol Fuel Cell for Handheld Electronics Applications	MeOH Power
	Fuel-Cell-Based Mobile Lighting	Sandia National Laboratories
	Ground Support Equipment Demonstration	Plug Power, Inc.
	High-Efficiency Polymer Electrolyte Membrane Fuel Cell Combined Heat and Power System	Intelligent Energy, Inc.
	Maritime Fuel Cell Generator Project	Sandia National Laboratories
	Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.

[1] Note: Formerly NexTech Materials, Ltd.

Table 3.10 Fuel Cell Tasks and Related Emerging Technologies/Innovations

Tasks*	Innovation	Organization
Membranes Electrode Assemblies, Cells, and Other Stack Components	Affordable High Performance, Intermediate Temperature Solid Oxide Fuel Cells	Redox Power Systems
	Engineered Nanostructured MEA Technology for Low-Temperature Fuel Cells	OneD Material LLC
	High Performance, Durable, Low Cost MEAs for Transportation Applications	3M Company
	Platinum and Fluoropolymer Recovery from PEM Fuel Cells	Ion Power, Inc.
	Platinum-Group-Metal Recycling Technology	BASF Catalysts LLC
	Nitrided Metallic Bipolar Plates for PEM Fuel Cells	Oak Ridge National Laboratory
	Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd.
Membranes/Electrolytes	Dimensionally-Stable High-Performance Membrane	Giner Electrochemical Systems, LLC
	High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.
	New Fuel Cell Membranes with Improved Durability and Performance	3M Company

* Note: The fuel cell tasks are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf and manufacturing topics at http://energy.gov/sites/prod/files/2015/06/f22/fcto_myrdd_manufacturing.pdf.

Table 3.11 Production Technology Pathway Items and Delivery Challenges and Related Emerging Technologies/Innovations

Technology Pathway Items or Challenges*	Innovation	Organization
Auxiliary	Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC
	Reversible Liquid Carriers	Air Products and Chemicals, Inc.
Biological	Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	UC Berkeley
Containment	Advanced Barrier Coatings for Harsh Environments	GVD, Corp.
	Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory
	Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap	Wiretough Cylinders, LLC
	Materials Solutions for Hydrogen Delivery in Pipeline	Secat, Inc.
Dispensing	Flexhose: Cryogenically Flexible, Low Permeability Thoraeus Rubber Hydrogen Dispenser Hose	NanoSonic, Inc.
	Hydrogen Station Equipment Performance (HyStEP) Device	Sandia National Laboratories
Electrolysis	Catalysts/Electrodes for Hydrogen Production by Waste Electrolysis	Proton OnSite
	Economical Production of Hydrogen with High-Efficiency Electrocatalysts for Alkaline Membrane Electrolysis	Proton OnSite
	High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis	Giner, Inc.
	High-Pressure PEM Electrolyzer and Composite Tank Hydrogen Storage	Applied Nanotech, Inc.
	High-Temperature, High-Pressure Electrolysis	Giner Electrochemical Systems, LLC
	Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory
Photoelectrochemical (PEC)	Nanotube Array Photocatalysts	Synkera Technologies, Inc.[1]
Pressurization	Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC
	Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.
	Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)	Southwest Research Institute
	Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.
	Hydrogen by Wire – Home Fueling System	Proton OnSite
	Hydrogen Production for Refineries	TDA Research, Inc.
	Integrated Hydrogen Energy Station	Air Products and Chemicals, Inc.
	Integrated Short Contact Time Hydrogen Generator	GE Global Research Center
	Low-Cost Hydrogen Generation from Renewable Energy	Proton OnSite
	Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage	Proton OnSite

[1] Acquired by Integrated Device Technology, Inc.

Table 3.11 Production Technology Pathway Items and Delivery Challenges and Related Emerging Technologies/Innovations

Technology Pathway Items or Challenges*	Innovation	Organization
Pressurization (contd.)	Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen	FuelCell Energy, Inc.
Separation and purification systems	Composite Membrane for High Temperature Hydrogen Separation	Bettergy Corporation
	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

* Note: These production technology pathway items are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf and for delivery challenges at http://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf.

Table 3.12 Storage Challenges and Related Emerging Innovations/Technologies

Challenges*	Innovation	Organization
Materials Storage	Electrochemical Reversible Formation of Alane	Savannah River National Laboratory
	Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers, LLC
Physical Storage	Achieving Hydrogen Storage Goals Through High-Strength Glass	PPG Industries, Inc.
	Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks	Pacific Northwest National Laboratory
	Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory
	Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Oak Ridge National Laboratory
	Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites, Inc.
	Ultra-Lightweight High Pressure Fuel Tanks Reinforced with Carbon Nanotubes	Applied Nanotech, Inc.
	Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage	Oak Ridge National Laboratory

* Note: The storage challenges are described in the FCTO Multi-Year Research, Development, and Demonstration Plan at http://energy.gov/sites/prod/files/2015/05/f22/fcto_myrdd_storage.pdf

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Appendix A: Technology Innovations Tracking List

A.1 Fuel Cell Technology Innovations

Fuel Cell Technology Innovations

Technology Title	Company
Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells	Redox Power Systems
Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells	Pacific Northwest National Laboratory
Bio-Fueled Solid Oxide Fuel Cells	TDA Research
Cathode Catalysts and Supports for PEM Fuel Cells	3M Company
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	National Renewable Energy Laboratory
Direct Methanol Fuel Cell for Handheld Electronics Applications	MeOH Power
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	OneD Material, LLC
Extended Continuous Pt Nanostructures in Thick, Dispersed Electrodes	National Renewable Energy Laboratory
FARADAYIC ElectroEtching of Stainless Steel Bipolar Plates	Faraday Technology, Inc.
Fuel Cell Membrane Measurement System for Manufacturing	Scribner Associates, Inc.
Fuel Cell Turbocompressor	Honeywell International, Inc.
Fuel-Cell-Based Mobile Lighting	Sandia National Laboratory
GCtool: Fuel Cell Systems Analysis Software Model	Argonne National Laboratory
GenDrive™ Fuel Cell Power System	Plug Power, Inc.
Ground Support Equipment Demonstration	Plug Power, Inc.
High-Efficiency PEM Fuel Cell Combined Heat and Power System	Intelligent Energy, Inc.
High Performance, Durable, Low Cost MEAs for Transportation Applications	3M Company.
High-Performance, Low-Pt Cathodes Containing New Catalysts and Layer Structure	Cabot Superior MicroPowders
High Performance Water Vapor Membranes for Improved Fuel Cell Balance of Plant	Tetramer Technologies
High-Temperature Membrane with Humidification-Independent Cluster Structure	FuelCell Energy, Inc.

Fuel Cell Technology Innovations

Technology Title	Company
Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods	NuVant Systems, Inc.
Low-Cost 3-10 kW Tubular SOFC Power System	Atrex Energy, Inc.
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	Brookhaven National Laboratory
Manufacture of Durable Seals for PEM Fuel Cells	Freudenberg-NOK General Partnership
Maritime Fuel Cell Generator Project	Sandia National Laboratory
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
Nano Structured Metal Bipolar Plates for Low-Cost Fuel Cell Stacks	TreadStone Technologies, Inc.
New Fuel Cell Membranes with Improved Durability and Performance	3M Company
Nitrided Metallic Bipolar Plates for PEM Fuel Cells	Oak Ridge National Laboratory
Novel Manufacturing Process for PEM Fuel Cell Stacks	Protonex Technology Corporation
Nuvera® Fuel Cell System	Nuvera Fuel Cells, Inc.
Orion™: Fuel Cell Technology for Hybrid Power Applications	Nuvera Fuel Cells, Inc.
Platinum and Fluoropolymer Recovery from PEM Fuel Cells	Ion Power, Inc.
Platinum-Group-Metal Recycling Technology	BASF Catalysts, LLC
Platinum Monolayer Electrocatalysts on Stable Low-Cost Supports	Brookhaven National Laboratory
Portable Reformed Methanol Fuel Cells	UltraCell Corporation
Reduction in Fabrication Costs of Gas Diffusion Layers	AvCarb, LLC
Resin-Impregnated, Expanded-Graphite GRAFCELL® Bipolar Plates	GrafTech International Ltd
Roots Air Management System with Integrated Expander	Eaton Corporation
Sensors for Automotive Fuel Cell Systems	Nexceris, LLC
Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications	SAFCell, Inc.
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.

A.2 Production/Delivery Technology Innovations

Production/Delivery Technology Innovations

Technology Title	Company
Active Magnetic Regenerative Liquefier	Emerald Energy NW, LLC
Advanced Barrier Coatings for Harsh Environments	GVD Corp.
California Hydrogen Refueling Stations	Air Products and Chemicals, Inc.
Catalysts/Electrodes for Hydrogen Production by Water Electrolysis	Proton OnSite
Centrifugal Hydrogen Pipeline Gas Compressor	Concepts NREC
Composite Membrane for High Temperature Hydrogen Separation	Bettergy Corporation
Composite Pipeline Technology for Hydrogen Delivery	Oak Ridge National Laboratory
DetecTape™: Early Warning Visual Hydrogen Leak Detector	Element One, Inc.
Economical Production of Hydrogen through Development of Novel, High-Efficiency Electrocatalysts for Alkaline Membrane Electrolysis	Proton OnSite
Efficient Solid-State Electrochemical Hydrogen Compressor	FuelCell Energy, Inc.
Flexhose: Cryogenically Flexible, Low Permeability Thoraeus Rubber Hydrogen Dispenser Hose	NanoSonic, Inc.
H2 ProGen: A Total Supply Solution for Hydrogen Vehicles	Atlas Copco
High-Performance Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis	Giner, Inc.
High-Pressure PEM Electrolyzer and Composite Tube Hydrogen Storage	Proton OnSite
High Temperature, High Pressure Electrolysis	Giner Electrochemical Systems, LLC
HRS-100™ Hydrogen Recycling System	Sustainable Innovations, LLC
Hydrogen By Wire - Home Fueling System	Proton OnSite
Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)	Southwest Research Institute
Hydrogen Gas Sensing System	Intelligent Optical Systems, Inc.
Hydrogen Generation from PEM Electrolysis	Proton OnSite
Hydrogen Production for Refineries	TDA Research, Inc.
Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor	Media and Process Technology, Inc.
Hydrogen Safety Sensor for Energy Applications	Nexceris, LLC
Hydrogen Station Equipment Performance (HyStEP) Device	Sandia National Laboratory
Integrated Ceramic Membrane System for Hydrogen Production	Praxair, Inc.
Integrated Hydrogen Energy Station	Air Products and Chemicals, Inc.
Integrated Short Contact Time Hydrogen Generator	GE Global Research Center

Production/Delivery Technology Innovations

Technology Title	Company
Intellipigment™: Visible Hydrogen Gas Leak Detection Material	HySense Technology, LLC
Leak Detection and Hydrogen Sensor Development	Los Alamos National Laboratory
Low-Cost Hydrogen Generation from Renewable Energy	Proton OnSite
Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap	Wiretough Cylinders, LLC
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage	Proton OnSite
Materials Solutions for Hydrogen Delivery in Pipelines	Secat, Inc.
Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures	University of California - Berkeley
ME100 Methanol Reforming Hydrogen Generator	REB Research & Consulting
MEMS Hydrogen Sensor for Leak Detection	Oak Ridge National Laboratory
Nanoscale Water Gas Shift Catalysts	Nexceris, LLC
Nanotube Array Photocatalysts	Synkera Technologies, Inc.
Novel Catalytic Fuel Reforming	InnovaTek, Inc.
Oil Free Hydrogen Compressor	Mohawk Innovative Technology, Inc.
PEM Electrolyzer Incorporating a Low-Cost Membrane	Giner Electrochemical Systems, LLC
Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen	FuelCell Energy, Inc.
Renewable Electrolysis Integrated System Development and Testing	National Renewable Energy Laboratory
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	Hexagon Lincoln
Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi	Giner, Inc.

Technologies highlighted in red are commercial and blue are emerging.

A.3 Storage Technology Innovations

Storage Technology Innovations

Technology Title	Company
Achieving Hydrogen Storage Goals through High-Strength Fiber Glass	PPG Industries, Inc.
Electrochemical Reversible Formation of Alane	Savannah River National Laboratory
Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks	Pacific Northwest National Laboratory
Hydrogen Composite Tanks	Quantum Fuel Systems, LLC
Hydrogen Storage in Cryo-Compressed Vessels	Lawrence Livermore National Laboratory
Low-Cost, Efficient Metal Hydride Hydrogen Storage System for Forklift Applications	Hawaii Hydrogen Carriers, LLC
Low-Cost, High Strength Commercial Textile Precursor (PAN-MA)	Oak Ridge National Laboratory
Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders	Profile Composites, Inc.
Ultra-Lightweight High Pressure Hydrogen Fuel Tanks Reinforced with Carbon Nanotubes	Applied Nanotech, Inc.
Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage	Oak Ridge National Laboratory

Technologies highlighted in red are commercial and blue are emerging.

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Appendix B: Patent Status List

B.1 Fuel Cell Patents Status

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,379,393	06/28/16	Nanotek Instruments, Inc.	Carbon cladded composite flow field plate, bipolar plate and fuel cell	A carbon-cladded composite composition for use as a fuel cell flow field plate or bipolar plate. The composition comprises a core composite layer sandwiched between two clad layers, a conductive carbon or graphite material (e.g., carbon nano-tubes, nano-scaled graphene plates, graphitic nano-fibers, and fine graphite particles) and the core composite layer comprising of a matrix resin and a conductive filler.	Research complete; seeking to license.
9,343,758	05/17/16	Protonex Technology Corporation	Solid oxide fuel cell systems with hot zones having improved reactant distribution	A Solid Oxide Fuel Cell (SOFC) system having a hot zone with a center cathode air feed tube for improved reactant distribution, a CPOX 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.	Still being used in ongoing research.
9,276,273	03/01/16	3M Company	Fuel cell water management via reduced anode reactant pressure	A method is provided for operation of a fuel cell with improved water management by maintaining reduced anode pressure relative to cathode pressure, relative to atmospheric pressure, or both. Typically, the fuel cell comprises a membrane electrode assembly comprising nanostructured thin film cathode catalyst.	Research complete; seeking to license.
9,246,177	01/26/16	Argonne National Laboratory	Bimetallic alloy electrocatalysts with multilayered platinum-skin surfaces	Compositions and methods of preparing a bimetallic alloy having enhanced electrocatalytic properties are provided. The composition comprises a PtNi substrate having a surface layer, a near-surface layer, and an inner layer, where the surface layer comprises a nickel-depleted composition, such that the surface layer comprises a platinum skin having at least one atomic layer of platinum.	Still being used in ongoing research.
9,234,843	01/12/16	National Renewable Energy Laboratory	On-line, continuous monitoring in solar cell and fuel cell manufacturing using spectral reflectance imaging	A monitoring system comprising a material transport system providing for the transportation of a substantially planar material through a monitoring zone. A data processing system is also provided. The processing system is configured to receive data from the line camera and provides information relating to a quality parameter of the material.	Research complete; seeking to license.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,228,954	01/05/16	University of Central Florida	Method of detecting defects in ion exchange membranes of electrochemical cells by chemochromic sensors	A method of detecting defects in membranes such as ion exchange membranes of electrochemical cells. A chemochromic sensor is placed above the cathode and flow isolation hardware lateral to the ion exchange membrane being tested. The anode side is exposed to a first reactant fluid including hydrogen. The chemochromic sensor is examined for a color change after the exposure. A color change indicates the ion exchange membrane has at least one defect that permits hydrogen transmission.	Licensed to HySense Technology LLC. Part of a commercial hydrogen production technology.
9,227,224	01/05/16	Stanford University	Method of forming macro-structured high surface area transparent conductive oxide electrodes	A method of forming a high surface area transparent conducting electrode including deposition of a transparent conducting thin film on a conductive substrate forming a transparent conducting electrode.	Research complete; seeking to license.
9,203,100	12/01/15	Intelligent Energy, Inc.	Fuel cell system	A fuel cell system comprising a fuel cell stack and an electrical control unit configured to adjust operating parameters for optimized operation using voltage deviations from the cells in the fuel cell stack.	Still being used in ongoing research.
9,186,653	11/17/15	Northeastern University	Highly stable platinum alloy catalyst for methanol electrooxidation	A catalyst for use in the anode of direct methanol fuel cells. The material core is an alloy of platinum and gold and surrounded by coatings of ruthenium and a ternary alloy of platinum, gold, and ruthenium. The catalyst can be made by a reverse-micelle method or by a single-phase scalable method. The catalyst is highly stable under conditions of use and resists dissolution of ruthenium or platinum.	Still being used in ongoing research.
9,178,244	11/03/15	Intelligent Energy, Inc.	Fuel cells and fuel cell components having asymmetric architecture and methods thereof	A composite for a fuel cell layer with alternating layers of electron conducting components and ion conducting components. At least one of the ion conducting components or the electron conducting components is geometrically asymmetric in one or more dimensions.	Still being used in ongoing research.
9,169,140	10/27/15	Los Alamos National Laboratory	Non-precious metal catalysts prepared from precursor comprising cyanamide	A catalyst comprising of graphitic carbon and methods for fabrication. A catalyst for oxygen reduction reaction for an alkaline fuel cell is prepared by heating a mixture of cyanamide, carbon black, iron sulfate salt and an iron acetate salt at 700 to 1100 degrees under an inert atmosphere.	Still being used in ongoing research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,160,021	10/13/15	3M Company	Proton conducting materials	Materials are provided that may be useful as ionomers or polymer ionomers, including compounds including bis sulfonyl imide groups which may be highly fluorinated and may be polymers.	Still being used in ongoing research.
9,126,830	09/08/15	Bettergy Corporation	Metal doped zeolite membrane for gas separation	Inorganic membranes and methods for separating gases, vapors, and liquids using the same. The composite zeolite membrane is prepared by TS-1 zeolite membrane synthesis, and subsequent palladium doping.	Still being used in ongoing research. Part of an emerging technology.
9,093,685	07/28/15	Los Alamos National Laboratory	Methods of making membrane electrode assemblies	Membrane electrode assembly comprising of ink printed ionomer and catalyst layers to form a membrane assembly.	Still being used in ongoing research.
9,080,242	07/14/15	General Electric Company	Pressurized electrolysis stack with thermal expansion capability	Systems and methods for mounting an electrolyzer stack in an outer shell to allow for differential thermal expansion. This accommodates thermal expansion which can lead to damage to the electrolyzer stack.	Still being used in ongoing research.
9,065,142	06/23/15	Argonne National Laboratory	Fuel cell electrodes	A process for patterning the surface of a platinum group metal-based electrode by contacting the electrode with an adsorbate to form a patterned platinum group metal-based electrode with both absorbate blocked and unblocked platinum group metal sites.	Still being used in ongoing research.
9,051,431	06/09/15	Los Alamos National Laboratory	Poly(arylene)-based anion exchange polymer electrolytes	Poly(arylene) electrolytes including copolymers lacking ether groups in the polymer may be used as membranes and binders for electrocatalysts in preparation of anodes for electrochemical cells such as solid alkaline fuel cells.	Still being used in ongoing research.
9,048,480	06/02/15	Los Alamos National Laboratory	Anion exchange polymer electrolytes	Anion exchange polymer electrolytes that include guanidinium functionalized polymers may be used as membranes and binders for electrocatalysts in preparation of anodes for electrochemical cells such as solid alkaline fuel cells.	Still being used in ongoing research.
9,045,839	06/02/15	General Electric Company	Methods and systems for in-situ electroplating of electrodes	Electrochemical device having enhanced electrodes with surfaces that facilitate operation, such as formation of a porous nickel layer on an operative surface, e.g. a cathode. The device's enhanced electrode and its operation can be used in various electrochemical devices, in particular, electrodes in an electrolyzer useful for splitting water into hydrogen and oxygen.	Still being used in ongoing research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,034,165	05/19/15	Brookhaven National Laboratory	Underpotential deposition-mediated layer-by-layer growth of thin films	A method of depositing contiguous, conformal submonolayer-to-multilayer thin films with atomic- level control. This process is especially suitable for the formation of a catalytically active layer on core-shell particles for use in energy conversion devices such as fuel cells.	Research complete; seeking to license.
9,023,553	05/05/15	Chemsultants International	Multilayered composite proton exchange membrane and a process for manufacturing the same	A multilayered membrane for use with fuel cells and related applications. The multilayered membrane includes a carrier film, with alternating layers of undoped conductive polymer electrolyte material and conductive polymer electrolyte material. Each layer of conductive polymer electrolyte material is doped with nanoparticles.	No longer being used in research/ no longer being pursued.
9,023,550	05/05/15	Savannah River National Laboratory	Nanocrystalline cerium oxide materials for solid fuel cell systems	A process in which a hydrogen storage metal amide is modified by a ball milling process using an additive of TPP. The resulting product provides for a hydrogen storage metal amide having a coating that renders the hydrogen storage metal amide resistant to air, ambient moisture, and liquid water while improving useful hydrogen storage and release kinetics.	Still being used in ongoing research; seeking to license.
9,017,900	04/28/15	Lawrence Livermore National Laboratory	Fuel cell components and systems having carbon-containing electrically-conductive hollow fibers	Process for forming fuel cell structure using an ionically-conductive, electrically-resistive electrolyte/ separator layer which covers the inner or outer surface of a carbon-containing electrically-conductive hollow fiber. The fiber contains provision for a catalyst, anode and cathode that extend along at least part of the length of the structure, the cathode being on an opposite side of the hollow fiber as the anode.	Research complete; seeking to license.
9,017,530	04/28/15	Brookhaven National Laboratory	Method and electrochemical cell for synthesis and treatment of metal monolayer electrocatalysts metal, carbon, and oxide nanoparticles ion batch, or in continuous fashion	An apparatus and method for synthesis and treatment of electrocatalyst particles using batch or continuous processing.	Licensed to name withheld (Confidential).

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,012,344	04/21/15	Argonne National Laboratory	Electrocatalysts using porous polymers and method of preparation	A method of producing an electrocatalyst article using porous polymers that are designed to receive transition metal groups disposed at ligation sites and activate transition metals to form an electrocatalyst which can be used in a fuel cell.	Still being used in ongoing research.
9,005,331	04/14/15	Brookhaven National Laboratory	Platinum-coated non-noble metal-noble metal core-shell electrocatalysts	A process to encapsulate core-shell particles with a thin film of a catalytically active metal is described. The particles are preferably nanoparticles comprising a non-noble core with a noble metal shell which preferably do not include Pt. The overall process is a robust and cost-efficient method for forming Pt-coated non-noble metal-noble metal core-shell nanoparticles that can be used as an electrocatalyst.	Licensee name withheld (Confidential).
8,968,432	03/03/15	Pacific Northwest National Laboratory	Rapid start fuel reforming systems and techniques	An on-board fuel processor includes a microchannel steam reforming reactor, a water vaporizer in a cross-flow panel configuration is heated in series with a combustion gas. Fuel is directly injected into the steam, and during a rapid cold start which can be achieved in under 30 seconds with a manageable amount of electric power consumption.	Research complete; seeking to license.
8,962,132	02/24/15	Giner Electrochemical	Solid polymer electrolyte composite membrane comprising a porous support and a solid polymer electrolyte including a dispersed reduced noble metal or noble metal oxide	Solid polymer electrolyte composite membrane and its manufacture. The composite membrane consists of a thin, rigid, dimensionally-stable, non-electrically-conducting support with cylindrical, straight-through pores between top and bottom surfaces of the support. The pores are filled with a solid polymer electrolyte including dispersed reduced noble metal or noble metal oxide.	Research complete; seeking to license.
8,944,437	02/03/15	Air Products & Chemicals, Inc.	Seal between metal and ceramic conduits	A seal between a ceramic conduit and a metal conduit of an ion transport membrane device consisting of a sealing surface of ceramic conduit, a single gasket body, and a single compliant interlayer.	Still being used in ongoing research.
8,939,293	01/27/15	Synkera Technologies, Inc.	Composite membrane with integral rim	Composite membranes that can be adapted for separation, purification, filtration, analysis, reaction and sensing. The membranes can include a porous support structure having elongate pore channels extending through the support structure.	Still being used in ongoing research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,927,453	01/06/15	Brookhaven National Laboratory	Molybdenum and tungsten nanostructures and methods for making and using same	Process to form molybdenum and tungsten nanostructures, for example, nanosheets and nanoparticles. These formed nanostructures could be used as catalysts for hydrogen evolution reactions.	Still being used in ongoing research.
8,906,575	12/09/14	Los Alamos National Laboratory	Minimizing electrode contamination in an electrochemical cell	An electrochemical cell assembly that is expected to prevent or at least minimize electrode contamination includes one or more getters that trap a component or components leached from a first electrode and prevents or at least minimizes them from contaminating a second electrode.	Still being used in ongoing research.
8,906,270	12/09/14	Colorado School of Mines	Acidic ion exchange membrane and method for making and using the same	The invention relates generally to a polymeric composition and a method for making and using the polymeric composition, more specifically to a polymeric composition and a method for making and using the polymeric composition in the form of a membrane.	Research complete; seeking to license.
8,895,206	11/25/14	Johns Hopkins University	Porous platinum-based catalysts for oxygen reduction	A porous metal catalyst containing platinum with a specific surface area in the range 5 - 75 m2/g is used coat the electrodes of a fuel cell for oxygen reduction. The porous metal is produced by forming an alloy consisting of platinum and nickel and dealloying the alloy in a substantially pH neutral solution to reduce an amount of nickel in the alloy to produce the porous metal.	Research complete; seeking to license.
8,895,204	11/25/14	Intelligent Energy, Inc.	Water reactive hydrogen fuel cell power system	A water reactive hydrogen fueled power system including devices and methods to combine reactant fuel materials and aqueous solutions to generate hydrogen. The generated hydrogen is converted in a fuel cell to provide electricity. The water reactive hydrogen fueled power system includes a fuel cell, a water feed tray, and a fuel cartridge to generate power for portable power electronics.	Still being used in ongoing research.
8,889,316	11/18/14	Arkema	Organic/inorganic composite blend membrane compositions of polyelectrolye blends with nanoparticles	Composite blend membranes formed from blends of one or more polyelectrolytes, and one or more types of nanoparticles. Preferably the blend also includes one or more fluoropolymers. The addition of the nanoparticles was found to enhance the conductivity and mechanical properties of the membranes.	Still being used in ongoing research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,865,040	10/21/14	Nanotek Instruments, Inc.	Highly conductive composites for fuel cell flow field plates and bipolar plates	A fuel cell flow field plate or bipolar plate with flow channels on the faces of the plate which is made from an electrically conductive polymer composite. The composite is composed of mainly polymer binder material with conductive filler, weight reinforcement fibers, expanded graphite platelets, graphitic nano-fibers, and/or carbon nano-tubes.	Research complete; seeking to license.
8,835,343	09/16/14	Argonne National Laboratory	Non-platinum group metal electrocatalysts using metal organic framework materials and method of preparation	A method of preparing a nitrogen containing electrode catalyst using a high surface area metal-organic framework (MOF) material free of platinum group metals to form catalytic active sites within the MOF using a high temperature thermal treatment. The electrode catalysts created in this manner may be used in various electrochemical systems, including a proton exchange membrane fuel cell.	Still being used in ongoing research.
8,814,964	08/26/14	Argonne National Laboratory	Method for improving catalyst function in auto-thermal and partial oxidation reformer-based processors	Method for reforming fuel, using an oxidation catalyst to partially oxidize the fuel and generate heat to warm incoming fuel and the reforming catalyst while simultaneously reacting partially oxidized fuel with steam from the reforming catalyst.	No longer being used in research/no longer being pursued.
8,771,899	07/08/14	Lawrence Livermore National Laboratory	Fuel cell components and systems having carbon-containing electrically-conductive hollow fibers	Process for forming fuel cell structure using an ionically-conductive, electrically-resistive electrolyte/ separator layer which covers the inner or outer surface of a carbon-containing electrically-conductive hollow fiber. The fiber contains provision for a catalyst, anode and cathode that extend along at least part of the length of the structure, the cathode being on an opposite side of the hollow fiber as the anode.	Research complete; seeking to license.
8,765,327	07/01/14	3M Company	Fuel cell electrodes with conduction networks	A fuel cell electrode layer may include a catalyst, an electronic conductor, and an ionic conductor. Within the electrode layer are interspersed electronic and ionic conductor rich networks.	Still being used in ongoing research.
8,741,454	06/03/14	Case Western Reserve University	Proton exchange membrane for fuel cell	A proton exchange membrane (PEM) with an ion exchange capacity consisting of a polymer based on polyphosphazene polyaromatic chemistry. This increases thermal, and chemical stability with excellent ionic conductivity and low water swelling.	Still being used in ongoing research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,734,632	05/27/14	H2Pump	Hydrogen furnace system and method	Apparatus and operating methods for controlled atmosphere furnace systems. Hydrogen is injected and circulated within the enclosure from a gas inlet to a gas outlet. The temperature is raised to a predetermined threshold while the gas is pumped using an electrochemical hydrogen pump.	Still being used in ongoing research. Part of commercialized technology.
8,709,295	04/29/14	Los Alamos National Laboratory	Nitrogen-doped carbon-supported cobalt-iron oxygen reduction catalyst	A method for making a non-precious-metal catalyst for carrying out the oxygen reduction reaction in polymer electrolyte membrane fuel cells.	Still being used in ongoing research.
8,703,355	04/22/14	Florida State University	Catalytic electrode with gradient porosity and catalyst density for fuel cells	A membrane electrode assembly for a fuel cell comprising a gradient catalyst structure and a method of making the same.	Research complete; seeking to license.
8,699,207	04/15/14	Brookhaven National Laboratory	Electrodes synthesized from carbon nanostructures coated with a smooth and conformal metal adlayer	High-surface-area carbon nanostructures coated with a smooth and conformal submonolayer-to-multilayer thin metal films and their method of manufacture.	Part of an emerging fuel cell technology. Seeking to license.
8,691,177	04/08/14	University of Missouri	High surface area carbon and process for its production	The present invention provides a high surface area porous carbon material and a process for making this material. In particular, the carbon material is derived from biomass and has large mesopore and micropore surfaces that promote improved adsorption of materials and gas storage capabilities.	Still being used in ongoing research.
8,663,448	03/04/14	H2Pump	Hydrogen furnace system and method	Apparatus and operating methods for controlled atmosphere furnace systems. Hydrogen is injected and circulated within the enclosure from a gas inlet to a gas outlet. The temperature is raised to a predetermined threshold while the gas is pumped from the gas outlet to the gas inlet using an electrochemical hydrogen pump.	Still being used in ongoing research. Part of commercialized technology.
8,658,329	02/25/14	Los Alamos National Laboratory	Advanced membrane electrode assemblies for fuel cells	A method for constructing membrane electrode assemblies for use in fuel cell applications.	Still being used in ongoing research.
8,652,709	02/18/14	Argonne National Laboratory	Method of sealing a bipolar plate supported solid oxide fuel cell with a sealed anode compartment	Methods for sealing a bipolar plate supported solid oxide fuel cell with a sealed anode compartment. A single-step high temperature sintering process is used to form gastight containment seals.	Research complete; seeking to license.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,647,497	02/11/14	University of Central Florida	Method and system for hydrogen sulfide removal	A system for hydrogen sulfide removal from a sour gas mixture including hydrogen sulfide. The sour gas mixture is reacted with a transition metal compound in a scrubber. Sulfide from the hydrogen sulfide is oxidized to form elemental sulfur and the transition metal is reduced to form a reduced state transition metal compound.	Research complete; seeking to license.
8,642,308	02/04/14	University of New Mexico	Biofuel cell electrocatalysts utilizing enzyme-carbon nanotube adducts	Electrodes for fuel cells that contain enzymes (biological catalysts) bound to the walls of carbon nanotubes.	Still being used in ongoing research.
8,637,205	01/28/14	3M Company	Fuel cell subassemblies incorporating subgasketed thrifted membranes	A fuel cell roll subassembly is described that includes individual electrolyte membranes. Gaskets are attached to the individual electrolyte membranes to form a "grid" of the individual electrolyte membranes exposed through the apertures formed by the gaskets. Part of the gasket web that forms the "grid" may have little or no adhesive on the subgasket surface facing the electrolyte membrane.	Still being used in ongoing research.
8,637,193	01/28/14	3M Company	Fuel cell nanocatalyst with voltage reversal tolerance	Fuel cell catalyst having a catalyst surface bearing a non-occluding layer of iridium or a surface bearing a sub-monolayer of iridium with a planar equivalent thickness of between 1 and 100 Angstroms. The catalyst has a nanostructure with microstructured support whiskers bearing a thin film of nanoscopic catalyst particles. The catalyst typically has no electrically conductive carbon material and at least a portion of the iridium in the zero oxidation state.	Still being used in ongoing research.
8,632,928	01/21/14	Signa Chemistry, Inc.	Water reactive hydrogen fuel cell power system	A water reactive hydrogen fueled power system including devices and methods to combine reactant fuel materials and aqueous solutions to generate hydrogen. The generated hydrogen is converted in a fuel cell to provide electricity. The water reactive hydrogen fueled power system includes a fuel cell, a water feed tray, and a fuel cartridge to generate power for portable power electronics.	Licensed to name withheld (Confidential) Part of a former commercial hydrogen production technology.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,628,891	01/14/14	Acumentrics Corporation	Interconnection of bundled solid oxide fuel cells	A system and method for electrically interconnecting a plurality of fuel cells to provide dense packing of the fuel cells. Each fuel cell has discrete electrical connection points along the outer surface. Adjacent fuel cells electrical connections are interconnected to allow higher packing density. In tubular solid oxide fuel cells the discrete electrical connection points are spaced along the length of the fuel cell.	Still being used in ongoing research. Part of a commercial fuel cell technology.
8,628,871	01/14/14	3M Company	High durability fuel cell components with cerium salt additives	Fuel cell membrane electrode assembly is comprising of a polymer electrolyte membrane with bound anionic functional groups and cerium cations.	Still being used in ongoing research; Part of an emerging fuel cell technology.
8,624,105	01/07/14	Synkera Technologies, Inc.	Energy conversion device with support member having pore channels	Devices for energy conversion and storage and their manufacture. The devices comprise of a support with an array of pore channels. Material layers for energy conversion materials and conduction are coaxially disposed in the pore channels to form rods. The material structure can be varied in the pore channels to fabricate various energy devices, e.g. photovoltaic (PV) devices, radiation detectors, capacitors and batteries.	Still being used in ongoing research.
8,617,765	12/31/13	E.I. du Pont de Nemours and Company	Chemically stabilized ionomers containing inorganic fillers	Ionomeric polymers that are chemically stabilized and contain inorganic fillers are prepared, and show reduced degradation. The ionomers care useful in membranes and electrochemical cells.	Research complete - company holding IP.
8,614,023	12/24/13	Protonex Technology Corporation	Solid oxide fuel cell systems with hot zones having improved reactant distribution	A Solid Oxide Fuel Cell (SOFC) system having a hot zone with a center cathode air feed tube for improved reactant distribution, a CPOX 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.	Still being used in ongoing research.
8,586,252	11/19/13	Acumentrics Corporation	Integral reactor system and method for fuel cells	A reactor system is integrated internally within an anode-side cavity of a fuel cell. The reactor system is configured to convert higher hydrocarbons to smaller species while mitigating the lower production of solid carbon. The reactor system may incorporate one or more of a pre-reforming section, an anode exhaust gas recirculation device, and a reforming section.	Still being used in ongoing research. Part of a commercial fuel cell technology.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,585,807	11/19/13	Argonne National Laboratory	Low-cost method for fabricating palladium and palladium-alloy thin films on porous supports	A process for forming a palladium or palladium alloy membrane on a ceramic surface using a pre-colloid mixture of palladium powder, carrier fluid, dispersant, pore former and binder.	Research complete; seeking to license.
8,557,480	10/15/13	Lawrence Livermore National Laboratory	High power density fuel cell comprising an array of microchannels	Fuel cell with a porous electrolyte support structure formed by an array of microchannels. The array could be formed using a combination of molding, stamping, extrusion, injection and electrodeposition processes.	Research complete; seeking to license.
8,545,657	10/01/13	Lawrence Livermore National Laboratory	Methods for tape fabrication of continuous filament composite parts and articles of manufacture thereof	Process for forming a composite structure using bonding material in the form of a tape. The tape comprises of fiber and a matrix, wherein the bonding material has a short curing time (< 1 sec). The tape can be wrapped around a substrate to manufacture larger parts.	Research complete; seeking to license.
8,530,109	09/10/13	Los Alamos National Laboratory	Anion exchange polymer electrolytes	Solid anion exchange polymer electrolytes that include chemical compounds consisting of a polymer backbone with side chains that include guanidinium cations.	Still being used in ongoing research.
8,518,608	08/27/13	Los Alamos National Laboratory	Preparation of supported electrocatalyst comprising multiwalled carbon nanotubes	A process for preparing a durable non-precious-metal oxygen reduction electrocatalyst that involves heat treatment of a ball-milled mixture of polyaniline and multiwalled carbon nanotubes in the presence of an iron species.	Still being used in ongoing research.
8,518,603	08/27/13	Nanotek Instruments, Inc.	Sheet molding compound flow field plate, bipolar plate and fuel cell	A highly electrically conductive sheet molding compound (SMC) composition to fabricate a fuel cell flow field plate or bipolar plate. The structure consists of top and bottom sheets with a resin mixture sandwiched between. At least one of the top or bottom sheets are made from flexible graphite sheet with a planar outer surface and formed fluid flow channels. The resin composition is a thermoset resin with conductive filler to provide sufficient flow field plate electrical conductivity. The assembled graphite sheets form a bipolar plate for use in proton exchange membrane fuel cell applications.	Research complete; seeking to license.
8,518,596	08/27/13	General Motors Corporation	Low cost fuel cell diffusion layer configured for optimized anode water management	A gas diffusion layer that enables passive fuel cell water balance by retaining some product water under dry operating conditions and removing excess product water during wet operating conditions.	Still being used in ongoing research.
8,501,307	08/06/13	Nanotek Instruments, Inc.	Recompressed exfoliated graphite articles	An electrically conductive, recompressed exfoliated graphite article that can be made in a thin foil or sheet form for use as bipolar plates in fuel cells.	Part of an emerging fuel cell technology.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,492,049	07/23/13	Los Alamos National Laboratory	Anion exchange polymer electrolytes	Anion exchange polymer electrolytes consisting of a guanidine base and a cation-stabilizing spacer moiety between the base and the polymer.	Still being used in ongoing research.
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.	Part of a commercial fuel cell technology.
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.	Seeking to license. Part of an emerging fuel cell technology.
8,455,152	06/04/13	Bing Energy International	Integrated PEM fuel cell	A process for integrating a membrane electrode assembly with a bipolar plate in a fuel cell.	No longer being pursued.
8,439,534	05/14/13	Sandia National Laboratory	Mobile lighting apparatus	A mobile lighting apparatus that includes a portable frame such as a moveable trailer or skid having a light tower thereon. A hydrogen-powered fuel cell is located on the portable frame to provide electrical power to an array of energy-efficient lights on the light tower.	Still being used in ongoing research. Part of an emerging fuel cell technology.
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.
8,415,012	04/09/13	Florida State University	Carbon nanotube and nanofiber film-based membrane electrode assemblies	A membrane electrode assembly for a fuel cell comprising a catalyst layer and a method of making the same. The catalyst layer can include a plurality of catalyst nanoparticles, such as platinum, positioned on the surface of a porous buckypaper film.	Research complete; seeking to license.
8,404,613	03/26/13	Brookhaven National Laboratory	Platinum-based electrocatalysts synthesized by depositing contiguous adlayers on carbon nanostructures	High-surface-area carbon nanostructures coated with a smooth and conformal submonolayer-to-multilayer thin metal films and their method of manufacture.	Part of an emerging fuel cell technology. Seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
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; seeking to license.
8,394,298	03/12/13	Los Alamos National Laboratory	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.
8,334,014	12/18/12	University of New Mexico	Microparticles with hierarchical porosity	Oxide microparticles with engineered hierarchical porosity that can be used as electrocatalyst support structures in fuel cells.	Still being used in ongoing research.
8,333,941	12/18/12	University of New Mexico	Spray pyrolysis synthesis of mesoporous NbRuyOz as electrocatalyst supports in fuel cells	Mesoporous conductive niobium and niobium-ruthenium particles that can be used in fuel cell catalysts.	Still being used in ongoing research.
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.
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.
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.
8,308,989	11/13/12	Brookhaven National Laboratory	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.	Part of an emerging fuel cell technology. Seeking to license.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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.
8,273,495	09/25/12	General Electric Company	Electrochemical cell structure and method of making the same	An electrochemical cell structure that includes an anode, a cathode spaced apart from the anode, an electrolyte in ionic communication with the anode and the cathode, and a nonconductive frame.	Still being used in ongoing research.
8,252,711	08/28/12	University of New Mexico	Self supporting structurally engineered non-platinum electrocatalyst for oxygen reduction in fuel cells	A method for producing a highly dispersed, unsupported, non-platinum electrocatalyst for use in fuel cells.	Still being used in ongoing research.
8,236,207	08/07/12	Los Alamos National Laboratory	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.
8,232,017	07/31/12	Delphi	Fuel cell stack including non-fuel cell cassette	A fuel cell stack with a non-fuel cell cassette having temperature sensing elements. The temperature sensing elements are in one or more void spaces in the non-fuel cell cassette and connected to openings in the side of the non-fuel cell cassette for lead wires to communicate information to components outside of the fuel cell stack.	Still being used in ongoing research.
8,227,147	07/24/12	Los Alamos National Laboratory	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.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
8,227,135	07/24/12	Case Western Reserve University	Electrolytes to enhance oxygen reduction reaction (ORR) in the cathode layer of PEM fuel cell	Polymer-based materials for use as an electrode binder in a fuel cell. A fuel cell consisting of electrodes including a catalyst and an electrode binder with an electrolyte located between the electrodes. The electrolyte may be a proton-exchange membrane (PEM). The electrode binder includes one or more polymers, such as a polyphosphazene.	Still being used in ongoing research.
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 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.
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	Argonne National Laboratory	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.
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	Argonne National Laboratory	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.
8,129,306	03/06/12	Argonne National Laboratory	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.

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Patent Number	Award Date	Organization	Title	Description	Status
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 of a PEM fuel cell can be recycled by dissolving the MEA with a lower alkyl alcohol solvent to separate 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 and then separated by filtration.	Research complete - company holding IP. Part of an emerging fuel cell technology.
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 be used in ongoing research; Part of an emerging fuel cell technology.
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.
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.
8,071,701	12/06/11	Symyx Technologies, Inc.	Polydentate heteroatom ligand containing metal complexes, catalysts and methods of making and using the same	Metal complexes comprising certain polydentate heteroatom containing ligands, catalysts, and coordination polymerization processes employing the same are suitably employed to prepare polymers having desirable physical properties.	Still being used in ongoing research
8,062,552	11/22/11	Brookhaven National Laboratory	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.	Part of an emerging fuel cell technology. Seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
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.	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	Brookhaven National Laboratory	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.	Part of an emerging fuel cell technology. Seeking to license.
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.
8,029,942	10/04/11	Case Western Reserve University	Fuel cell system with flow field capable of removing liquid water from the high-pressure channels	Fuel cell system with flow fields capable of operating interdigitated flow fields and simultaneously allowing removal of liquid water collected in the high-pressure channels, throughout individual exhaust passages. Ideally the channels follow radial-circumferential trajectories, each channel being provided with individual exhaust passages. Alternatively, each channel could be provided with a valve control in both individual supply passages and individual exhaust passages allowing the system to operate alternatively as an interdigitated flow field as well as an open-channel flow field.	Still being used in ongoing research.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
8,021,795	09/20/11	General Electric Company	Method for manufacturing solid oxide electrochemical devices	Methods for connecting and sealing solid oxide fuel cells into a stack assembly.	Still being used in ongoing research.
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 the thermal output of the heat pump is increased by abstraction of heat from the SOFC exhaust.	No longer being used.
7,981,319	07/19/11	Los Alamos National Laboratory	Non-aqueous liquid compositions comprising ion exchange polymers	Compositions for formation of uniformly- dispersed electrodes, which can be used in membrane-electrode assemblies for, e.g., fuel cells, sensors and capacitors.	Still being used in ongoing research.
7,955,759	06/07/11	Oak Ridge National Laboratory	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.
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	Argonne National Laboratory	Catalytic membranes for fuel cells	A fuel cell with 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.
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. 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.

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Patent Number	Award Date	Organization	Title	Description	Status
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	Lawrence Berkeley National Laboratory	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.
7,896,949	03/01/11	General Electric Company	Membranes for separation of carbon dioxide	Describes methods for separating carbon dioxide from a fluid stream at a temperature higher than 200 degrees with selectivity higher than Knudsen diffusion selectivity using a porous membrane in a fluid stream. The porous membrane includes a porous support and a continuous porous separation layer. The porous support comprises alumina, silica, zirconia, stabilized zirconia, stainless steel, titanium, nickel-based alloys, aluminum- based alloys, zirconium-based alloys or a combination thereof. Median pore size of the porous separation layer is less than about 10 nm.	No longer being used in research/ no longer being pursued.
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.
7,871,738	01/18/11	Argonne National Laboratory	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.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
7,855,021	12/21/10	Brookhaven National Laboratory	Electrocatalysts having platinum monolayers on palladium, palladium alloy, and gold alloy core-shell nanoparticles, and uses thereof	Platinum-coated particles used in fuel cell electrocatalysts. The particles consist of a noble metal or metal alloy core at least partially encapsulated by an atomically thin surface layer of platinum atoms. The process 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. Seeking to license.
7,851,399	12/14/10	Los Alamos National Laboratory	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.	No longer being used.
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.
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.
7,829,652	11/09/10	General Electric Company	Polyarylether composition and membrane	A polyarylether copolymer that can be used as a cation-conducting membrane in fuel cells.	Still being used in ongoing research.
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.
7,829,194	11/09/10	Oak Ridge National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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.
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.
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	Oak Ridge National Laboratory	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	Pacific Northwest National Laboratory	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 600oC 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.
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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,790,285	09/07/10	Nanotek Instruments, Inc.	Nano-scaled graphene platelets with a high length-to-width aspect ratio	A nano-scaled graphene platelet (NGP) having a thickness no greater than 100 nm and a length-to- width ratio no less than 3 (preferably greater than 10). The NGP is prepared by intercalating a carbon fiber or graphite fiber with an intercalate to form an intercalated fiber and then exfoliating the intercalated fiber to obtain graphene sheets or flakes. The graphene sheets or flakes are separated to obtain nano-scaled graphene platelets. An electrically conductive nanocomposite material can be fabricated which could be useful for shielding of sensitive electronic equipment against electromagnetic interference (EMI) or radio frequency interference (RFI), and for electrostatic charge dissipation.	Research complete; seeking to license.
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.	No longer being used.
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	Los Alamos National Laboratory	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.	No longer being used.
7,767,616	08/03/10	Argonne National Laboratory	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	Sandia National Laboratory	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.
7,758,921	07/20/10	Argonne National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,758,783	07/20/10	Nanotek Instruments, Inc.	Continuous 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.
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.	No longer being pursued.
7,704,919	04/27/10	Brookhaven National Laboratory	Electrocatalysts 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.	Part of an emerging fuel cell technology. Seeking to license
7,704,918	04/27/10	Brookhaven National Laboratory	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	Argonne National Laboratory	Corrosion-resistant, electrically-conductive plate for use in a fuel cell stack	A corrosion resistant, electrically-conductive, durable plate partially coated with an anchor coating and a corrosion resistant coating. The plate is used as a bipolar plate in a proton exchange membrane fuel cell stack.	Being used in continuing research efforts at ANL.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,691,780	04/06/10	Brookhaven National Laboratory	Platinum- and platinum alloy-coated palladium and palladium alloy particles and uses thereof	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. 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.
7,678,728	03/06/10	University of New Mexico	Self supporting structurally engineered non-platinum electrocatalyst for oxygen reduction in fuel cells	A method for producing a highly dispersed, unsupported, non-platinum electrocatalyst for use in fuel cells.	Still being used in ongoing research.
7,670,988	03/02/10	University of New Mexico	Nanostructured anode PT-RU electrocatalysts for direct methanol fuel cells	An aerosol-assisted method for synthesis of nanostructured metallic electrocatalysts for direct methanol fuel cells. The resulting unsupported electrocatalysts are homogenous and highly dispersed.	Still being used in ongoing research.
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 containing an aromatic heterocyclic group modified by fluorinated sulfonamide groups and linear or branched perfluoroalkylene groups. The resulting particles and molecules can used in polymer electrode membranes, membrane electrode assemblies, and 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.
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.	No longer being used.
7,645,535	01/12/10	General Electric Company	Method and materials for bonding electrodes to interconnect layers in solid oxide fuel cell stacks	A method and related bonding compositions for use in assembling a solid oxide fuel cell stack having thermally and chemically stable and electrically conductive bonds between alternating fuel cells and interconnect components in the stack.	Still being used in ongoing research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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.	No longer being pursued.
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	Brookhaven National Laboratory	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. Seeking to license
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	Argonne National Laboratory	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; 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; seeking to license.
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.	No longer being used.

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Patent Number	Award Date	Organization	Title	Description	Status
7,589,047	09/15/09	Los Alamos National Laboratory	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 Los Alamos National Laboratory.
7,588,857	09/15/09	Los Alamos National Laboratory	Chalcogen catalysts for polymer electrolyte 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.	No longer being used.
7,575,824	08/18/09	Los Alamos National Laboratory	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.
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.	No longer being used.

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Patent Number	Award Date	Organization	Title	Description	Status
7,550,223	06/23/09	Los Alamos National Laboratory	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.
7,550,216	06/23/09	Foster-Miller, Inc.	Composite solid polymer electrolyte membranes	Composite solid polymer electrolyte membranes which include a porous polymer substrate interpenetrated with a water soluble ion-conducting material. These membranes are useful in electrochemical applications, including fuel cells and electrodialysis.	Still being used in ongoing research.
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 for use at high operating temperatures while preserving proton conductivity.	Part of a commercial fuel cell technology.
7,507,495	03/24/09	Brookhaven National Laboratory	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.	Part of an emerging fuel cell technology. Non-exclusive license to N.E. Chemcat Corporation.
7,482,083	01/27/09	General Electric Company	Corrosion resistant coated fuel cell bipolar plate with filled-in fine scale porosities	A corrosion resistant coated fuel cell plate and method of making the same are embodied in a metal plate provided with a multilayered conductive coating and then with an overcoat which fills in fine scale porosities in the coating. In one preferred embodiment, the overcoating is amorphous graphite applied through a deposition process. In another preferred embodiment, overcoating is a thin layer of oxide created by chemical anodization process.	Still being used in ongoing research.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
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.
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.	No longer being used.
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.
7,375,176	05/20/08	Case Western Reserve University	Liquid crystal poly(phenylene sulfonic acids)	A rigid, rod liquid crystal polymer includes a poly(phenylene sulfonic acid).	Still being used in ongoing research.
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	Argonne National Laboratory	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.	No longer being used.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,264,778	09/04/07	Sandia National Laboratory	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.
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	Oak Ridge National Laboratory	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.	Still being used in ongoing research. Part of an emerging fuel cell technology.
7,214,442	05/08/07	Los Alamos National Laboratory	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	Oak Ridge National Laboratory	Corrosion-resistant metallic bipolar plate	An electrically conductive component such as a bipolar plate for a PEM fuel cell. The component has an external, continuous layer of chromium nitride.	Still being used in ongoing research. Part of an emerging fuel cell technology.
7,195,835	03/27/07	Argonne National Laboratory	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.
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	Lawrence Berkeley National Laboratory	Polymeric electrolytes based on hydrosilyation reactions	New polymer electrolytes 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 insoluble in organic solvents and have high mechanical strength.	Being used in research at LBNL and seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
7,101,635	09/05/06	Los Alamos National Laboratory	Methanol-tolerant cathode catalyst composite for direct methanol fuel cells	Direct methanol fuel cell having a methanol fuel supply, oxidant supply, and membrane electrode assembly.	Not licensed and not being used at LANL for research.
7,101,527	09/05/06	Iowa State University	Mixed anion materials and compounds for novel proton conducting membranes	Amorphous or partially crystalline mixed anion chalcogenide compounds for use in proton exchange membranes which can 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	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	Sandia National Laboratory	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	Los Alamos National Laboratory	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	Pacific Northwest National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,986,963	01/17/06	Oak Ridge National Laboratory	Metallization of bacterial cellulose for electrical and electronic device manufacture	Metallized bacterial cellulose used in constructing fuel cells and other electronic devices.	No commercialization and no further development being pursued using this patent.
6,986,961	01/17/06	Los Alamos National Laboratory	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	Argonne National Laboratory	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	Los Alamos National Laboratory	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	Lawrence Livermore National Laboratory	Chemical microreactor and method thereof	A chemical microreactor for generation of hydrogen fuel from liquid sources such as ammonia, methanol, and butane by steam reforming. The microreactor 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	Lawrence Berkeley National Laboratory	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 airflow 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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
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.	No longer being used in research/ no longer being pursued.
6,864,007	03/08/05	Hybrid Power Generation Systems, LLC	Corrosion resistant coated fuel cell plate with graphite protective barrier and method of making the same	A corrosion resistant coated fuel cell plate and method of construction using a metal plate with a graphite emulsion coating and a layer of graphite foil pressed over the coating. The graphite emulsion bonds the graphite foil to the metal plate and seals fine scale porosities in the graphite foil. Flow fields are formed by stamping the coated fuel cell plate.	No longer being used in research/ no longer being pursued.
6,864,004	03/08/05	Los Alamos National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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	Los Alamos National Laboratory	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.	Still being used in ongoing research; seeking to license.
6,808,838	10/26/04	Los Alamos National Laboratory	Direct methanol fuel cell and system	A fuel cell having an anode and a cathode and a polymer electrolyte membrane located between anode and cathode gas diffusion backings uses a methanol vapor fuel supply.	Not licensed and not being used at LANL for research.
6,790,548	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	Los Alamos National Laboratory	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	Argonne National Laboratory	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	Brookhaven National Laboratory	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.	Still being used in research and seeking to license. Part of an emerging fuel cell technology.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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.
6,649,031	11/18/03	Hybrid Power Generation Systems, LLC	Corrosion resistant coated fuel cell bipolar plate with filled-in fine scale porosities and method of making the same	A corrosion resistant coated fuel cell plate and method of construction using a metal plate with a multilayered conductive coating and an overcoating which fills in fine scale porosities. The overcoating can be amorphous graphite or a thin layer of oxide created by a chemical anodization.	No longer being used in research/ no longer being pursued.
6,635,378	10/21/03	Hybrid Power Generation Systems, LLC	Fuel cell having improved condensation and reaction product management capabilities	A fuel cell bipolar plate including a plurality of reactant channels defining respective inlets and outlets and at least two flow restrictors respectively associated with at least two adjacent reactant channels.	No longer being used in research/ no longer being pursued.
6,635,369	10/21/03	Los Alamos National Laboratory	Method for improving fuel cell performance	A method is provided for operating a fuel cell at high voltage for sustained periods of time.	Still being used in ongoing research; seeking to license.
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.
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	Los Alamos National Laboratory	Air breathing direct methanol fuel cell	A method for activating a membrane electrode assembly for a direct methanol fuel cell is disclosed. The method comprises operating the fuel cell with humidified hydrogen as the fuel followed by running the fuel cell with methanol as the fuel.	Not licensed and not being used at LANL for research.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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, LLC	Fuel cell membrane hydration and fluid metering	A hydration system includes fuel cell fluid flow plate(s) and injection port(s).	No longer being used.
6,517,965	02/11/03	Symyx Technologies, Inc.	Platinum-ruthenium-nickel alloy for use as a fuel cell catalyst	An improved noble metal alloy composition for a fuel cell catalyst, the alloy containing platinum, ruthenium, and nickel. The alloy shows methanol oxidation activity.	Not licensed and no research being done with this patent.
6,498,121	12/24/02	Symyx Technologies, Inc.	Platinum-ruthenium-palladium alloys for use as a fuel cell catalyst	A noble metal alloy composition for a fuel cell catalyst, a ternary alloy composition containing platinum, ruthenium and palladium. The alloy shows increased activity compared with well-known catalysts.	Not licensed and no research being done with this patent.
6,497,970	12/24/02	General Motors Corporation	Controlled air injection for a fuel cell system	A method and apparatus for injecting oxygen into a fuel cell reformate stream to reduce the level of carbon monoxide while preserving the level of hydrogen in a fuel cell system.	Being used in continuing research at the company.
6,492,052	12/10/02	Los Alamos National Laboratory	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	Pacific Northwest National Laboratory	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	Los Alamos National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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	Los Alamos National Laboratory	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. - Part of a fuel cell commercial technology.
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.
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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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.
6,322,919	11/27/01	Allied Signal Inc.	Fuel cell and bipolar plate for use with same	A fuel cell bipolar plate including a fuel side having a series of fuel channels defining respective fuel paths and an oxidant side having a series of oxidant channels defining respective oxidant paths. Some fuel channels are offset from adjacent oxidant channels in a direction transverse to the fuel and oxidant paths. Manifolds are connected to the fuel and oxidant channels. One of the two manifolds is located between the biplate and the other manifold, where a connector extends from whichever manifold is outermost to the associated fuel or oxidant channels.	No longer being used in research/ no longer being pursued.
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	Los Alamos National Laboratory	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.
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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 H2 - O2 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	Los Alamos National Laboratory	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	Composite solid polymer electrolyte membranes which include a porous polymer substrate interpenetrated with an ion-conducting material. These membranes can be used in fuel cells and electrodialysis.	Being used in continuing research at the company.
6,248,467	06/19/01	Los Alamos National Laboratory	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 Bulk Molding Compounds, Inc. Part of a commercial fuel cell technology.
6,245,214	06/12/01	Allied Signal Inc.	Electro-catalytic oxidation (ECO) device to remove CO from reformate for fuel cell application	A method and apparatus that removes carbon monoxide from hydrogen rich fuel by means of a catalytic material that preferentially adsorbs with carbon monoxide. The catalytic material is regenerated by an oxidizing agent that reacts with the absorbed carbon monoxide. The reaction is initiated by an electrical current generated either galvanically or electrolytically.	No longer being used in research/ no longer being pursued.
6,232,005	05/15/01	General Motors Corporation	Fuel cell system combustor	A fuel cell system including a fuel reformer heated by a catalytic combustor fired by anode and cathode effluents.	No longer being pursued, abandoned.
6,207,312	03/27/01	Energy Partners, L.C.	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	Los Alamos National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,200,536	03/13/01	Pacific Northwest National Laboratory	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	Pacific Northwest National Laboratory	Active microchannel fluid processing unit and method of making	An active microchannel fluid processing unit.	Exclusive license to Velocys, Inc.
6,183,894	02/06/01	Brookhaven National Laboratory	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, L.C.	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	Oak Ridge National Laboratory	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.	No longer being used.
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	Pacific Northwest National Laboratory	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.
6,126,723	10/03/00	Pacific Northwest National Laboratory	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., H2S and CO) from the fuel stream.	Exclusive license to Velocys, Inc.
6,117,577	09/12/00	Los Alamos National Laboratory	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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 H2 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.
6,037,072	03/14/00	Los Alamos National Laboratory	Fuel cell with metal screen flow field	A polymer electrolyte membrane (PEM) fuel cell is provided with electrodes supplied with a reactant on each side of a catalyzed membrane assembly (CMA). The fuel cell includes a metal mesh defining a rectangular flow-field pattern having an inlet at a first corner and an outlet at a diagonally opposed second corner. All the flow paths from the inlet to the outlet through the square flow field pattern are equivalent to uniformly distribute the reactant over the CMA. The bipolar plates can be electrically connect to adjacent fuel cells, cooling plates can also be incorporated for distributing cooling water flow over the electrodes to remove heat generated by the fuel cells.	No longer being used in research/ no longer being pursued.
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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,007,933	12/28/99	Plug Power, LLC	Fuel cell assembly unit for promoting fluid service and electrical conductivity	Fluid service and/or electrical conductivity for a fuel cell assembly.	Still being used in research.
6,001,499	12/14/99	General Motors Corporation	Fuel cell CO sensor	The CO concentration in the H2 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.	No longer being used.
5,952,119	09/14/99	Los Alamos National Laboratory	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 H2 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	Lawrence Livermore National Laboratory	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	Lawrence Berkeley National Laboratory	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	Los Alamos National Laboratory	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	Savannah River National Laboratory	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.
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.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 for generating 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 filaments embedded in the face of the supporting the MEA and conducting current to contiguous electrode plates.	Being used in continuing research at the company.
5,654,109	08/05/97	Dow Chemical Company	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 in a fuel cell.	No longer being used in research/ no longer being pursued.
5,641,586	06/24/97	Los Alamos National Laboratory	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	Lawrence Livermore National Laboratory	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	Lawrence Livermore National Laboratory	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
5,595,834	01/21/97	Los Alamos National Laboratory	Annular feed air breathing fuel cell stack	A stack of polymer electrolyte fuel cells is formed from a plurality of unit cells where each unit cell includes fuel cell components stacked along a common axis. Each fuel cell component has a polymer electrolyte membrane, anode, cathode as well as provision for fuel and oxygen flow fields. A fuel distribution manifold is connected to deliver fuel to the fuel flow field in each of the unit cells.	Not licensed and not being used for research at LANL.
5,558,961	09/24/96	Lawrence Berkeley National Laboratory	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	Lawrence Berkeley National Laboratory	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	Argonne National Laboratory	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.
5,234,777	08/10/93	Los Alamos National Laboratory	Membrane catalyst layer for fuel cells	A gas reaction fuel cell incorporates a thin catalyst layer between a solid polymer electrolyte (SPE) membrane and a porous electrode backing. The film is formed as an ink that is spread and cured on a film release blank. The cured film is then transferred to the SPE membrane and hot pressed into the surface to form a catalyst layer having a controlled thickness and catalyst distribution. The catalyst layer can also be formed by direct application of a perfluorosulfonate ionomer directly to the membrane, drying the film at a high temperature, and then converting the film back to the protonated form of the ionomer. The layer has adequate gas permeability so that cell performance is not affected.	Not licensed and not being used for research at LANL.

Fuel Cell Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
5,211,984	05/18/93	Los Alamos National Laboratory	Membrane catalyst layer for fuel cells	A gas reaction fuel cell incorporates a thin catalyst layer between a solid polymer electrolyte (SPE) membrane and a porous electrode backing. The film is formed as an ink that is spread and cured on a film release blank. The cured film is then transferred to the SPE membrane and hot pressed into the surface to form a catalyst layer having a controlled thickness and catalyst distribution.	Not licensed and not being used for research at LANL.
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	Los Alamos National Laboratory	Fuel processor for fuel cell power system	A catalytic organic fuel processing apparatus, which can be used in a fuel cell power system, contains within a housing a catalyst chamber, a variable speed fan, and a combustion chamber.	Not licensed and not being used for research at LANL.

B.2 Production/Delivery Patents Status

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,391,334	07/12/16	Intelligent Energy, Inc.	Hydrogen gas generator	Hydrogen generator includes a removable cartridge of multiple thermal conductors with surface deposited fuel pellets which carry a hydrogen-containing reactant that will react to release hydrogen gas when heated. The hydrogen generator also includes heating elements to selectively heat one or more fuel pellets to initiate a reaction to produce hydrogen gas.	Still being used in ongoing research.
9,295,958	03/29/16	Intelligent Energy, Inc.	Fuel unit, refillable hydrogen generator and fuel cell system	A packaged fuel unit and a refillable hydrogen generator that uses the fuel unit to produce hydrogen gas. The fuel unit includes a reactant that can undergo a thermal decomposition reaction to produce hydrogen gas when heated to at least a minimum initiation temperature. The fuel unit is removable and contains a heating system for heating the fuel unit. The hydrogen generator can be part of a fuel cell system including a fuel cell battery that is provided with hydrogen gas from the hydrogen generator.	Still being used in ongoing research.
9,243,560	01/26/16	Intelligent Energy, Inc.	Hydrogen generator having a thermal actuator	A hydrogen generator having one or more actuators coupled to one or more heating elements in which the actuator(s) are used to improve the transfer of thermal energy from heating element(s) to one or more fuel units contained within the generator. The actuators containing the fuel units can be inserted or removed without removing the heating element(s).	Still being used in ongoing research.
9,162,201	10/20/15	Intelligent Energy, Inc.	Hydrogen generator having liquid delivery member	A hydrogen generator is provided for generating hydrogen gas for a fuel cell stack. The hydrogen generator includes container, and a first reactant storage area. The hydrogen generator also includes a reaction area and a solid second reactant within the reaction area, and a hydrogen outlet. The hydrogen generator also includes a flexible liquid delivery member extending into the reaction area and configured to deliver either liquid reactant or solid reactant.	Still being used in ongoing research.
9,150,968	10/06/15	Brookhaven National Laboratory	Platinum-based electrocatalysts synthesized by depositing contiguous adlayers on carbon nanostructures	A manufacturing process involving initial oxidation of the carbon nanostructures followed by immersion in an alkaline solution containing one or more noble metals. The process can be used for high-performance electrodes in supercapacitors, batteries, or other electric storage devices.	Still being used in ongoing research.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,139,432	09/22/15	University of Central Florida	Apparatus for decomposing water and releasing hydrogen	A methods and apparatus for producing high purity hydrogen from water. Metals or alloys capable of reacting with water to produce hydrogen in aqueous solutions at ambient conditions are reacted with one or more inorganic hydrides to release hydrogen and transition metal compounds or alkali metal-based compounds are used to catalyze the reaction.	Research complete; seeking to license.
9,102,528	08/11/15	Intelligent Energy, Inc.	Hydrogen generation systems and methods utilizing sodium silicide and sodium silica gel materials	Systems, devices, and methods combine thermally stable reactant materials and aqueous solutions to generate hydrogen and a non-toxic liquid by-product. The reactant materials can be either sodium silicide or sodium silica gel. The hydrogen generation devices are used in fuels cells and other industrial applications.	Still being used in ongoing research.
9,093,681	07/28/15	Intelligent Energy, Inc.	Hydrogen generation having CO2 removal with steam reforming	A method for producing hydrogen using fuel cell off gases by feeding hydrocarbon fuel to a sulfur adsorbent to produce a desulfurized fuel and a spent sulfur adsorbent. Desulfurized fuel and water are then fed to an adsorption enhanced reformer to produce hydrogen.	Still being used in ongoing research.
9,079,146	07/14/15	Intelligent Energy, Inc.	Hydrogen generation systems utilizing sodium silicide and sodium silica gel materials	Systems, devices, and methods combine thermally stable reactant materials and aqueous solutions to generate hydrogen and a non-toxic liquid by-product. The reactant materials can be either sodium silicide or sodium silica gel. The hydrogen generation devices are used in fuels cells and other industrial applications.	Still being used in ongoing research.
9,057,136	06/16/15	University of South Carolina	Production of low temperature electrolytic hydrogen	A process for electrochemical hydrogen production using an electrochemical cell consisting of an anode, cathode and a membrane separator. The process feeds gaseous reactant at the anode, oxidizing one or more molecules of the gaseous reactant to produce gas product and protons. The protons pass through the membrane to the cathode where reduction forms hydrogen gas.	Research complete; seeking to license.
9,028,720	05/12/15	Air Products & Chemicals, Inc.	Ion transport membrane reactor systems and methods for producing synthesis gas	Cost-effective systems and methods for producing a synthesis gas product using a steam reformer system and an ion transport membrane (ITM) reactor having multiple stages, without requiring inter-stage reactant injections. The system compensates for changes in membrane performance degradation and system operating conditions.	Still being used in ongoing research.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,005,486	04/14/15	Savannah River National Laboratory	Proton conducting ceramics in membrane separations	Perovskite materials of the general formula $SrCeO_3$ and $BaCeO_3$ with improved conductivity and an original ratio of chemical constituents. The process alters the microstructure of the material using wet chemical techniques.	Still being used in ongoing research; seeking to license.
8,835,153	09/16/14	National Renewable Energy Laboratory	Process and genes for expression and over expression of active [FeFe] hydrogenases	The invention relates to the use of genes to provide expression and over-expression of any active [FeFe]-hydrogenases, expressed in any suitable host, using an [FeFe]-hydrogenase assembly of genes from a suitable organism.	Research complete; seeking to license.
8,834,587	09/16/14	Virent Energy Systems, Inc.	Method of producing gaseous products using a downflow reactor	Reactor systems and methods are provided for the catalytic conversion of liquid feedstocks to synthesis gases and other noncondensable gaseous products. The reactor systems include a heat exchange reactor configured to allow the liquid feedstock and gas product to flow concurrently. The reactor systems and methods can be used for producing hydrogen and light hydrocarbons from biomass-derived oxygenated hydrocarbons using aqueous phase reforming.	Still being used in ongoing research. Non-exclusive license to Equilon Enterprises LLC d/b/a as Shell Oil Products U.S. (a subsidiary of Royal Dutch Shell)
8,754,263	07/17/14	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 from biomass using hydrogen produced from the biomass.	Still being used in ongoing research. Non-exclusive license to Equilon Enterprises LLC d/b/a as Shell Oil Products U.S. (a subsidiary of Royal Dutch Shell)
8,728,202	05/20/14	Air Products & Chemicals, Inc.	Staged membrane oxidation reactor system	An ion transport membrane system for converting methane to synthesis gas (hydrogen and carbon monoxide).	No longer being pursued.
8,721,973	05/13/14	Catacel Corporation	Stackable structural reactors	A reactor for carrying out catalytic reactions. The reactor includes a reactor component optionally arranged on a central rod in a reactor tube. The reactor component can have fluid ducts for directing fluid flow through the reactor. The fluid ducts are effective for increasing heat transfer in the reactor. The reactor component can further have a washer attached to a top or bottom surface for directing fluid flow.	Part of a commercial hydrogen production technology.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,715,868	05/06/14	University of South Carolina	Electrochemical removal of contaminants from hydrogen	A proton exchange membrane fuel cell including a twin-cell electrochemical filter. A flow of reformate H_2 and pulse potential are switched between each respective filter cell and CO-contaminated H_2 is fed to one filter, a pulse potential is simultaneously applied to the other.	Research complete; seeking to license.
8,703,642	04/22/14	University of Central Florida	Method of forming supported doped palladium containing oxidation catalysts	A method of forming palladium-containing, supported oxidation catalysts that can be used as a chemochromic (color-changing) pigment for detecting hydrogen leaks.	Licensed to HySense Technology LLC. Part of a commercial production technology.
8,691,068	04/08/14	University of Central Florida	Solar metal sulfate-ammonia based thermochemical water splitting cycle for hydrogen production	Describes two classes of hybrid/thermochemical water splitting processes for the production of hydrogen and oxygen based on (1) metal sulfate-ammonia cycles (2) metal pyrosulfate-ammonia cycles.	Research complete; seeking to license.
8,685,878	04/01/14	Argonne National Laboratory	Highly durable nanoscale electrocatalyst based on core shell particles	A nanoscale catalyst having a core enveloped by a shell with high catalytic activity and improved durability. The core/shell nanoparticles comprise a gold particle coated with a catalytically active platinum bimetallic material. The nanoparticles may be dispersed on a high surface area substrate for use as a catalyst.	Still being used in ongoing research.
8,685,364	04/01/13	Los Alamos National Laboratory	Liquid composition having ammonia borane and decomposing to form hydrogen and liquid reaction product	Liquid compositions of ammonia borane and a suitably chosen amine borane material were prepared and subjected to conditions suitable for their thermal decomposition in a closed system that resulted in hydrogen and a liquid reaction product.	Still being used in ongoing research.
8,663,958	03/04/14	National Renewable Energy Laboratory	Oxygen-resistant hydrogenases and methods for designing and making same	An oxygen-resistant iron-hydrogenases ([Fe]-hydrogenases) for use in the production of H_2. The methods used to design and engineer these oxygen-resistant [Fe]-hydrogenases are provided. A process that utilizes the transformed, oxygen insensitive, host cells in the bulk production of H_2 in a light catalyzed reaction with water as the reactant is also described.	Research complete; seeking to license.
8,652,993	02/18/14	University of Central Florida	Doped palladium containing oxidation catalysts	A palladium-containing oxidation catalyst that can be used as a chemochromic (color-changing) pigment for detecting hydrogen leaks.	Licensed to HySense Technology LLC. Part of a commercial production technology.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,623,662	01/07/14	University of Central Florida	Methods of forming visual hydrogen detector with variable reversibility	Methods of forming a chemochromic hydrogen detector with variable, reversible color change. In the presence of hydrogen, a hydrogen-sensitive pigment changes color from white or light-gray or light-tan to dark gray, navy-blue or black depending on the exposure time and hydrogen concentration. After hydrogen exposure ceases, the original color of the pigment is restored, allowing the visual hydrogen detector to be used repeatedly.	Licensed to HySense Technology LLC. Part of a commercial production technology.
8,609,054	12/17/13	Bing Energy International	Hydrogen production from borohydrides and glycerol	A method of forming hydrogen gas utilizing an alcoholysis reaction of a borohydride component and a glycerol component.	No longer being pursued.
8,591,818	11/26/13	University of Central Florida	Gas permeable chemochromic compositions for hydrogen sensing	A hydrogen sensor composition that includes a gas-permeable matrix material intermixed and encapsulating at least one chemochromic pigment. The chemochromic pigment produces a detectable change in color of the overall sensor composition in the presence of hydrogen.	Licensed to HySense Technology LLC. Part of a commercial production technology.
8,568,582	10/29/13	National Renewable Energy Laboratory	Systems and methods for selective hydrogen transport and measurement	Systems and methods for selectively removing hydrogen gas from a hydrogen-containing fluid. The system contains a proton exchange membrane (PEM) selectively permeable to hydrogen with metal deposited as layers onto opposite sides or faces of the PEM to form a membrane-electrode assembly (MEA) that functions as a hydrogen selective membrane (HSM).	Research complete; seeking to license.
8,499,612	08/06/13	University of California - Irvine	Hydrogen gas detection using single palladium nanowires	Devices and methods for fast, sensitive hydrogen gas detection using a single palladium nanowire. The nanowire is able to rapidly and reversibly detect hydrogen down to 2 ppm with excellent reproducibility and baseline stability at room temperature.	Research complete; seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
8,496,909	07/30/13	Ohio State University	Calcium looping process for high purity hydrogen production integrated with capture of carbon dioxide, sulfur and halides	A process for producing hydrogen comprising of several steps, fuel gasifying into raw synthesis gas comprising CO, hydrogen, steam, sulfur and halide contaminants and passing the raw synthesis gas through a water gas shift reactor (WGSR) into which CaO and steam are injected. The CaO reacting with the shifted gas to remove CO_2, sulfur and halides in a solid-phase calcium-containing product. Then separation of the solid-phase calcium-containing product from an enriched gaseous hydrogen product occurs followed occurs by regenerating the CaO by calcining the solid-phase calcium-containing product.	Still being used in ongoing research.
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.).
8,491,679	07/23/13	Intelligent Energy, Inc.	Hydrogen generation utilizing integrated CO_2 removal with steam reforming	A steam reformer for hydrogen production that removes carbon dioxide from the product gas stream using pressure swing adsorption.	Still being used in ongoing research.
8,460,409	06/11/13	Ceramatec	Plasma-catalyzed fuel reformer	Fuel reformer that uses a plasma zone to receive a pre-heated mixture of reactants and ionize the reactants by applying an electrical potential. The reformer includes a reaction zone to chemically transform the ionized reactants into synthesis gas.	Research complete.
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.	No longer being pursued.
8,453,515	06/04/13	Oak Ridge National Laboratory	Apparatus and method for fatigue testing of a material specimen in a high-pressure fluid environment	Fatigue testing of a material specimen in a high pressure fluid environment. Pressurized fluid is provided in compression and tension chambers between a piston and a vessel allowing the specimen to be subjected to either compression or tension forces. The specimen when subjected to either force is surrounded by the pressurized fluid which in some examples can be hydrogen.	Still being used in ongoing research.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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 on substrates using an atomic layer deposition. The coatings are able to store energy such as solar energy, and to release that stored energy, via a redox reaction.	Licensed to ALD NanoSolutions, Inc.
8,372,170	02/12/13	Intelligent Energy, Inc.	Fuel steam reformer system and reformer startup process	A hydrogen generation system is disclosed that has a fuel vaporization section receiving fuel along with water which is passed to a reformer catalyst section heated by a combustor section to generate reformate gas and is fueled by off-gas from an H_2 purification unit and a combustion air source. An H_2 storage unit connected to the purification unit has an outlet selectively connectable to the reformer assembly process inlet during startup without the need for a spark igniter.	Still being used in ongoing research.
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 a commercial hydrogen production technology.
8,349,035	01/08/13	Argonne National Laboratory	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.
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; seeking to license.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,273,140	09/25/12	University of Central Florida	Method and apparatus for hydrogen production from water	A method, apparatuses and chemical compositions are provided for producing high purity hydrogen from water. Metals or alloys capable of reacting with water and producing hydrogen in aqueous solutions at ambient conditions are reacted with one or more inorganic hydrides capable of releasing hydrogen in aqueous solutions at ambient conditions.	Research complete; seeking to license.
8,268,392	09/18/12	University of Central Florida	Visual hydrogen detector with variable reversibility	Methods, processes and compositions are provided for a visual or chemochromic hydrogen-detector with variable or tunable reversible color change.	Licensed to HySense Technology LLC. Part of a commercial production technology.
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.	No longer being pursued.
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	Pacific Northwest National Laboratory	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.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,207,081	06/26/12	University of Central Florida	Nanocomposite for photocatalytic Hydrogen production and method for its preparation	Nanocomposite cocatalysts and their preparation method. The cocatalysts loaded on CdS photocatalyst enhances the photocatalytic activity.	Research complete; seeking to license.
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.).
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.	No longer being pursued.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,147,765	04/03/12	University of Central Florida	Apparatus for hydrogen and carbon production via carbon aerosol-catalyzed dissociation of hydrocarbons	A novel process and apparatus is disclosed for sustainable, continuous production of hydrogen and carbon by catalytic dissociation or decomposition of hydrocarbons at elevated temperatures using in- situ generated carbon particles. Carbon particles are produced by decomposition of carbonaceous materials in response to an energy input.	Research complete; seeking to license.
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. The seal uses a low temperature melting point metal, which forms when heated above the melting point which is greater than the purifier operating temperature.	Research complete; seeking to license.
8,088,261	01/03/12	Gas Technology Institute	CuCl thermochemical cycle for hydrogen production	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.
8,084,265	12/27/11	National Renewable Energy Laboratory	Method and Pd/V2 O5 device for H2 detection	Pd/V_2O_5 devices for hydrogen detection are described. The devices are chemochromic sensors and can detect hydrogen gas over a wide response range with stability during repeated exposure and removal of hydrogen gas.	Research complete; seeking to license.
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.
8,048,384	11/01/11	University of Central Florida	Chemochromic hydrogen sensors	A chemochromic hydrogen sensor includes supports including a plurality of metal oxide particles exclusive of titania, and a platinum group metal (PGM) compound on the supports.	Licensed to HySense Technology LLC. Part of a commercial production technology.
8,003,055	08/23/11	University of Central Florida	Visual hydrogen detector with variable reversibility	Methods, processes and compositions are provided for a visual or chemochromic hydrogen-detector with variable or tunable reversible color change.	Licensed to HySense Technology LLC. Part of a commercial production technology.
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.	Research complete; seeking to license.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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	Argonne National Laboratory	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.
7,981,261	07/19/11	Argonne National Laboratory	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.
7,951,283	05/31/11	Idaho National Laboratory	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. The hydrogen separation membrane system 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	Idaho National Laboratory	Apparatus for chemical synthesis	A method and apparatus for forming a chemical hydride using a pseudo-plasma-electrolysis reactor. The reactor has a cathode and a movable anode. The anode is moved into and out of fluidic, ohmic electrical contact with the chemical hydride forming solution.	No longer being used in research/no longer being pursued.

Production/Delivery Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,932,437	04/26/11	Oak Ridge National Laboratory	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	Pacific Northwest National Laboratory	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.
7,914,683	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	National Renewable Energy Laboratory	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.	Licensed to Element One, Inc. Part of commercial production/ delivery technology.
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.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,896,953	3/1/11	University of South Florida	Practical method of CO_2 sequestration	A process and device to capture of CO_2 at its originating source, such as a power plant, is disclosed. Absorbent material is recharged by desorbing CO_2, so that it may be sequestered or used in another application.	Research complete; seeking to license.
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.
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 OnSite in a commercial product.
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.
7,820,022	10/26/10	General Electric Company	Photoelectrochemical cell and method of manufacture	An apparatus that generates hydrogen by using solar energy to electrolyze water. The photoelectrochemical cell has a particulate-loaded thermoplastic film membrane within an interior cavity of the cell.	No longer being used in research/no longer being pursued.
7,818,993	10/26/10	Argonne National Laboratory	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.
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 and a series of planar ion transport membrane modules. A gas manifold is connected to each membrane module.	No longer being pursued.

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Patent Number	Award Date	Organization	Title	Description	Status
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.).
7,766,986	08/03/10	Air Products & Chemicals, Inc.	Dehydrogenation of liquid fuel in microchannel catalytic reactor	Process for the storage and delivery of hydrogen by the reversible hydrogenation and dehydrogenation of an organic compound wherein the organic compound is initially in its hydrogenated state.	Still being used in ongoing research.
7,763,217	07/27/10	Pacific Northwest National Laboratory	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 some electric power consumption, making the device advantageous for use in automotive fuel cell applications.	Research complete; seeking to license.
7,763,086	07/27/10	Intelligent Energy, Inc.	Hydrogen purification process and system	A hydrogen generation system including a fuel reforming reactor generating a hydrogen-rich reformate gas, a pressure swing adsorption (PSA) hydrogen purification unit that separates hydrogen from the reformate gas, and a catalytic reactor downstream of the PSA to convert carbon monoxide and hydrogen into methane.	Still being used in ongoing research.
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 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 OnSite in a commercial product.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,732,174	06/08/10	National Renewable Energy Laboratory	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 photo-production 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	Argonne National Laboratory	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 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.	No longer being pursued.
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.	No longer being pursued.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,687,051	03/30/10	Symyx Technologies, Inc.	Platinum and rhodium and/or iron containing catalyst formulations for hydrogen generation	A method and catalysts for producing a hydrogen-rich syngas using CO-containing gas which contacts a water gas shift (WGS) catalyst. The water gas shift catalyst is formulated from Pt, its oxides or mixtures thereof, at least one of Fe and Rh, their oxides and mixtures thereof, and at least one member selected from the group consisting of Sc, Y, Ti, Zr, V, Nb, Ta, Mo, Re, Co, Ni, Pd, Ge, Sn, Sb, La, Ce, Pr, Nd, Sm, and Eu, their oxides and mixtures thereof. The WGS catalyst may be supported on a carrier, such as any one member or a combination of alumina, zirconia, titania, ceria, magnesia, lanthania, niobia, yttria and iron oxide. Fuel processors containing such water gas shift catalysts are also disclosed.	Still being used in ongoing research.
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 OnSite in a commercial product.
7,666,534	02/23/10	Argonne National Laboratory	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 produce a product gas stream containing hydrogen and carbon oxides.	No longer being pursued.

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Patent Number	Award Date	Organization	Title	Description	Status
7,651,669	01/26/10	Pacific Northwest National Laboratory	Microsystem process networks	Applications of microsystem process networks improved by employing ortho-cascading mass, heat, or other unit process operations. One 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.
7,648,566	01/19/10	General Electric Company	Methods and apparatus for carbon dioxide removal from a fluid stream	An apparatus for purifying synthesis gas streams by performing the water-gas shift reaction and selectively removing the resulting carbon dioxide so that the product stream has a higher hydrogen purity.	No longer being used in research/no longer being pursued.
7,642,405	01/05/10	Oak Ridge National Laboratory	Switchable photosystem- II designer algae for photobiological hydrogen production	A switchable photosystem-II designer algae for photobiological hydrogen production. The transgenic algae includes at least two transgenes for enhanced photobiological H_2 production.	No longer being used.
7,604,771	10/20/09	Argonne National Laboratory	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.	No longer being pursued.

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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 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).	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	Argonne National Laboratory	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.
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.	No longer being pursued.
7,540,475	06/02/09	Pacific Northwest National Laboratory	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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,520,917	04/21/09	Pacific Northwest National Laboratory	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.
7,519,462	04/14/09	Caterpillar	Crowd force control in electrically propelled machine	A method of operating an electrically propelled machine including the power source, and limiting output torque of the electrical propulsion motor system based upon the occurrence of a crowd force condition of the machine.	Research complete.
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.	No longer being pursued.
7,507,690	03/24/09	Argonne National Laboratory	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.	No longer being used in research/no longer being pursued.
7,501,270	03/10/09	National Renewable Energy Laboratory	Oxygen-resistant hydrogenases and methods for designing and making same	Oxygen-resistant iron-hydrogenases ([Fe]-hydrogenases) for use in the production of H_2 and methods for the design and engineering of the oxygen-resistant [Fe]-hydrogenases. Also provided are methods for utilizing the transformed, oxygen insensitive, host cells in the bulk production of H_2 in a light catalyzed reaction having water as the reactant.	Being used in continuing research efforts at NREL and seeking to license.
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.
7,501,101	03/10/09	Pacific Northwest National Laboratory	Microchannel apparatus comprising plural microchannels and methods of conducting unit operations	A microchannel apparatus comprising a header and plural flow microchannels 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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.	No longer being pursued.
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 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. 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.	No longer being pursued.
7,452,407	11/18/08	Air Products & Chemicals, Inc.	Production of carbon monoxide-free hydrogen and helium from a high-purity source	A vacuum swing adsorption processes that produce carbon monoxide- free hydrogen or helium gas stream from, respectively, a high-purity (e.g., pipeline grade) hydrogen or helium gas stream using one or two adsorber beds.	Still being used in ongoing research.
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.

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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.	No longer being pursued.
7,419,635	09/02/08	National Renewable Energy Laboratory	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.
7,407,458	08/05/08	Caterpillar	In-line drivetrain and four wheel drive work machine using same	A four wheel drive articulated mine loader powered by a fuel cell and propelled by an in-line, single electric motor using a single reduction gear to power the four wheel drive mine loader.	Research complete.
7,396,382	07/08/08	General Electric Company	Functionalized inorganic membranes for gas separation	A porous membrane for separation of carbon dioxide from a fluid stream at a temperature higher than about 200 degrees with selectivity higher than Knudsen diffusion selectivity. The porous membrane comprises of porous support and separation layers comprising alumina, silica, zirconia or stabilized zirconia; and a functional layer comprising a ceramic oxide contactable with the fluid stream to preferentially transport carbon dioxide.	No longer being used in research/no longer being pursued.
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.	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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,344,576	03/18/08	Pacific Northwest National Laboratory	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.
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.	No longer being pursued.
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.	No longer being pursued.
7,297,324	11/20/07	Pacific Northwest National Laboratory	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.	No longer being pursued.
7,276,306	10/02/07	Lawrence Livermore National Laboratory	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	Pacific Northwest National Laboratory	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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,270,905	09/18/07	Pacific Northwest National Laboratory	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.
7,242,311	07/10/07	Caterpillar	Method and system for providing work machine multi-functional user interface	A multi-functional user interface on a work machine for displaying suggested corrective action. Status information associated with the work machine is analyzed to determine an abnormal condition and then a display warning message indicating the abnormal condition and one or more corrective actions.	Research complete.
7,233,034	06/19/07	National Renewable Energy Laboratory	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	National Renewable Energy Laboratory	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 produce a product gas stream containing hydrogen and carbon oxides.	No longer being pursued.
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.
7,157,167	01/02/07	University of Central Florida	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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,148,389	12/12/06	University of Michigan	Selective sorbents for purification of hydrocarbons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent. 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	Pacific Northwest National Laboratory	Microsystem process networks	Applications of microsystem process networks which can be improved by employing ortho-cascading mass, heat, or other unit process operations.	Exclusive license to Velocys, Inc.
7,122,873	10/17/06	University 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.	No longer being used.
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.
7,094,333	08/22/06	University of Michigan	Selective sorbents for purification of hydrocarbons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent. 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	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, ceramic tubes, and equipment such as seals and conduits.	No longer being pursued.
7,087,211	08/08/06	Argonne National Laboratory	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.

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Patent Number	Award Date	Organization	Title	Description	Status
7,074,369	07/11/06	University of Central Florida	Method and apparatus for decoupled thermo-catalytic pollution control	Method for design and scale-up of thermo- catalytic processes based on optimizing process energetics by decoupling of the process energetics from the DRE for target contaminants. The method is based on the implementation of polymeric and other low-pressure drop support for thermo-catalytic media as well as the multifunctional catalytic media in conjunction with a novel rotating fluidized particle bed reactor.	Research complete; seeking to license.
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 a commercial hydrogen production/ delivery technology.
7,066,973	06/27/06	Nuvera Fuel Cells, Inc.	Integrated reformer and shift reactor	A hydrocarbon fuel reformer for producing diatomic hydrogen gas.	No longer being used in research/no longer being pursued.
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 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. 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 hydrocarbons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent. 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.
7,051,540	05/30/06	Pacific Northwest National Laboratory	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 hydrocarbons	A method for removing thiophene and thiophene compounds from liquid fuel using an adsorbent. 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.	No longer being pursued.
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 ongoing research.
7,001,446	02/21/06	Eltron Research & Development, Inc.	Dense, layered membranes for hydrogen separation	Hydrogen-permeable membranes for separation of hydrogen from hydrogen-containing gases. The membranes are multi-layer having a central hydrogen-permeable layer with one or more catalyst layers, barrier layers, and/or protective layers. Membranes could be used in reactors for separation of hydrogen from a hydrogen-containing gas. These reactors could be combined with additional reactor systems for direct use of the separated hydrogen.	Still being used in ongoing research.
6,989,252	01/24/06	National Renewable Energy Laboratory	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.	Research complete; seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
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.	No longer being pursued.
6,967,063	11/22/05	Argonne National Laboratory	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.
6,899,744	05/31/05	Eltron Research & Development, Inc.	Hydrogen transport membranes	Composite hydrogen transport membranes used for extraction of hydrogen from gas mixtures. Support materials are chosen to be lattice matched to the metals and metal alloys with high permeability for hydrogen such as vanadium, niobium, tantalum, zirconium, palladium, and alloys thereof.	Still being used in ongoing research.
6,887,728	05/03/05	University 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.	No longer being used.
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	Pacific Northwest National Laboratory	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. Being developed for distillation uses.

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Patent Number	Award Date	Organization	Title	Description	Status
6,872,378	03/29/05	National Renewable Energy Laboratory	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	Pacific Northwest National Laboratory	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.
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. 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	Argonne National Laboratory	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	National Renewable Energy Laboratory	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	Sandia National Laboratory	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 and no research being done at SNL.
6,713,040	03/30/04	Argonne National Laboratory	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.

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Patent Number	Award Date	Organization	Title	Description	Status
6,666,909	12/23/03	Pacific Northwest National Laboratory	Microsystem capillary separations	Laminated, multiphase separators and contactors having wicking structures and gas flow channels. Some preferred embodiments are combined with microchannel heat exchange.	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.	No longer being used in research/no longer being pursued.
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.
6,582,666	06/24/03	University of Central Florida	Apparatus for high flux photocatalytic pollution control using a rotating fluidized bed reactor	An apparatus based on optimizing photoprocess energetics by decoupling of the process energy efficiency from the DRE for target contaminants. The technique is applicable to both low- and high-flux photoreactor design and scale-up. An apparatus for high-flux photocatalytic pollution control is based on the implementation of multifunctional metal oxide aerogels and other media in conjunction with a novel rotating fluidized particle bed reactor.	Research complete; seeking to license.
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 photo-catalytic 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.
6,524,550	02/25/03	Nuvera Fuel Cells, Inc.	Process for converting carbon monoxide and water in a reformate stream	A process for converting carbon monoxide and water in a reformate stream into carbon dioxide and hydrogen.	No longer being used in research/no longer being pursued.
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.	No longer being pursued.

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Patent Number	Award Date	Organization	Title	Description	Status
6,478,077	11/12/02	Sandia National Laboratory	Self supporting heat transfer element	An improved internal heat exchange element arranged so as to traverse the inside diameter of a container vessel such that it makes good mechanical contact with the interior wall of that vessel.	Not licensed and no research being done at SNL.
6,468,499	10/22/02	Argonne National Laboratory	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.	No longer being used in research/no longer being pursued.
6,448,068	09/10/02	National Renewable Energy Laboratory	System for rapid biohydrogen phenotypic screening of microorganisms using a chemochromic sensor	A system for identifying a hydrogen gas producing organism.	Research complete; seeking to license.
6,395,252	05/28/02	Oak Ridge National Laboratory	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.
6,342,128	01/29/02	University of Central Florida	Apparatus and Method for Decoupled Thermo-Photocatalytic Pollution Control	Method for design and scale-up of photocatalytic and thermocatalytic processes based on optimizing photoprocess energetics by decoupling of the process energy efficiency from the DRE for target contaminants.	Not licensed and no research being done at University of Central Florida.
6,334,936	01/01/02	University of Central Florida	Apparatus for decoupled thermo-photocatalytic pollution control	Method for design and scale-up of thermocatalytic processes based on optimizing process energetics by decoupling of the process energetics from the DRE for target contaminants.	Not licensed and no research being done at University of Central Florida.
6,315,870	11/13/01	University of Central Florida	Method for High Flux Photocatalytic Pollution Control	A new method for design and scale-up of photocatalytic and thermocatalytic processes is disclosed. The method is based on optimizing photoprocess energetics by decoupling of the process energy efficiency from the DRE for target contaminants.	Not licensed and no research being done at University of Central Florida.

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Patent Number	Award Date	Organization	Title	Description	Status
6,309,611	10/30/01	University of Central Florida	Apparatus for Low Flux Photocatalytic Pollution Control	A new apparatus for design and scale-up of photocatalytic and thermocatalytic processes is disclosed. The apparatus is based on optimizing photoprocess energetics by decoupling of the process energy efficiency from the DRE for target contaminants and is applicable to both low- and high-flux photoreactor design and scale-up.	Not licensed and no research being done at University of Central Florida.
6,303,098	10/16/01	Argonne National Laboratory	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.	No longer being pursued.
6,277,589	08/21/01	National Renewable Energy Laboratory	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.	Research complete; seeking to license.
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.	No longer being used by Nuvera in research.
6,248,218	06/19/01	University of Central Florida	Closed cycle photocatalytic process for decomposition of hydrogen sulfide to its constituent elements	A method and system for separating hydrogen and sulfur from hydrogen sulfide gas being produced from oil and gas waste streams. The hydrogen sulfide gas is first scrubbed and filtered into a polysulfide solution. Elemental sulfur is freed when the hydrogen sulfide interacts with the solution, the sulfur is filtered through a porous media such as a ceramic frit, and continues to a stripper unit where the excess H_2S is removed from the sulfide solution. The excess H_2S returns to the scrubber and filtration unit, while the sulfide solution passes into a photoreactor containing a semiconductor photocatalyst.	Research complete; seeking to license.

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Patent Number	Award Date	Organization	Title	Description	Status
6,244,367	06/12/01	Argonne National Laboratory	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	General Motors Corporation	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.	No longer being used by Nuvera in research.
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.	No longer being used by Nuvera in research.
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.	No longer being used by Nuvera in research.
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.	No longer being pursued.

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Patent Number	Award Date	Organization	Title	Description	Status
6,110,861	08/29/00	Argonne National Laboratory	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.	No longer being used by Nuvera in research.
6,051,125	04/18/00	Lawrence Livermore National Laboratory	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	Argonne National Laboratory	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	Argonne National Laboratory	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	Argonne National Laboratory	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	Sandia National Laboratory	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.
5,871,952	02/16/99	National Renewable Energy Laboratory	Process for selection of oxygen-tolerant algal mutants that produce H2 under aerobic conditions	A process for selecting oxygen-tolerant algal mutants that produce hydrogen under aerobic conditions, based on the toxic effect of metronidazole on photosynthetic organisms.	Being used in continuing research and seeking to license.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
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.
5,541,486	05/07/96	Los Alamos National Laboratory	Annular feed air breathing fuel cell stack	A stack of polymer electrolyte fuel cells is formed from a plurality of unit cells where each unit cell includes fuel cell components stacked along a common axis. Each fuel cell component has a polymer electrolyte membrane, anode, cathode as well as provision for fuel and oxygen flow fields. A fuel distribution manifold is connected to deliver fuel to the fuel flow field in each of the unit cells.	Not licensed and not being used for research at LANL.
5,451,920	09/19/95	Oak Ridge National Laboratory	Thick film hydrogen sensor	A thick film hydrogen sensor element includes an essentially inert, electrically-insulating substrate having deposited thereon a thick film metallization forming at least two resistors. The metallization is a sintered composition of Pd and a sinterable binder such as glass frit. An essentially inert, electrically insulating, hydrogen impermeable passivation layer covers at least one of the resistors.	Licensed to DCH Technology, Inc.
5,367,283	11/22/94	Oak Ridge National Laboratory	Thin film hydrogen sensor	A hydrogen sensor comprised of an inert, electrically-insulating substrate having a thin-film metallization layer deposited to form at least two resistors on the substrate. The metallization comprises a layer of Pd or a Pd alloy for sensing hydrogen and an underlying intermediate metal layer for providing enhanced adhesion of the metallization to the substrate. An inert, electrically insulating, hydrogen impermeable passivation layer covers at least one of the resistors, and at least one of the resistors is left uncovered. The difference in electrical resistances between the covered and uncovered resistors determines the hydrogen concentration in the gas the sensor is exposed to.	No longer being used.
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.

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Patent Number	Award Date	Organization	Title	Description	Status
4,358,429	11/09/82	Argonne National Laboratory	Oxygen stabilized zirconium vanadium intermetallic compound	A new oxygen stabilized intermetallic compound that can repeatedly sorb hydrogen from a mixture of gases.	No licensee and no further development of this technology at ANL.
4,142,300	03/06/79	Argonne National Laboratory	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.

B.3 Storage Patents Status

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,365,685	06/14/16	Oak Ridge National Laboratory	Method of improving adhesion of carbon fibers with a polymeric matrix	A functionalized carbon fiber having covalently bound on its surface a partially cured epoxy or amine-containing sizing agent. Composites comprised of these functionalized carbon fibers embedded in a polymeric matrix are also described and used for producing the functionalized carbon fibers and composites.	Still being used in ongoing research.
9,340,677	05/17/16	Oak Ridge National Laboratory	Apparatus and process for the surface treatment of carbon fibers	A method for surface treating a carbon-containing material in which carbon-containing material is reacted with decomposing ozone in a reactor (e.g., a hollow tube reactor), wherein a concentration of ozone is maintained throughout the reactor by appropriate selection of processing temperature, gas stream flow rate, reactor dimensions, ozone concentration entering the reactor to produce a surface-oxidized carbon or carbon-containing material. The resulting surface- oxidized carbon material and solid composites made therefrom are also described.	Still being used in ongoing research.
9,321,638	04/26/16	Savannah River National Laboratory	Use of triphenyl phosphate as risk mitigant for metal amide hydrogen storage materials	A process in a resulting product of the process in which a hydrogen storage metal amide is modified by a ball milling process using an additive of TPP. The resulting product provides for a hydrogen storage metal amide having a coating that renders the hydrogen storage metal amide resistant to air, ambient moisture, and liquid water while improving useful hydrogen storage and release kinetics.	Still being used in ongoing research; seeking to license.
9,234,626	01/12/16	Pacific Northwest National Laboratory	Conformable pressure vessel for high pressure gas storage	A non-cylindrical pressure vessel storage tank and internal structure is described. The internal structure is coupled to at least one wall of the storage tank which internally supports the storage tank. The pressure vessel storage tank has a conformability of about 0.8 to about 1.0. The internal structure can be, but is not limited to, a Schwarz-P structure, an egg-crate shaped structure, or carbon fiber ligament structure.	Still being used in ongoing research.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
9,057,483	06/16/15	Lawrence Livermore National Laboratory	Threaded insert for compact cryogenic-capable pressure vessels	An insert for a cryogenic capable pressure vessel for storage of hydrogen or other cryogenic gases at high pressure. The insert provides the interface between a tank and internal and external components of the tank system. The insert can be used with tanks with any or all combinations of cryogenic, high pressure, and highly diffusive fluids. The insert can be threaded into the neck of a tank with an inner liner. The threads withstand the majority of the stress when the fluid inside the tank that is under pressure.	Still being used in ongoing research.
9,006,137	04/14/15	Ford Motor Company	Adsorbent material with anisotropic layering	A compressed gaseous fuel storage pellet is provided comprising a gas adsorbent material and a thermally conductive material extending substantially an entire dimension of the pellet and having a thermal conductivity of at least 75 W/mK. The pellet may include at least two layers of gas adsorbent material spaced apart along a compression direction of the pellet and a continuous layer of the thermally conductive material disposed between at least two layers of gas adsorbent material. The pellet may further include thermally conductive projections which intersect the layer(s) of thermally conductive material.	Being used in ongoing research.
8,945,500	02/03/15	Savannah River National Laboratory	High capacity hydrogen storage nanocomposite materials	A novel hydrogen absorption material is provided comprising a mixture of a lithium hydride with a fullerene. The subsequent reaction product provides for a hydrogen storage material which reversibly stores and releases hydrogen at temperatures of about 270°C.	Still being used in ongoing research.
8,921,554	12/30/14	University of Oregon	Substituted 1,2-azaborine heterocycles	Aromatic heterocycles incorporating boron and nitrogen atoms, in particular, 1,2-azaborine compounds and their use as synthetic intermediates.	Still being used in ongoing research.
8,889,097	11/18/14	Pacific Northwest National Laboratory	Combined on-board hydride slurry storage and reactor system and process for hydrogen-powered vehicles and devices	An integrated storage and reactor system and process for storing and reacting variable concentration slurries containing hydride storage materials that release hydrogen on-board vehicles and devices.	Being used in continuing research at PNNL and seeking to license.
8,883,109	11/11/14	Savannah River National Laboratory	High capacity stabilized complex hydrides for hydrogen storage	Complex hydrides based on Al(BH4)3 are stabilized by the presence of one or more additional metal elements or organic adducts to provide high capacity hydrogen storage material.	Still being used in ongoing research.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,758,715	06/24/14	Savannah River National Laboratory	Porous wall hollow glass microspheres as a medium or substrate for storage and formation of novel materials	A porous wall hollow glass microsphere in which the pore walls and interior walls of the microsphere provide at least one of a patterned surface, an improved substrate, or a nucleating site for the formation of a nanomaterial which may include a hydrogen storage material.	Research complete; seeking to license.
8,517,206	08/27/13	Quantum Fuel Systems Technologies Worldwide, Inc.	High pressure storage vessel	Composite pressure vessel with a liner, polar boss and a blind boss. A shell is formed around the liner via one or more filament wrappings continuously disposed around the liner assembly.	Still being used in ongoing research. Part of commercial storage technology.
8,470,156	08/07/12	Savannah River National Laboratory	Electrochemical process and production of novel complex hydrides	A process for producing aluminum hydride, which can be used as a source of hydrogen for vehicles or fuel cell devices.	Still being used in ongoing research.
8,440,100	05/14/13	University of South Florida	Method of generating hydrogen-storing hydride complexes	A method for preparing complex hydride materials composed of lightweight elements or compounds for hydrogen storage applications.	Research complete; seeking to license.
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 spillover of the hydrogen to the receptor.	Research complete; seeking to license.
8,410,185	04/02/13	Argonne National Laboratory	Porous polymeric materials for hydrogen storage	A hydrogen storage medium that consists of a porous polymer tribeenzohexazatriphenylene (TBHTP) and its derivatives as created through the polymer synthesis method. These polymers have a high specific area, narrow micropore distribution, and are thermally stable up to 250°C.	Still being used in ongoing research.
8,377,555	02/19/13	Savannah River National Laboratory	Gas storage materials, including hydrogen storage materials	A material for the storage and release of gases that comprises a plurality of hollow elements, each hollow element comprising a porous wall enclosing an interior cavity, the interior cavity including structures of a solid-state storage material.	Research complete; seeking to license.
8,377,416	02/19/13	Purdue University	Method for releasing hydrogen from ammonia borane.	A method of releasing hydrogen from ammonia borane that consists of heating a pressurized aqueous ammonia borane solution to release hydrogen by hydrothermolysis.	Research complete; seeking to license.
8,377,415	02/19/13	Savannah River National Laboratory	Methods for synthesizing alane without the formation of adducts and free of halides	Processes and methods for synthesizing aluminum hydride and other hydrogen storage materials to be used in the development of onboard hydrogen-fueled vehicles.	Still being used in ongoing research.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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	Los Alamos National Laboratory	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.
8,268,288	09/18/12	Brookhaven National Laboratory	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.	No longer being used in research/ no longer being pursued.
8,236,196	08/07/12	Savannah River National Laboratory	Systems and methods for facilitating hydrogen storage using naturally occurring nanostructure assemblies	Recyclable canisters containing microorganisms called diatoms, which contain naturally occurring nanostructure assemblies. These nanostructure assemblies can be used to store hydrogen until it is ultimately used as a fuel for vehicles or other applications.	Exclusive License to Microbes Unlimited LLC
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^oC. 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; 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; seeking to license.
8,147,796	04/03/12	University of Utah	Hydrogen storage in a combined $M_xAlH_6/M'_y(NH_2)_z$ 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	Sandia National Laboratory	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.
8,124,559	02/28/12	Savannah River National Laboratory	Destabilized and catalyzed borohydride for reversible hydrogen storage	A process for forming a hydrogen storage material from a first material (a metal containing borohydride) and a second material (a metal alanate). The resulting material has a lower hydrogen release temperature than the first material and a higher hydrogen gravimetric density than the second material.	Research complete; seeking to license.
8,119,198	02/21/12	University of Central Florida	Three-dimensional carbon fibers and method and apparatus for their production	This invention relates to three-dimensional (3D) carbon fibers which are original (or primary) carbon fibers (OCF) with secondary carbon filaments (SCF) grown thereon, and, if desired, tertiary carbon filaments (TCF) are grown from the surface of SCF forming a filamentous carbon network with high surface area. The methods and apparatus are provided.	Research complete; seeking to license.
8,105,974	01/31/12	Savannah River National Laboratory	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	Los Alamos National Laboratory	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.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
8,083,907	12/27/11	University of South Florida	Hydrogen storage nano-foil and method of manufacture	A hydrogen storage system using a coiled nano- foil hydride and methods for forming the hydrogen absorbing nano-foil coil without backing materials.	Research complete; seeking to license.
8,076,382	12/13/11	Argonne National Laboratory	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.
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.
7,963,116	06/21/11	Pacific Northwest National Laboratory	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; seeking to license.
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	Pacific Northwest National Laboratory	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	Los Alamos National Laboratory	Regeneration of polyborazylene	The invention provides methods for regenerating ammonia borane, a hydrogen storage material, from polyborazylene.	Being used in continuing research at LANL.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,837,852	11/23/10	Los Alamos National Laboratory	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.
7,816,004	10/19/10	University of Central Florida	Three-dimensional carbon fibers and method and apparatus for their production	A novel three-dimensional (3D) carbon fiber which are original (or primary) carbon fibers (OCF) with secondary carbon filaments (SCF) grown thereon, and, if desired, tertiary carbon filaments (TCF) are grown from the surface of SCF forming a filamentous carbon network with high surface area. The methods and apparatus are provided for growing SCF on the OCF by thermal decomposition of carbonaceous gases (CG) over the hot surface of the OCF without use of metal-based catalysts. The thickness and length of SCF can be controlled by varying operational conditions of the process. An optional activation step enables one to produce 3D activated carbon fibers with high surface area. The TCF growth on SCF is by thermal decomposition of carbonaceous gases over the hot surface of the SCF using metal catalyst particles.	Research complete; seeking to license.
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.
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	Sandia National Laboratory	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.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
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	Los Alamos National Laboratory	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	Los Alamos National Laboratory	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	Universal Oil Products, LLC (UOP, LLC)	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.
7,666,807	02/23/10	Savannah River National Laboratory	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	Los Alamos National Laboratory	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.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,608,233	10/27/09	Sandia National Laboratory	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	Los Alamos National Laboratory	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	Brookhaven National Laboratory	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.	No longer being used in research/ no longer being pursued.
7,402,234	07/22/08	Idaho National Laboratory	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	Savannah River National Laboratory	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	Sandia National Laboratory	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	Lawrence Livermore National Laboratory	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.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
7,250,386	07/31/07	Energy Conversion Devices, Inc.	Quantum limit catalysts and hydrogen storage materials	A quantum limit catalyst comprised of atomic aggregations whose dimensions correspond to the quantum limit. The electronic interactions possible in the quantum limit results in modifications to the electron density at catalytic sites that improve the catalytic properties.	No licenses issued and no internal research being done with this patent.
7,191,602	03/20/07	Lawrence Livermore National Laboratory	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.
7,160,530	01/09/07	National Renewable Energy Laboratory	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	Savannah River National Laboratory	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 storage technology.
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 in research/ no longer being pursued.
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	Sandia National Laboratory	Direct synthesis of catalyzed hydride compounds	Method of producing complex hydride compounds comprising mechanically milling powders of a simple alkali metal hydride material with a metal and a titanium catalyst compound followed by high pressure hydrogenation.	Being used in research at SNL but no licensees.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
6,787,229	09/07/04	University of Central Florida	Three-dimensional carbon fibers and method and apparatus for their production	A novel three-dimensional (3D) carbon fiber which are original (or primary) carbon fibers (OCF) with secondary carbon filaments (SCF) grown thereon, and, if desired, tertiary carbon filaments (TCF) are grown from the surface of SCF forming a filamentous carbon network with high surface area. The methods and apparatus are provided for growing SCF on the OCF by thermal decomposition of carbonaceous gases (CG) over the hot surface of the OCF without use of metal-based catalysts. The thickness and length of SCF can be controlled by varying operational conditions of the process. An optional activation step enables one to produce 3D activated carbon fibers with high surface area. The TCF growth on SCF is by thermal decomposition of carbonaceous gases over the hot surface of the SCF using metal catalyst particles.	Research complete; seeking to license.
6,787,007	09/07/04	Idaho National Laboratory	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	Sandia National Laboratory	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	Lawrence Livermore National Laboratory	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.
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.
6,528,441	03/04/03	Savannah River National Laboratory	Hydrogen storage composition and method	A hydrogen storage material based on a metal hydride dispersed in an aerogel prepared by a sol-gel process.	No longer being used in research/ no longer being pursued.
6,471,935	10/29/02	University 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.	Being used in ongoing research.
6,418,962	07/16/02	Johns 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	Savannah River National Laboratory	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	Lawrence Livermore National Laboratory	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.

Storage Patents Status

Patent Number	Award Date	Organization	Title	Description	Status
5,965,482	10/12/99	Savannah River National Laboratory	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.
5,798,156	08/25/98	Lawrence Livermore National Laboratory	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	Savannah River National Laboratory	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	Savannah River National Laboratory	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 storage technology.
5,198,207	03/30/93	Safe Hydrogen, LLC	Method for the preparation of active magnesium hydride-magnesium hydrogen storage systems, which reversibly absorb hydrogen	Method for the preparation of active magnesium hydride-magnesium-hydrogen storage systems, which reversibly absorb hydrogen and addition of a catalyst for the absorption of hydrogen with the formation of hydride.	No longer being used in research/ no longer being pursued.

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Appendix C: R&D Technology Innovation Descriptions

C.1 Fuel Cell Innovations

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.

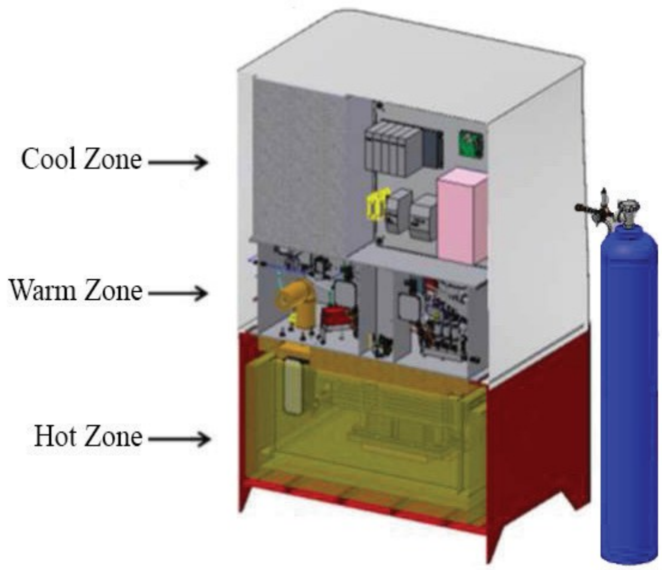
TDA have also developed, demonstrated and commercialized a sorbent, SulfaTrap™, that can remove both hydrogen sulfide and organic sulfur species from biogas, reducing their concentration < 10 parts per billion. The sorbent enables the production of a nearly sulfur-free biogas to replace natural gas in 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 2 kW 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



1.0 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

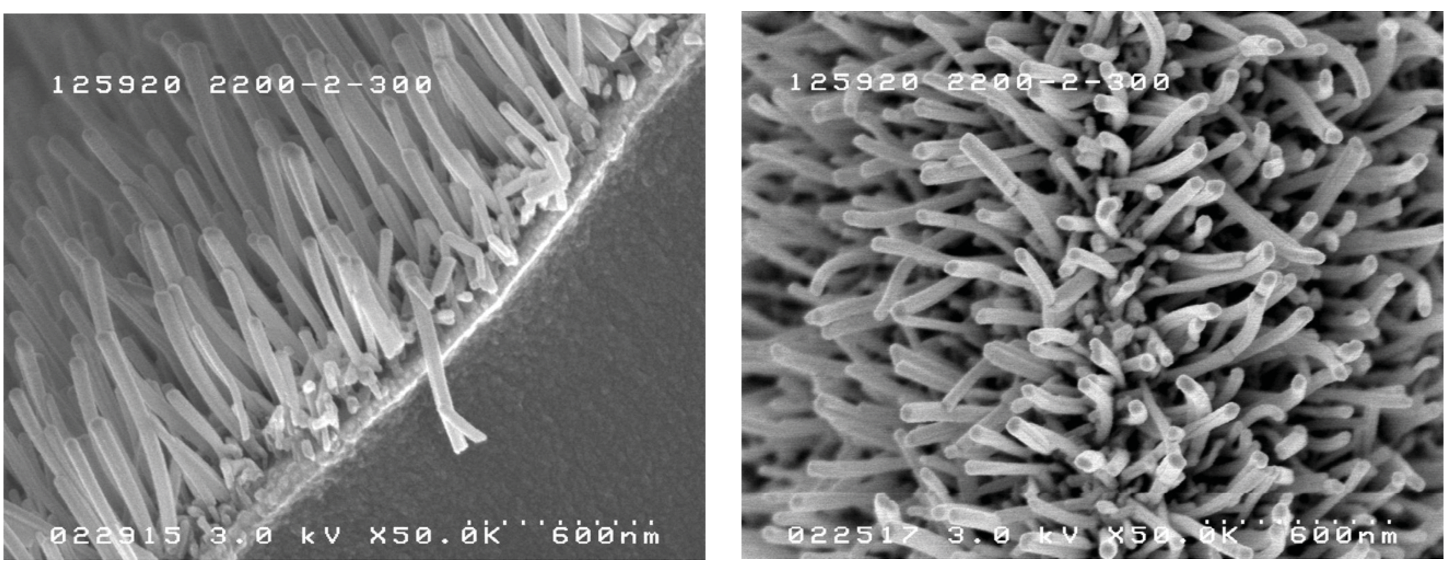
Cathode Catalysts and Supports for PEM Fuel Cells

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

Commercial Technology

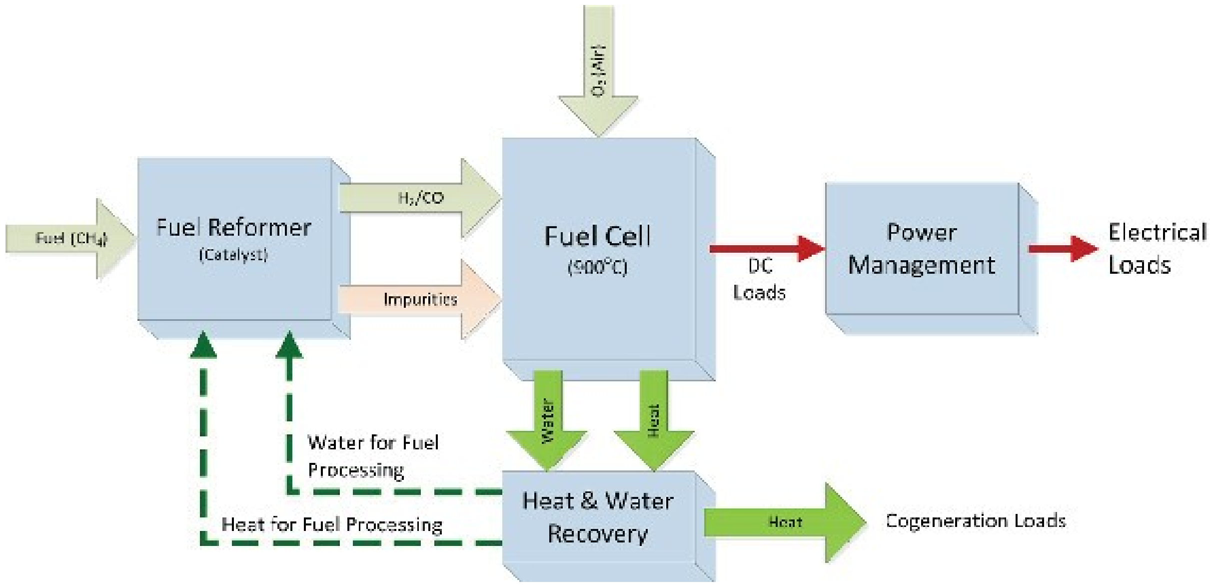
Technology Management, Inc. (TMI), with funding from FCTO through the Edison Materials Technology Center, developed an integrated reformer/solid oxide fuel cell (SOFC) system that operates on many fuels.

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.
- Continuing discussions with prospective licensees and partners in different markets.

TMI's AnywherEnergy© System Using Multi-Fuel SOFC Technology



Key Components of TMI's AnywherEnergy© System

Applications

Clean, quiet, continuous power in locations with no or unreliable power grids.

Capabilities

- Provides clean, continuous 24/7 power from untreated fuel(s).[1]
- Achieves clean exhaust and quiet operation for safe indoor siting.[1]
- Operates interchangeably (without shutdown) 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.
- Compact size allows plug and play field maintenance by end users.

Benefits

Cost Savings

Offers a simple cell stack 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

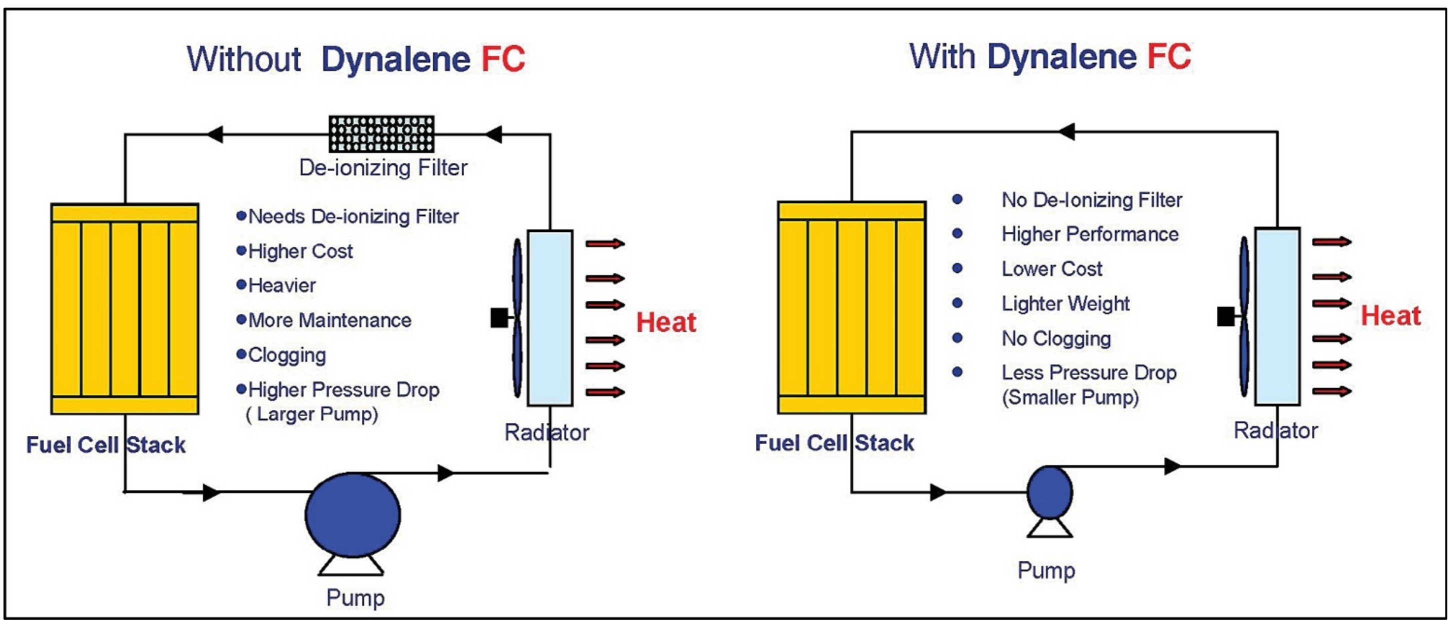
Complex Coolant for Polymer Electrolyte Membrane (PEM) Fuel Cells

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.

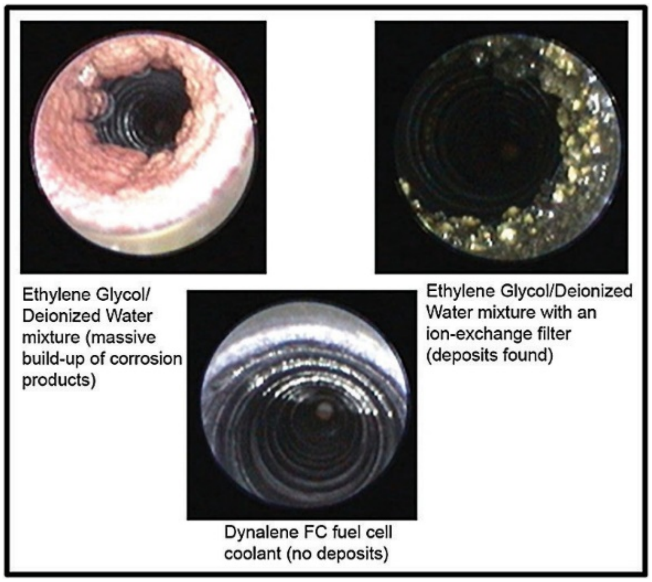
Technology History

- 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

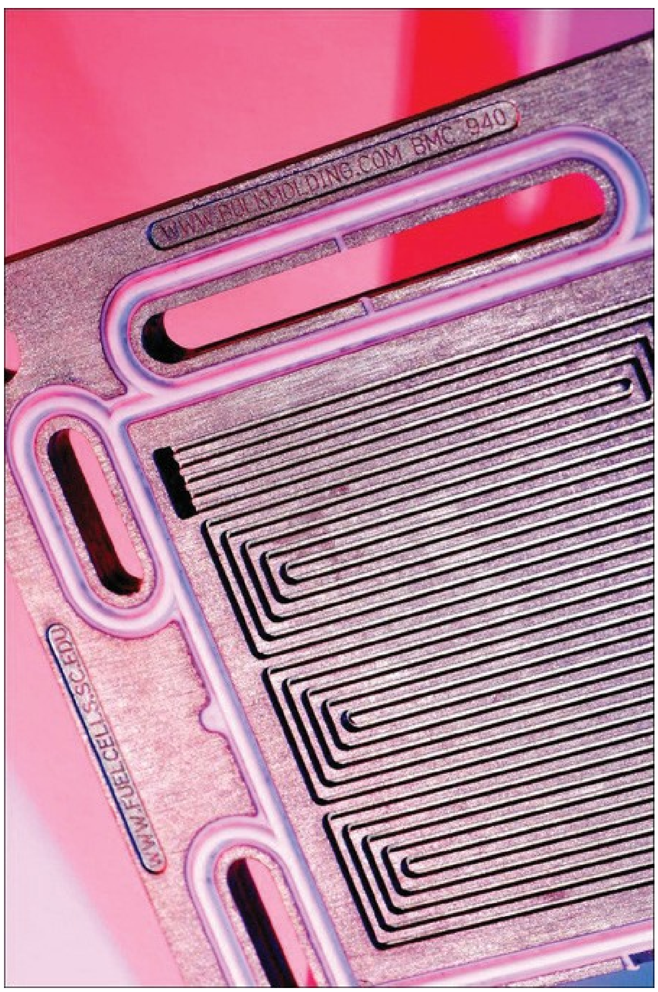
Commercial Technology

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.

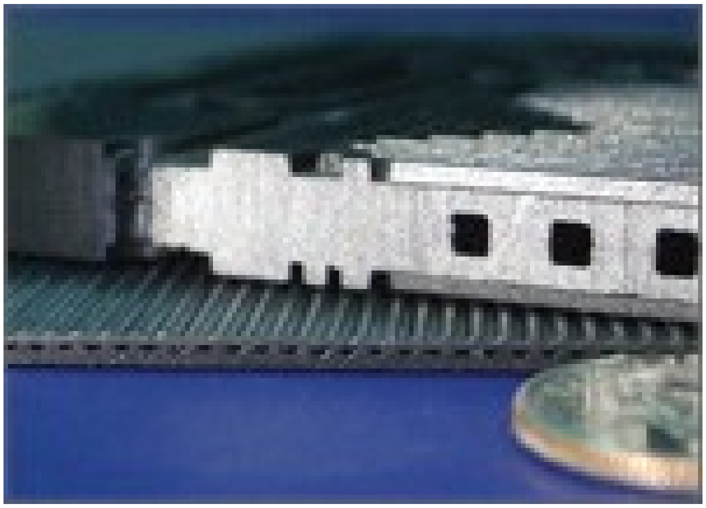
BMC 955, the latest addition to BMCI's fuel cell related product line, provides durability in the corrosive, high temperature environment of high temperature PEM applications. Based upon a phenolic resin system, it looks and processes much like BMCI's low temperature line of fuel cell products.

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., 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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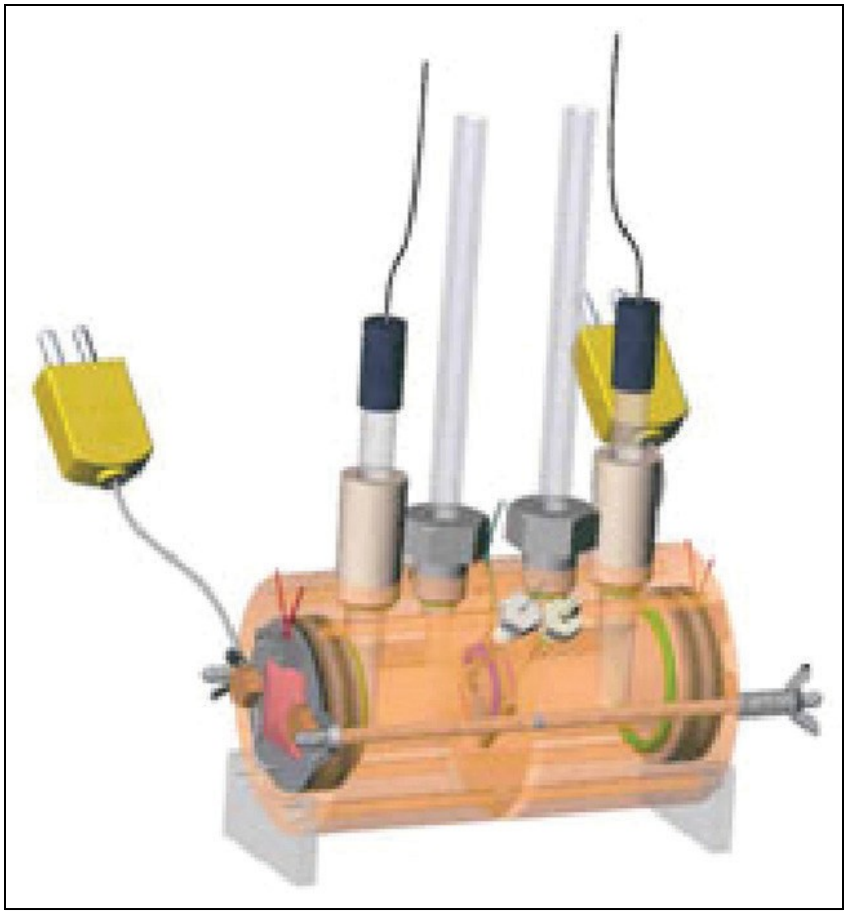
[1] For more information: http://engineeredcomposites.aschulman.com/products
[2] For more information: http://www.google.com/patents/US6248467
[3] For more information: http://cdn2.hubspot.net/hubfs/2015678/Documents/PDFs/BMC/BMC_940-8649.pdf?t=1474381217689

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.



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

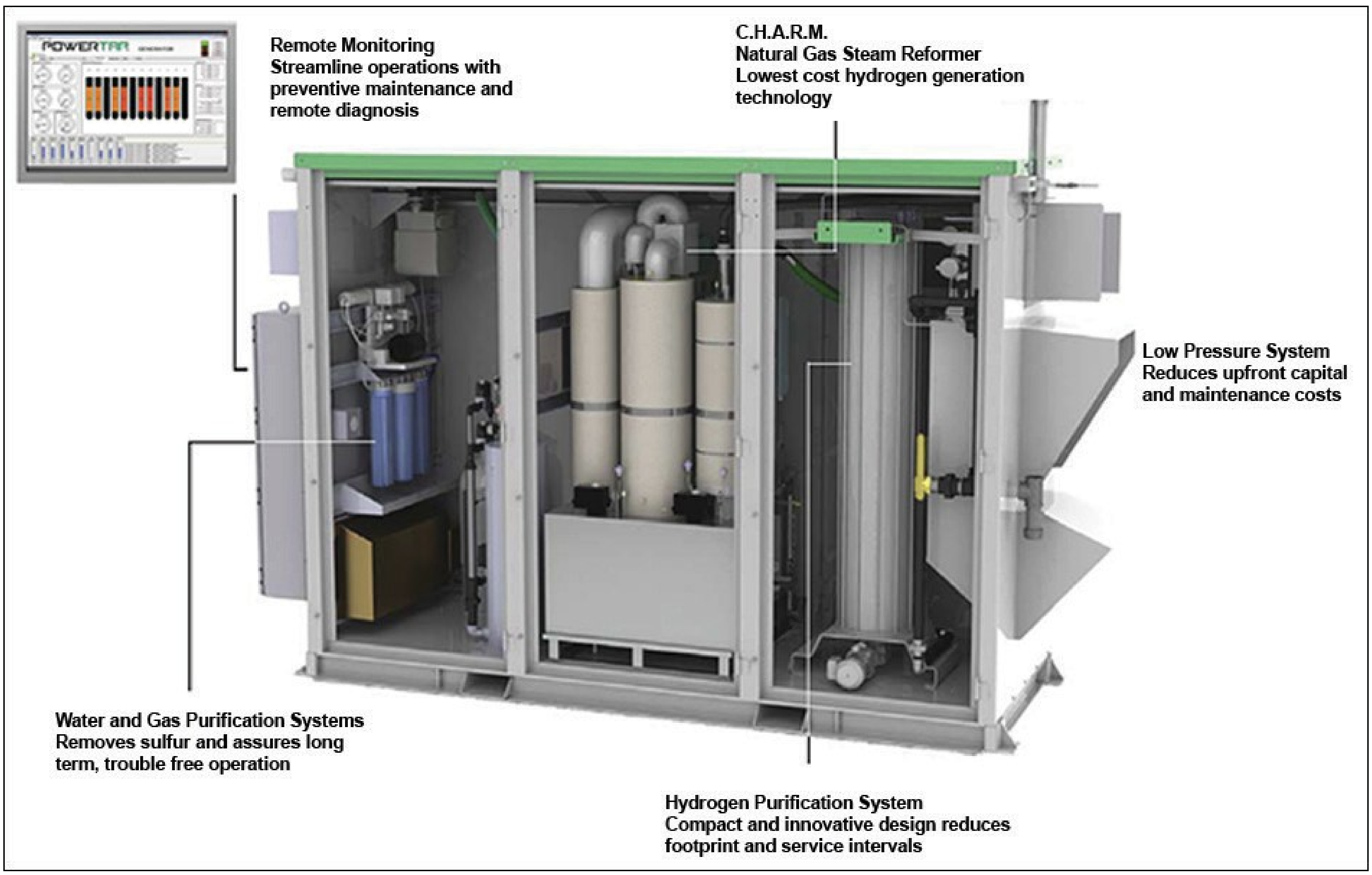
Cost-Effective, High-Efficiency, Advanced Reforming Module (CHARM)

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.



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

PowerTap 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).

Capabilities

- Generates pure (99.995% +) hydrogen at rates of up to 50 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

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.[2]

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.hydrogen.energy.gov/pdfs/htac_may2012_nuvera.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review11/h2ra008_block_2011_o.pdf

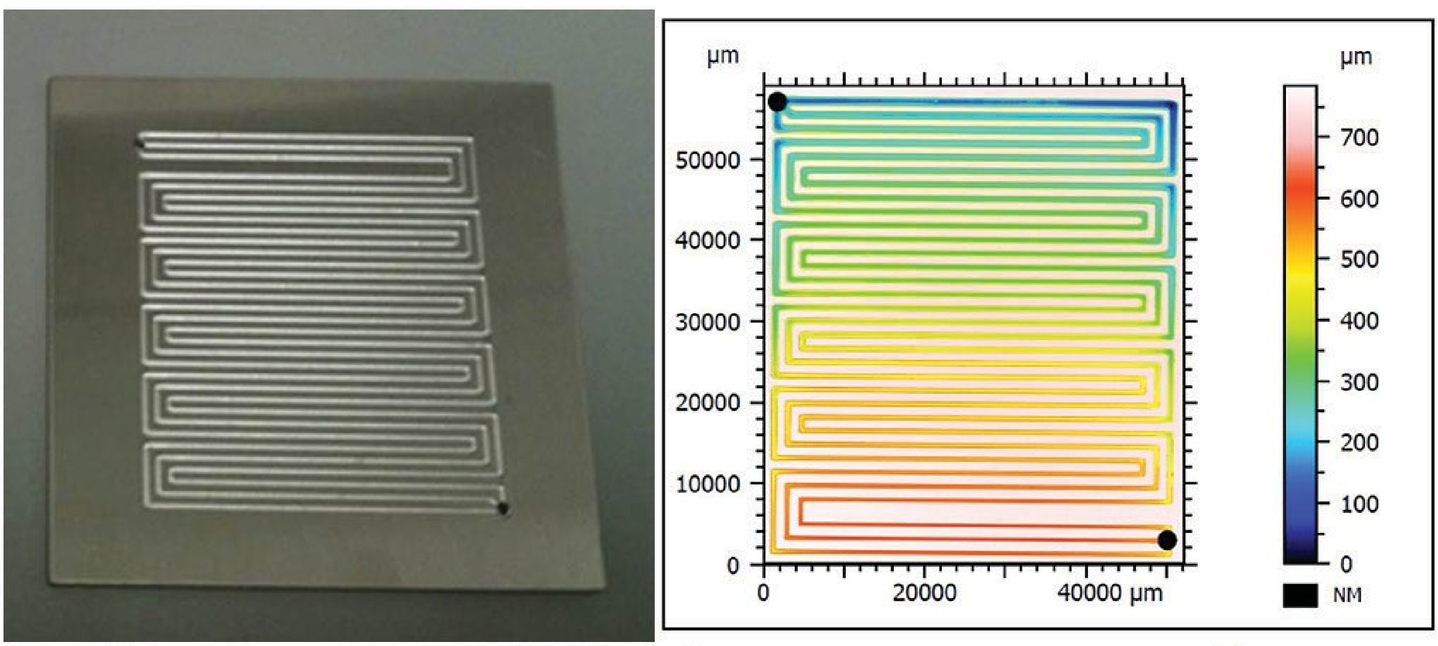
FARADAYIC® ElectroEtching of Stainless Steel Bipolar Plates

Commercial Technology

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 electro etching 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 Bipolar Plate with Gas Flow Fields Formed Using the FARADAYIC® ElectroEtching Process (left)
Non-Contact Optical Profilometer Map Illustrating the Decreasing Depth of the Flow Field Channels (right)

FARADAYIC®ElectroCell Etching Process Technology 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.
- Enables inexpensive manufacturing of both simple and complicated flow field designs.

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.
Versatility
Capable of forming complex shaped flow fields in a variety of metals and alloys.

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Fuel Cell Turbocompressor

Commercial Technology

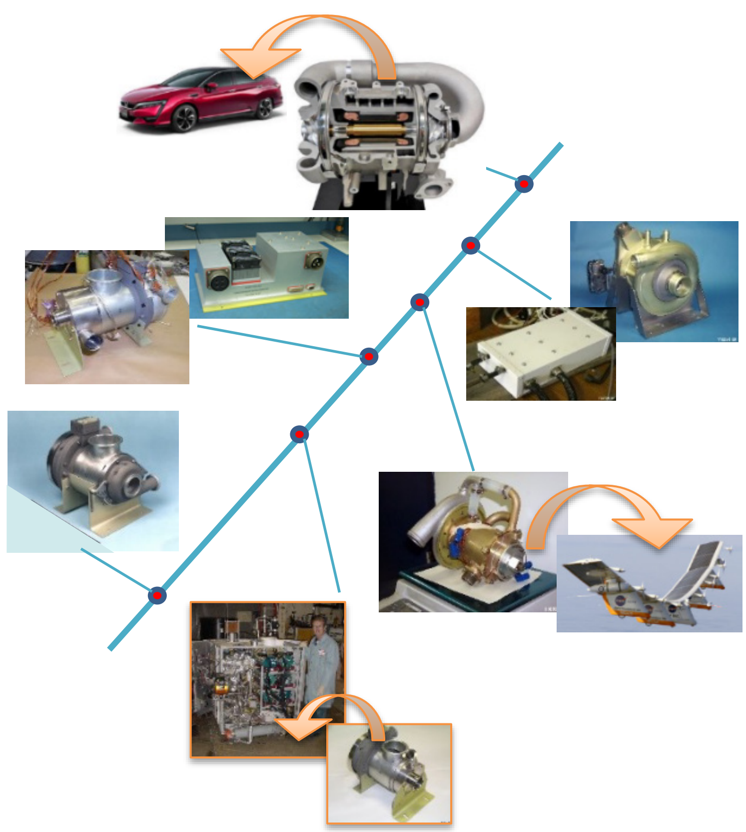
PEM (Proton Exchange Membrane) fuel cells are excellent candidates for transportation applications due to their high efficiencies. PEM fuel cell Balance of Plant (BOP) components, such as the air management sub-system, can have a significant effect on the overall system performance, but have traditionally not been addressed in research and development efforts. Recognizing this, the U.S. Department of Energy and Honeywell International Inc. funded the fuel cell turbocompressor efforts that emphasize the integration and optimization of such air management sub-systems. This effort is one of the major elements to assist the fuel cell system developers and original equipment manufacturers to achieve the goal of an affordable and efficient power system in a lightweight and compact package for transportation applications.

The efforts included analysis, design, fabrication, assembly and testing of various motor driven turbocompressor designs. A turbocompressor is a turbine assisted motor driven compressor, with the turbine powered by the fuel cell exhaust to minimize the system air management power. The designs were used for various component and PEM fuel cell system applications as shown in the figures below.

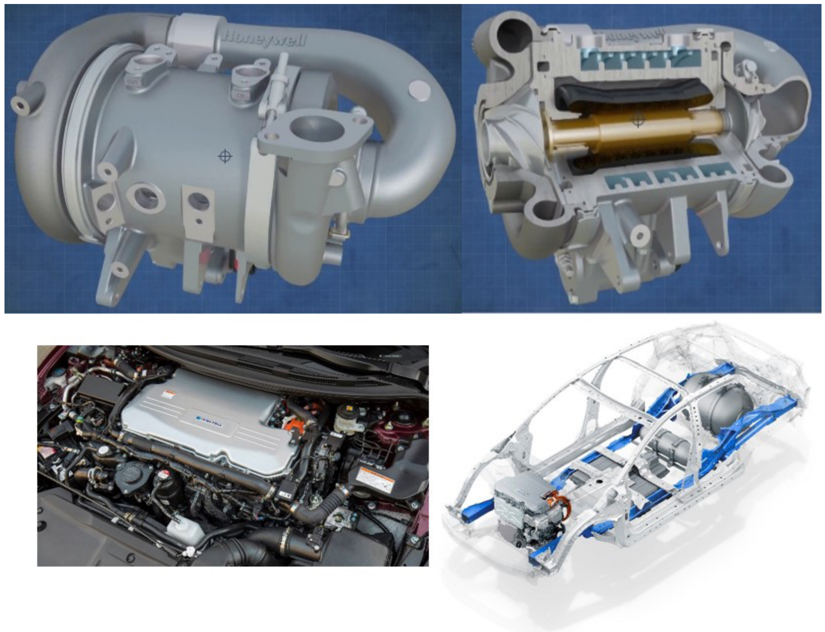
Honeywell's development of motor driven turbocompressors for fuel cell systems began in 1995. This pioneering work led to the development of multiple technologies including those for high speed and power motor and motor controllers, wide flow compressor and variable geometry turbines, in addition to further development to improve cost and performance. Honeywell is now working with the transportation and industrial sectors to develop applications of their fuel cell turbocompressors. In 2016, a major auto manufacturer released a Honeywell fuel cell turbocompressor equipped vehicle into the marketplace.

Technology History

- Developed by Honeywell.
- Commercialized in 2016.



Timeline of Honeywell's Turbocompressor Development for Automotive Applications 1995 – 2016



Honeywell's Fuel Cell Turbocompressor for Transportation Applications

Applications

- Fuel cell air pressurization (PEM, SOFC, etc.) for both transportation and industrial applications

Capabilities

- Provides contamination free, pressurized airflow to the fuel cell stack and recover fuel cell stack exhaust flow to minimize the turbocompressor parasitic power and reduce the fuel cell stack weight and volume.
- Provides variable geometry turbine for maximizing efficiency.
- Achieves reduced mechanical losses.
- Achieves zero maintenance, low noise operation using internally cooled foil air bearings to eliminate fuel cell poisoning with contaminants.

Benefits

Cost Savings

Provides cost savings using both automotive and aerospace methods and technologies while continuing to enable a lightweight, compact, efficient and reliable unit.

Flexibility

Modular design and mounting orientation flexibility allows ease of integration for multiple end user applications.

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GCtool: Fuel Cell Systems Analysis Software Model

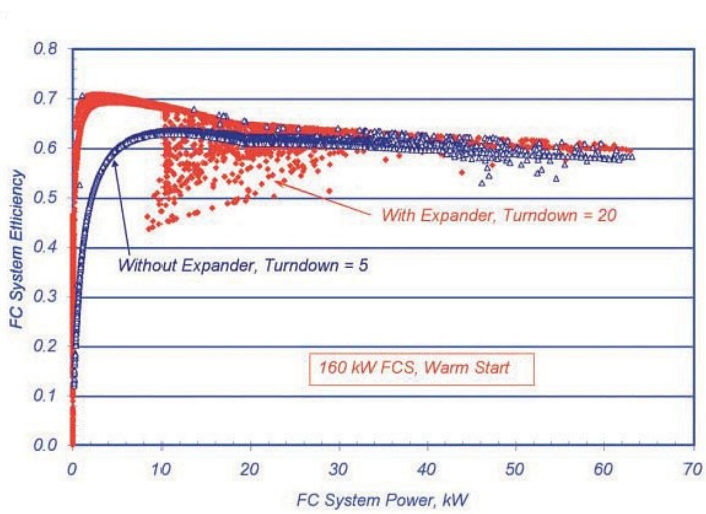
Commercial Technology

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.

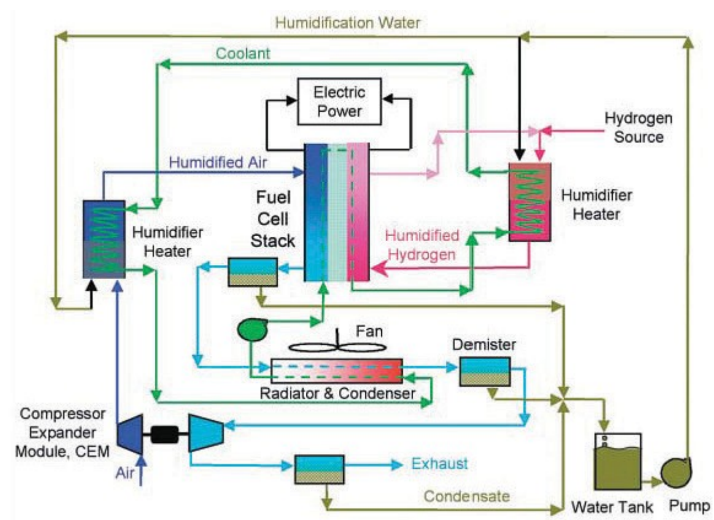
The GCtool can also be used to analyze a variety of automotive hydrogen storage options, some of which have an off- board regeneration component. GCtool can help determine the hydrogen storage system's gravimetric and volumetric capacities, hydrogen charge and discharge rates, and both on-board and off-board 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

Commercial Technology

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 4,500 units and 20 million operating hours logged.
- Plug Power Inc. completed the acquisition of Hy-pulsion, a joint venture in Europe.


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/products/gendrive/

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 1.5 - 14 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/products/gendrive/

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]

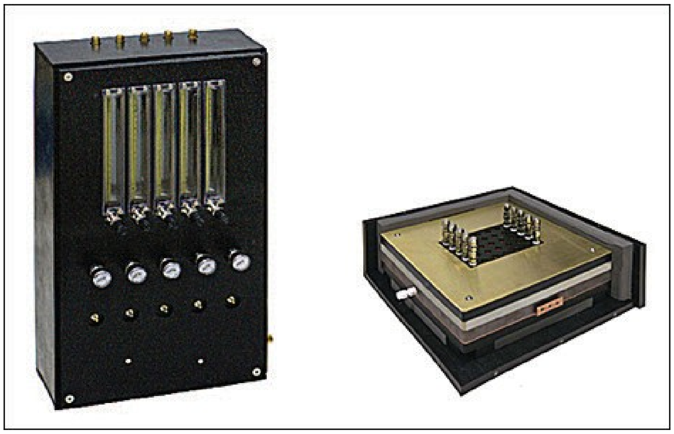
The system also comes with user friendly Arrayware software, which can control the Arraystat, up to 12 temperature controllers, and up to 6 mass flow controllers. The software allows users to write and execute sequences of variables to be analyzed. In addition to the system components and software, NuVant 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 photo-electrochemical 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.

Versatility

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/

Low-Cost 3-10 kW Tubular SOFC Power System

Commercial Technology

With funding from FCTO, Atrex Energy, Inc., (formerly Acumentrics Corporation) developed a solid oxide fuel cell (SOFC) power system. The Atrex Energy design employs discreet tubes bundled in parallel. Several key aspects of the system were investigated during development including, improved 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] Atrex Energy 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 Atrex Energy system has demonstrated electrical efficiencies of 35-40% and a CHP efficiency of 85%.1 On-site simultaneous generation of heat and power increases efficiency and lowers energy costs to consumers.[2]

Technology History

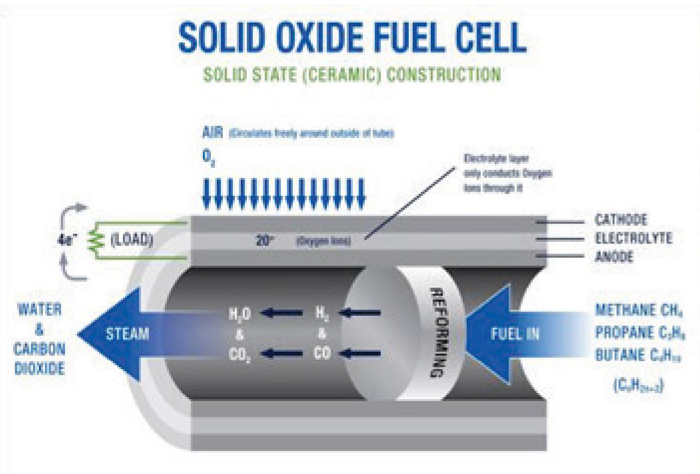
- Developed by Atrex Energy, Inc.
- Commercialized in 2016.
- Over 350 units deployed in the field.

Applications

Can be used for off-grid electricity generation (e.g., power for measurement/sensing equipment in remote locations) or to provide electricity and hot water in residential applications.

Field Installation of Atrex Energy's Tubular SOFC Power System

[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



Atrex Energy's SOFC Tubes

Capabilities

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

Commercial Technology

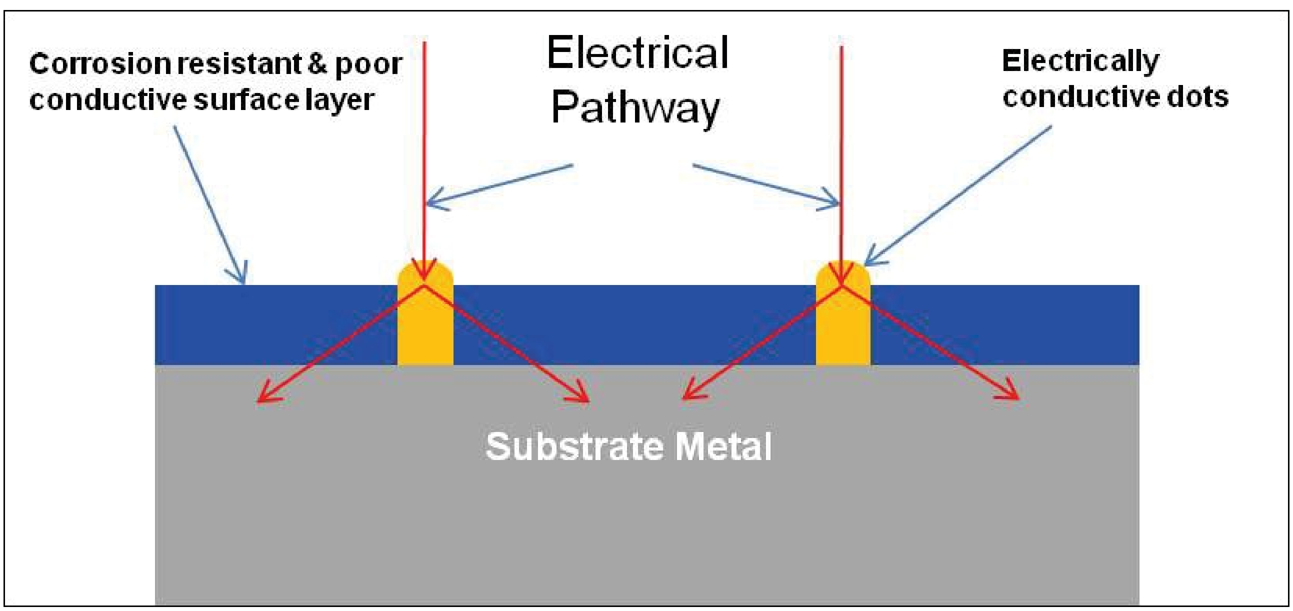
TreadStone, Inc., with funding from FCTO, has developed a corrosion-resistant metal bipolar plate. Typically, for protection and durability, the entire bipolar plate surface is coated with an electronically conductive, corrosion-resistant material and requires high-cost materials and processing techniques. 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

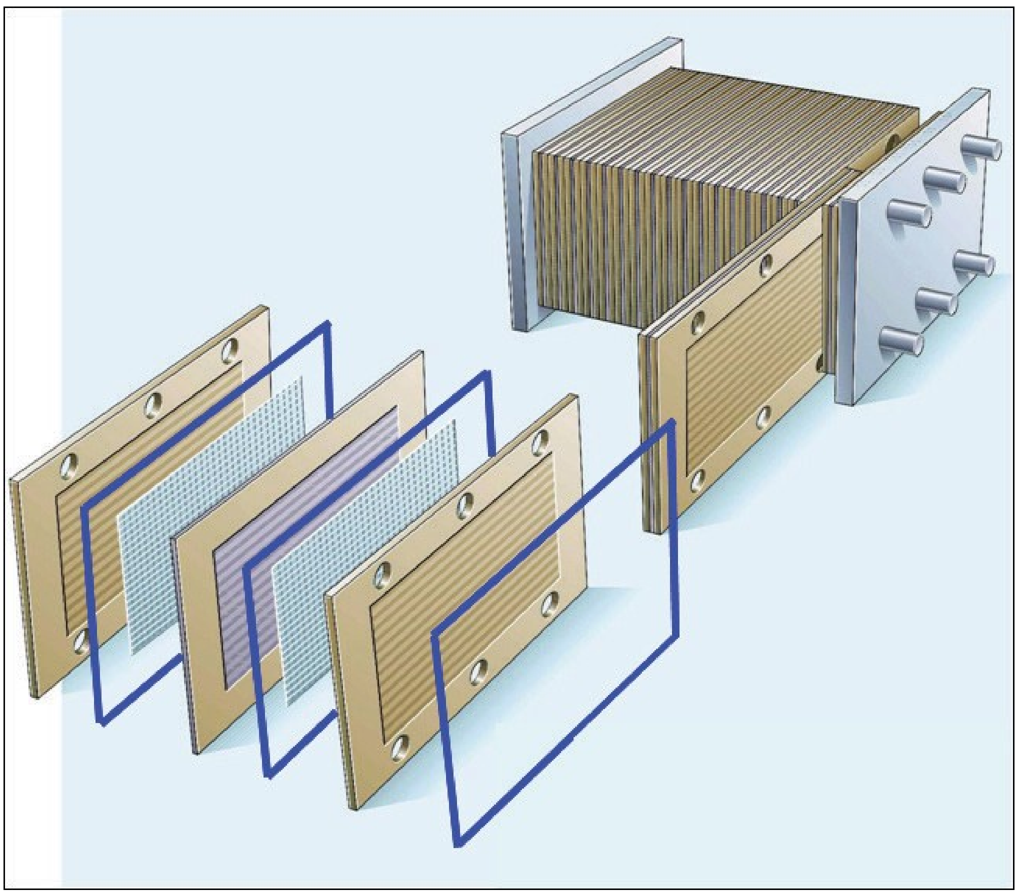
Manufacture of Durable Seals for PEM Fuel Cells

Commercial Technology

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.

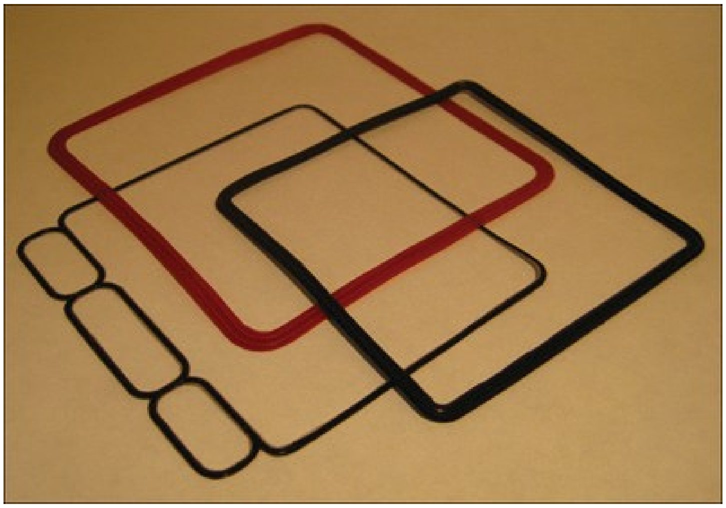
Technology History

- 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

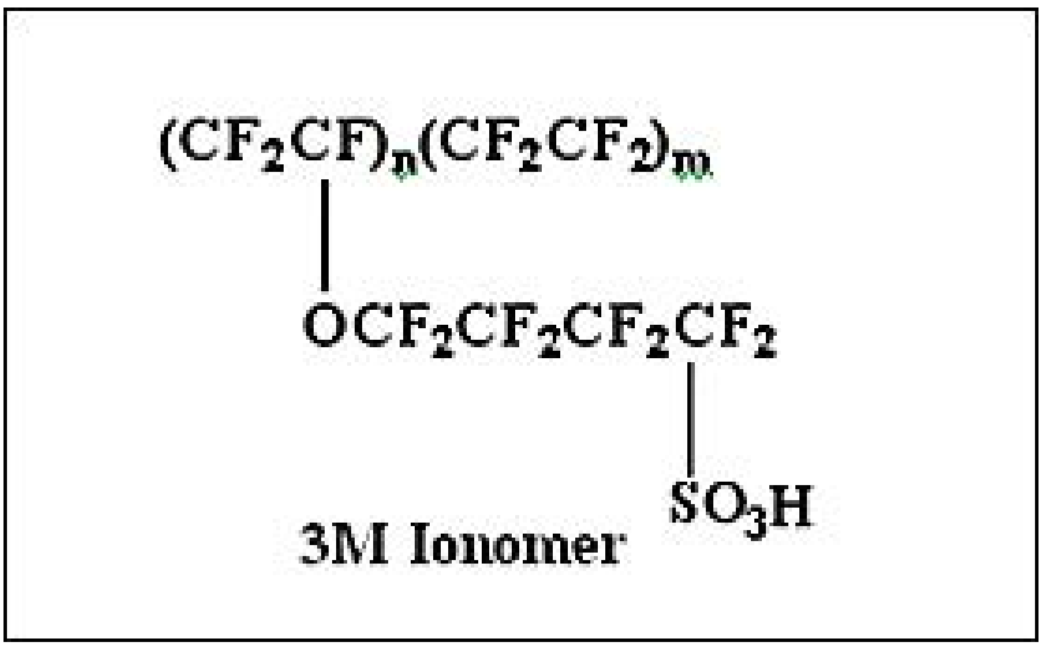
Commercial Technology

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]

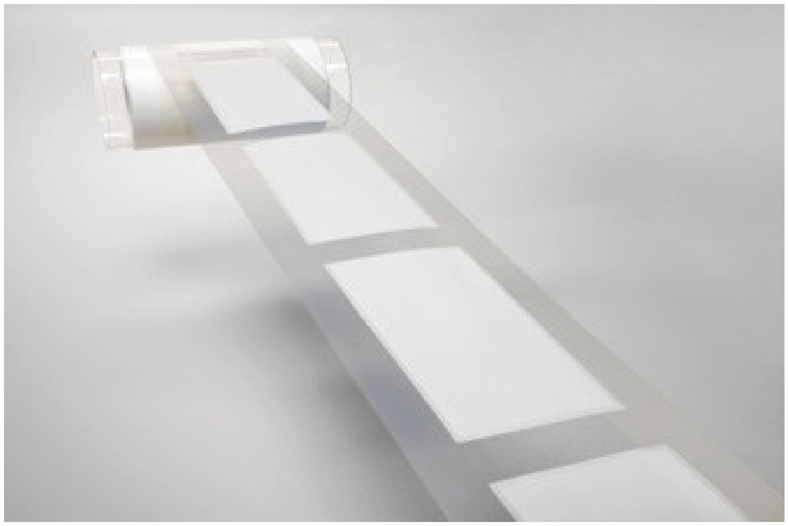
Technology History

- Commercialized in 2006.
- Introduced an improved 20 micron membrane in 2009.
- Introduced a 14 micron membrane in 2012.



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

[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

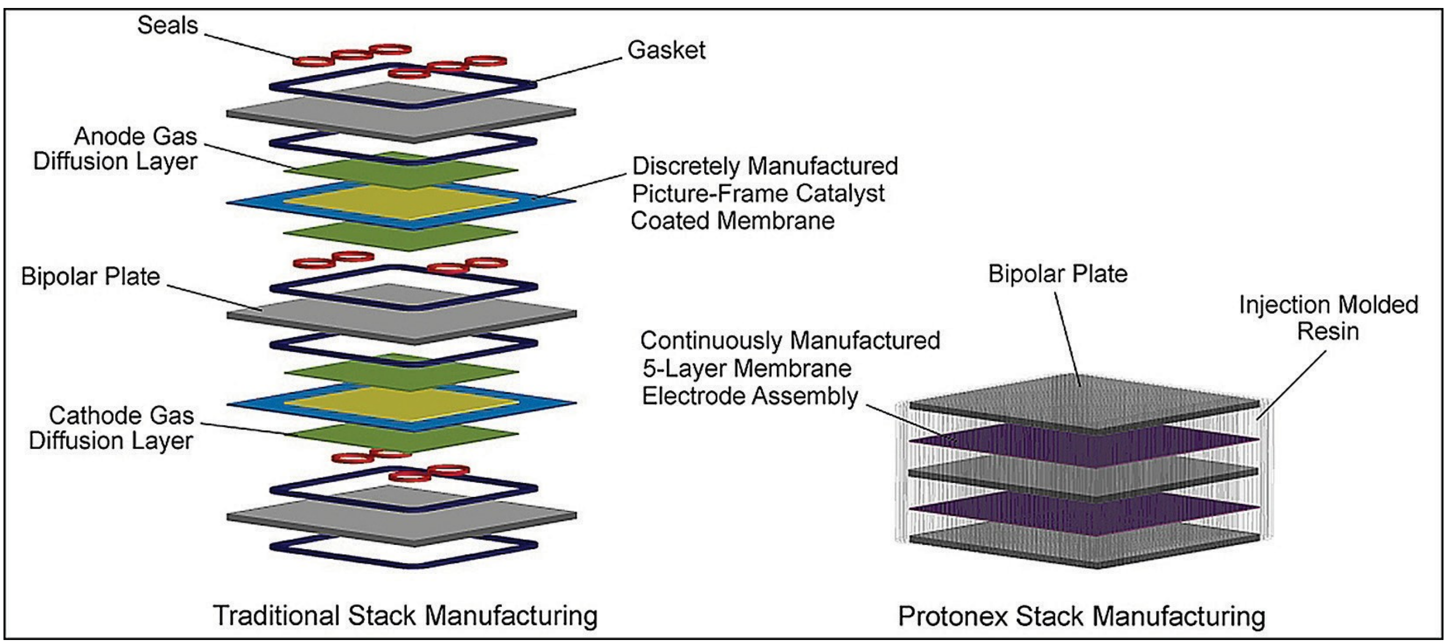
Commercial Technology

Protonex Technology Corporation, a wholly owned subsidiary of Ballard Power Systems, 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 100 M250-CX and M300-CX systems since 2010.



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

Nuvera® Fuel Cell System

Commercial Technology

With assistance from FCTO and the American Recovery and Reinvestment Act, Nuvera Fuel Cells, LLC, developed a fast-fueled power option to replace lead acid batteries for Class I, II, and III electric lift trucks. The Nuvera® fuel cell system consists of a hydrogen fuel cell, hybrid electric energy storage, a compressed hydrogen storage tank, and other balance-of-plant components, all packaged to be interchangeable with standard lead acid batteries. Forklift operators can refuel the system, which stays in the truck, in less than three minutes at a hydrogen dispenser similar to a typical gasoline pump.[1] The hydrogen can be produced on-site using Nuvera® steam methane reforming technology, or delivered by an industrial gas supplier and compressed, stored, and dispensed using Nuvera® refueling equipment.

Conversion of forklift fleets to fuel cells also provides environmental benefits. According to a study performed by Argonne National Laboratory, fuel cells using on-site hydrogen reduce forklift carbon dioxide emissions by approximately one-third compared to national averages for grid-generated electricity used for battery charging[2,3].

Technology History

- Developed by Nuvera Fuel Cells, LLC.
- Commercialized in 2016.

Installation and fueling of a Nuvera® C/D-series fuel cell system for Class 1 forklifts

[1] For more information: http://cdn2.hubspot.net/hubfs/1574587/Resources/Nuvera_FuelCellSystem_Specs.pdf?t=1473716124205
[2] For more information: http://cdn2.hubspot.net/hubfs/1574587/Resources/Nuvera_FuelCellSystem_Sustainability.
[3] For more information: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/forklift_anl_esd.pdf

Nuvera® Fuel Cell Systems for Class I, II, and III forklifts (shown from left to right).

Applications

Can be used as a drop-in replacement for lead acid batteries used to power Class I, II, and III electric forklifts.

Capabilities

- Fills up to 350 bar in less than 3 minutes at standard operating conditions (20°C and 100 kPa).
- Provides constant voltage output with no performance degradation.

Benefits

Emissions Reductions

Reduces carbon dioxide emissions attributable to forklift operation by approximately one-third compared with batteries charged with grid-generated electricity.[1]

Productivity

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

Versatility

Available in three different models to meet the needs of Class I (counterbalance), Class II (reach), and Class III (pallet jack) lift trucks.

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

ORION™: Fuel Cell Technology for Hybrid Power Applications

Commercial 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, this program effort was called the CIRRUS program. 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 Watt per cell) and reduce its thermal mass, enhancing freeze starting ability.

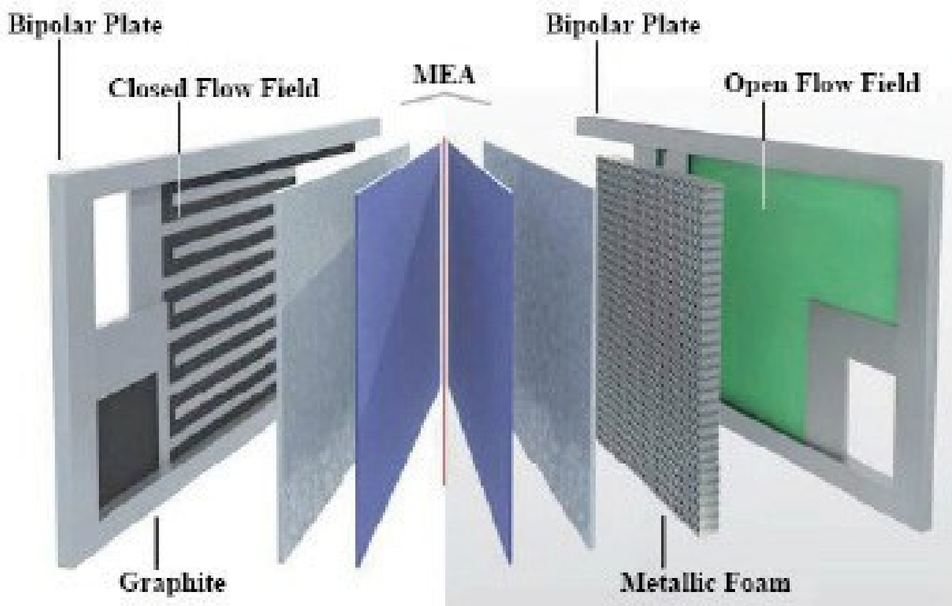
The Orion fuel cell stack features an integrated hydrogen management loop, ruggedized construction, control logic (SmartStack) and is designed to be repairable, remanufacturable and recyclable. The stack design achieves a startup to 50% of rated power in 28 seconds at -20°C and uses less than 3 MJ of energy for a complete start-up and shutdown cycle.[2] The ORION fuel stack is currently available in numerous power configurations up to 100 kW. Nuvera is targeting the industrial mobility, aerospace and automotive markets.

Technology History

- Developed by Nuvera Fuel Cells, Inc., in partnership with W.L. Gore & Associates, Inc., SGL Technologies, and the University of Delaware.
- Commercialized in 2013.

Nuvera's ORION Hydrogen Fuel Cell Stack with SmartStack Control Logic

[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



Nuvera's ORION Fuel Cell (R) Compared to Conventional Fuel Cell Technology (L)

Applications

Can be used to improve fuel cell performance in applications involving subfreezing conditions, such as automobiles, forklifts, 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).[1]
- Uses only 2.94 MJ of energy for a complete startup and shutdown cycle (41% below DOE target of 5 MJ).[1]
- Operates from -40°C to 60°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

Portable Reformed Methanol Fuel Cells

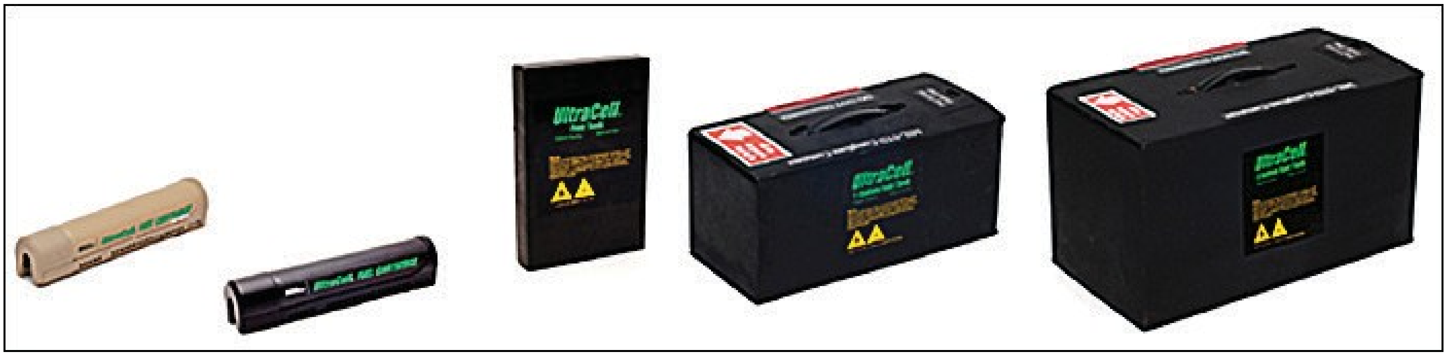
The XX25™ portable reformed methanol fuel cell is a self-contained, 25-W output power system that uses a fuel cell in conjunction with a methanol fuel source to generate power. The XX25 was developed by UltraCell Corporation with funding from FCTO, through the Edison Materials Technology Center. The 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

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

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C.2 Production/Delivery Innovations

California Hydrogen Refueling Stations

Commercial Technology

For nearly a decade Air Products and Chemicals, Inc., with FCTO funding, has been developing and demonstrating several filling stations and methods for supplying hydrogen that would be necessary to establish a hydrogen infrastructure in the state of California.[1] Throughout this process, data was collected on local permitting requirements and operational performance, cost, reliability, maintenance and environmental impact. Hydrogen station technologies were developed (fueling interface) through consumer experiences and feedback and by encompassing a variety of fuel cell vehicles, customer profiles and fueling experiences. Stations were opened to qualified vehicle providers to promote widespread use and to gain a broader public understanding of a hydrogen infrastructure. Major energy companies were engaged to provide a fueling experience similar to traditional gasoline station sites to foster public acceptance of hydrogen.

Air Products designed, constructed and operated several hydrogen fueling stations with different hydrogen supply chains. One station provides fueling services using hydrogen from a storage tank that is periodically replenished by over the road deliveries. Another site is connected to a renewable hydrogen supply derived from anaerobic digester gas (ADG). A third site is connected to a hydrogen pipeline fed by two steam methane reformer plants. Finally, two other locations were set up to meet short-term hydrogen fueling needs using Air Products' HF-150 mobile fuelers. Air Products' mobile refuelers were developed as part of their new delivery concept (NDC) initiatives to find new ways to reduce the cost of supplying hydrogen. The mobile fueler consists of an integrated, fully-automated gaseous hydrogen storage and dispensing system that sits on a wheeled trailer.

Currently, Air Products continue to use their NDC concepts to provide hydrogen and hydrogen refueling services in California and have contracts in place to continue to supply and operate several hydrogen filling stations.

Air Products' Various Filling Stations and ADG Facility (Bottom Left)

[1] For more information: http://www.osti.gov/scitech/biblio/1068156

Air Products Delivery Concepts

Technology History

- Developed by Air Products and Chemicals, Inc.
- Commercial production and delivery under contract began in 2013.

Applications

Can be used to deliver and supply hydrogen fueling services as dictated by location and demand.

Capabilities

- Provides 300 or 700 bar and up to 100 kg per day refueling services.[1]
- Provides up to 100 kg per day.[1]
- Provides permanent or temporary service options.[1]

Benefits

Cost Savings

Uses a variety of temporary and semi-temporary hydrogen delivery, storage and refueling services to reduce infrastructure installation costs.

Performance

Demonstrates the ability to deliver a reliable hydrogen supply and refueling services using either storage, pipeline or renewable sources.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review12/tv007_heydorn_2012_o.pdf

DetecTape®: Early Warning Visual Hydrogen Leak Detector

Commercial Technology

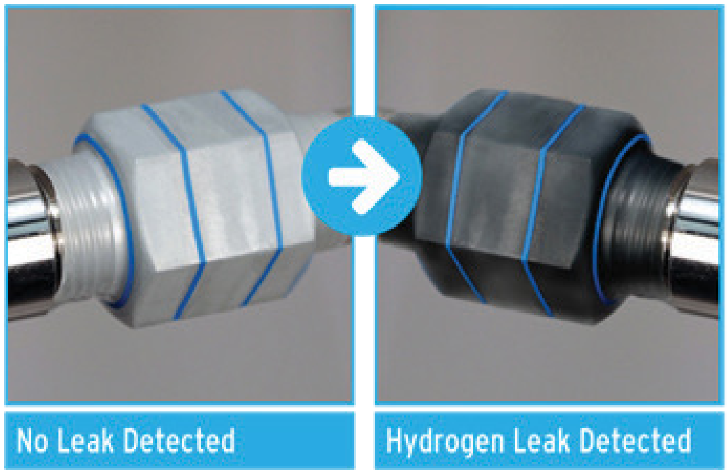
Element One, Inc., in collaboration with the National Renewable Energy Laboratory (NREL), has developed and commercialized DetecTape®, a visual hydrogen leak detector. The tape is a passive, color changing self-fusing silicone wrap designed to detect hydrogen gas leaks in fuel cell, transmission, storage, and generation facilities. DetecTape is a low-cost hydrogen indicating system based on patented chemo-chromic technology for detecting hydrogen. The indicating pigments rely upon the catalyzed reaction between a thin film or nano-particles of a transition metal oxide, such as tungsten oxide or molybdenum oxide and hydrogen. In the presence of hydrogen the catalyst dissociates the hydrogen, which reduces the oxide, changing it from a transparent insulator to a highly colored semiconductor. The system can detect the presence of gaseous hydrogen at levels well below the lower flammability limit. The material can also be deposited on substrates such as decals, paint, protective gear, equipment, or piping. DetecTape changes color rapidly and is non-reversible. Other versions are under development that are reversible or able to detect other hazardous gases are under development.

NREL's FCTO-funded Hydrogen Sensor Testing Laboratory worked with Element One in testing and evaluating the performance. NREL deployed DetecTape at several NREL hydrogen facilities, including a fueling station, several indoor operations, and under controlled laboratory conditions. DetecTape was investigated on numerous pneumatic components and identified leaks and the precise location that would have otherwise gone undetected. No false indications were observed. NREL determined that DetecTape was robust and immune to environmental extremes, as evidenced by its survival in the outdoor deployments with significant weather extremes during long term testing (approx. 1 year) in Golden, Colorado.[1]

In 2012, Element One's DetecTape technology was an entrant in DOE's 1st America's Next Top Energy Innovator Challenge. More recently in March 2016, the product was also showcased in an EERE FCTO webinar.[2] In 2015, Element One partnered with Midsun Specialty Products, Inc. to manufacture and market DetecTape.[3] It is anticipated that DetecTape will address the needs of the existing gas detection market, as well as a growing global hydrogen market.

Element One's DetecTape® Chemo-chromic Hydrogen Leak Detector Product

[1] For more information: http://www.nrel.gov/docs/fy16osti/66570.pdf
[2] For more information: http://energy.gov/eere/fuelcells/downloads/detectape-localized-visual-detector-hydrogen-leaks-webinar
[3] For more information: http://www.detectape.com/



DetecTape® Color Change Before and After Exposure to Hydrogen Leak

Technology History

- Developed by Element One, Inc. in collaboration with NREL.
- Commercialized in 2015 and available from Midsun Specialty Products, Inc.

Applications

Can be used in research laboratories, gas refineries fuel cell plants, and fueling stations to visually identify hydrogen leaks where hydrogen is used.

Capabilities

- Provides passive, visual location detection of hydrogen leaks down 400 ppm.[1]
- Provides quick response to the presence of H2 gas. (Less than 20s at 100% H2 gas).[1]
- Provides easy application to suspected leak areas with no specialized surface preparation required before application.[1]
- Available as a finished tape in precut widths with perforations for ease-of-use in the field.[1]
- Provides 1 year shelf-life and service life of several years.[1]

Benefits

Cost Savings

Low cost detector prevents plant closures and shutdowns by enabling quick and safe detection and identification of hydrogen gas leaks.

Safety

Inspection teams can use this low-cost hydrogen leak detector to accurately identify leak locations and begin repairs, expediting equipment restoration and improving facility safety.

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

H2 ProGen: A Total Supply Solution for Hydrogen Vehicles

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

HRS-100™ Hydrogen Recycling System

Commercial Technology

H2Pump, LLC with funding from DOE SBIR grants and FCTO developed 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 at the site's feedstock manifold pressure. The system is designed to extract up to 100 kg of hydrogen per day. The hydrogen separation, pumping, and pressurization process occurs in an electrochemical cell stack. Hydrogen and other gaseous impurities (e.g., CO, CO_2, NH_3 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 circuit and a proton exchange membrane, respectively. The electrons and protons recombine at the cathode to produce purified, pressurized hydrogen. The gaseous impurities, which do not pass through the membrane, are directed out of the system as a waste stream. The efficiency of the HRS "system," including all unit operations, is approximately 10kWh/kg of recycled, pressurized hydrogen. The system can be easily scaled to provide a wide range of hydrogen flowrates.

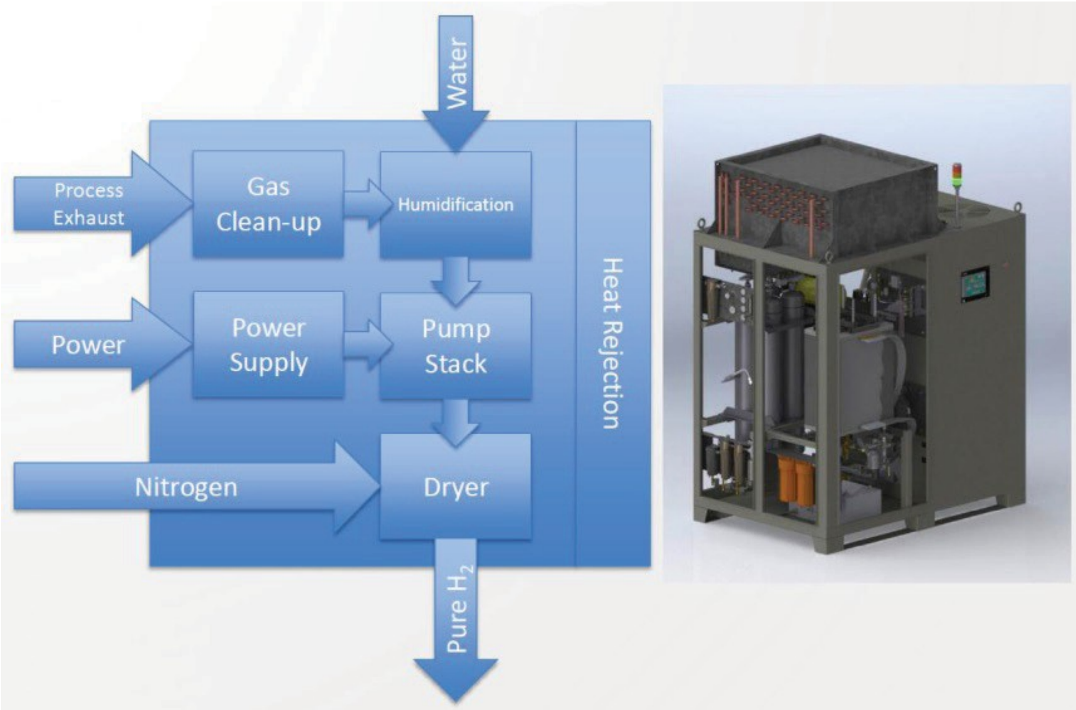
Sustainable Innovations, LLC has acquired a portion of H2Pump's assets in order to accelerate bringing a hydrogen recycling product, H2RENEW™, to the growing industrial hydrogen supply market.[1,2] Sustainable Innovations will use the H2Pump system design combined with elements of their core hydrogen separation and compression technology. The system offers hydrogen end users an efficient and effective alternative to hydrogen delivery. Hydrogen delivery costs can be substantial for processes such as stainless steel annealing, sintering of powdered metals, ore reduction, and manufacture of microelectronics.

Technology History

- Developed by H2Pump, LLC, with support from NYSERDA.
- Commercialized in 2014 and will be available from Sustainable Innovations, LLC starting in 2016.
- Industrial recycling process patents awarded in 2014.

H2Pump and Sustainable Innovation's Hydrogen Recycling System

[1] For more information: http://www.sustainableinnov.com/sustainable-innovations-successfully-completes-acquisition-of-assets-of- only-competitor-h2pump-llc/
[2] For more information: http://www.sustainableinnov.com/products/h2renew/



HRS' Hydrogen Recycling Process Flow Diagram

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 psi.1Achieves >80% pumping efficiency.1
- Purifies hydrogen to >99.99% (exact purity value depends on exhaust gas stream composition).1

Benefits

Cost Savings

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

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[1] For more information: http://www.sustainableinnov.com/products/h2renew/

Hydrogen Generation from PEM Electrolysis

Commercial Technology

Proton OnSite, with funding from FCTO, is leveraging advances in PEM fuel cell technology to reduce the cost and increase the efficiency of PEM electrolysis to make this hydrogen generation process commercially viable.[1]

As a result of this research, Proton OnSite has developed several product lines of hydrogen generators, being sold under the HOGEN® brand name.[2] These commercial electrolyzers are providing on-site generation capability for a diverse base of hydrogen users. Hydrogen production capacities available range from 200 cc/min, to over 400 Nm^3/hour. The figure below shows the relative production outputs for our industrial hydrogen generators. Partly through funding from FCTO, Proton has reduced the capital cost of its M-Series product by nearly 90% when compared to the S-Series product line on a per kW basis.

Through 2015 more than 2,200 HOGEN electrolyzer systems have been shipped worldwide. These systems are installed in applications ranging from power plant turbine generator cooling, to heat treating, to printed circuit board manufacturing. Reliability has been excellent, with an uptime availability of better than 99.9%. In addition, Proton has improved system efficiency by nearly 20% in scaling up from the S-Series to the M-Series.

Proton OnSite's Product Line of Hydrogen Generators

[1] For more information see FCTO Annual Reviews 2005 – 2014: https://www.hydrogen.energy.gov/annual_progress.html
[2] For more information: http://www.protononsite.com/hydrogen-fueling

Technology History

- Developed and marketed by Proton OnSite.
- Commercialized the HOGEN S-Series in 1999, the H-Series in 2004, the C-Series in 2011, and the M-Series in 2015.

Applications

Can be used to generate hydrogen for vehicle fueling, including forklifts, as well as electrical generator cooling, materials processing, and lifting gas for weather balloons. Proton also manufactures the electrolyzer cell stacks that provide oxygen on several classes of United States, British, and French submarines.

Capabilities

- Uses potable water and electricity to produce high-purity hydrogen and oxygen with no other byproduct.[1]
- Generates no pollutant output if the electricity is attained from renewable sources.[1]
- Produces hydrogen at 30 BAR without mechanical compression at a purity of 99.999%.[1]
- Provides hydrogen generation at 350 BAR without mechanical compression.[1]
- Provides scalable capacity to multi-MW applications such as renewable energy storage.[2]

Benefits

Dynamic Response

Responds to demand signals in less than one millisecond and achieve 100% turndown.

Environmental

Generates fuel cell grade hydrogen with no addition clean-up required and no caustic electrolytes to leak out or to be disposed.

Flexibility

Offers opportunity to bid into ancillary service markets as a demand response asset.

Safety

Solid polymer electrolyte and differential pressure operation provide a high level of system safety.

Simplicity

Plug and play design with no caustic liquid electrolyte management system provides easy, reliable operation with low maintenance requirements.

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[1] For more information: http://www.protononsite.com/products-proton-site/c10-c20-c30
[2] For more information see FCTO Annual Reviews 2005 – 2014: https://www.hydrogen.energy.gov/annual_progress.html

Hydrogen Safety Sensor for Energy Applications

Nexceris, LLC, formerly 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 NTM 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, Nexceris has reduced the flow sensitivity of the NTM SenseH_2 to provide an accurate and stable measurement of hydrogen over a wide range of flow conditions.

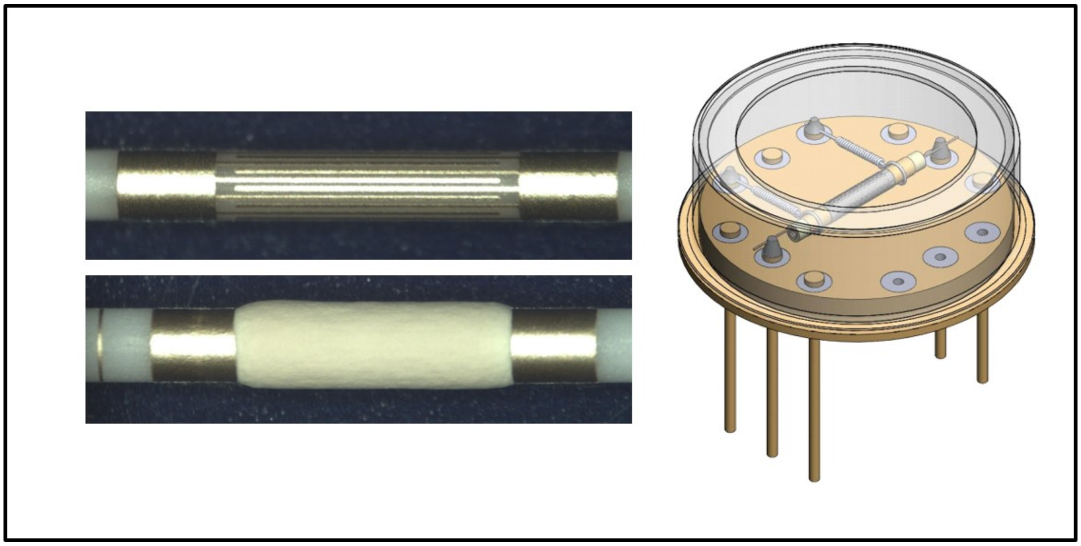
The NTM SenseH_2, which made its debut at the Fuel Cell Expo in Japan in March 2010, is being commercialized by NTM Sensors, a newly created division of Nexceris, LLC. NTM sensors intends to introduce several new products aimed at reduction of greenhouse gas and polluting emissions.

Technology History

- Developed by Nexceris, LLC beginning in May 2005.
- Commercialized in March 2010 and being marketed by Nexceris as the NTM SenseH_2.

Nexceris's NTM 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 NTM SenseH2

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 concentrations from 0.25 to 4 percent 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

Made from low-cost materials and inexpensive fabrication processes.

Performance

Offers 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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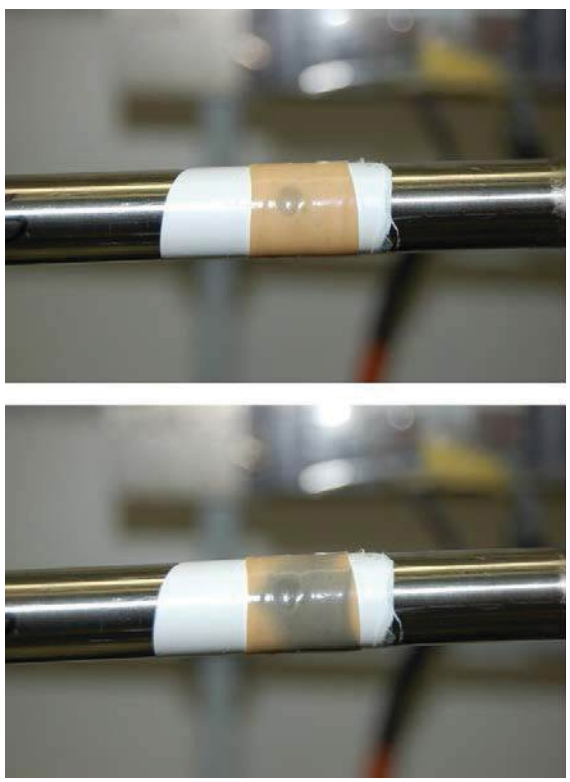
Intellipigment™: Visible Hydrogen Gas Leak Detection Material

HySense Technology LLC has developed and commercialized a chemochromic material in partnership with the University of Central Florida using FCTO funding (Florida Hydrogen Initiative) and NASA research grants.[1,2] Intellipigment™ was developed to provide a cost-effective, high specific chemochromic (visual) hydrogen leak detector for safety monitoring at any facility engaged in handling and use of hydrogen. Since hydrogen gas is odorless, colorless and flammable, an easy to use, safe, effective and non-powered solution to visually detect dangerous hydrogen leaks would be useful to identify and repair leaks when they occur.

The technology, which received a 2014 R&D 100 award, is a result of development work in chemochromic (visual) hydrogen sensitive materials with fast discoloration kinetics. The color changing mechanism, (beige to black) is the reduction of palladium-oxide (PdO) by hydrogen to metallic palladium. The PdO pigment compounds are combined within a silicon matrix. Various chemochromic pigments with permanent color change were investigated, and their performance (sensitivity) evaluated at different hydrogen concentrations in air (from 1 to 100 percent by volume) as well as within other hydrocarbon gas mixtures e.g. CH_4, C_3H_8. University of Central Florida's team was able to develop a barium sulfate ($BaSO_4$) pigment with an improved response time when compared to titanium dioxide (TiO_2) based materials developed elsewhere.

Technology History

- Developed by the University of Central Florida and available from HySense Technology LLC.
- Commercially available in 2013.



HySense Intellipigment Before (Top) and After Exposure to a Hydrogen Gas Leak

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/vii_6_block_2012.pdf
[2] For more information: http://www.hysensetechnology.com

HySense's Color Changing Intellipigment Leak Detection Tape

Applications

Can be used to detect hydrogen leaks at any facility engaged in the handling and use of hydrogen e.g. aerospace, laboratories, refineries, transportation, storage and power generation market segments.

Capabilities

- Provides a safe (unpowered) and location specific visual (color changing) means of pin-pointing hydrogen gas leaks.[1]
- Provides almost immediate visual leak detection (20 second response time with 100% H_2 gas and < 3 minutes with 1% H2 gas).[1]
- Provides accurate detection of hydrogen gas in the presence of other hydrocarbon gases e.g. CH_4.[1]
- Available as a finished tape whose length and width can be customized for specific applications.[1]
- Provides easy application to suspected leak areas and can be wrapped around pipes, flanges, fittings and valves.[1]

Benefits

Cost Savings

Prevents plant closures and shutdowns by enabling quick and safe detection and identification of hydrogen gas leaks.

Safety

Intellipigment provides quick and accurate pinpointing of hydrogen gas leaks which if detected could prevent property damage and human casualties.

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ME100 Methanol Reforming Hydrogen Generator

Commercial Technology

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.

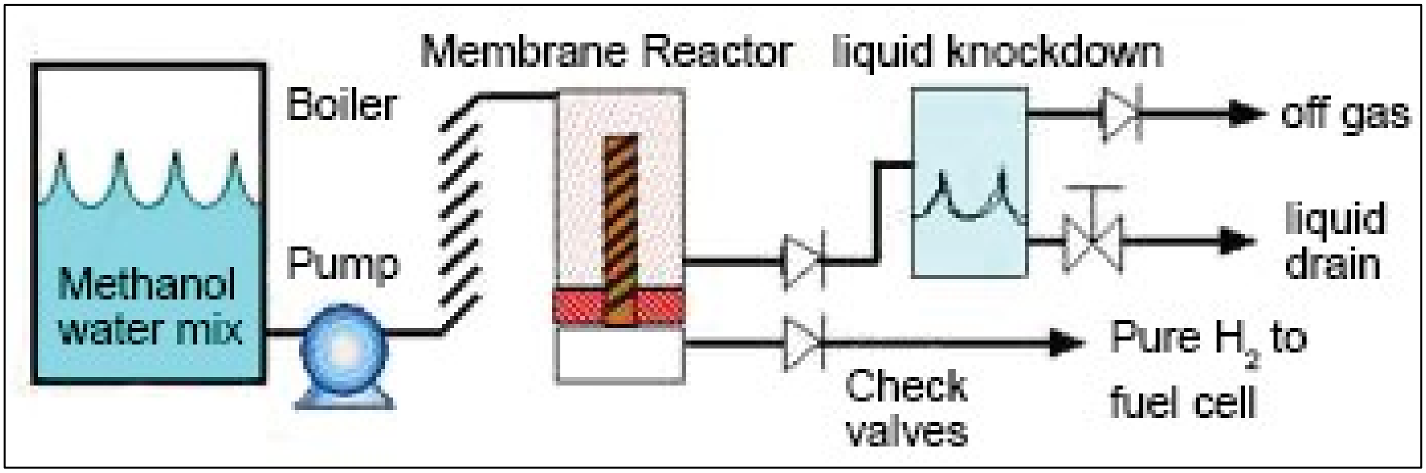
REB developed the membranes used in hydrogen generation reactors with support from FCTO and a DOE SBIR grant. REB designed and developed a form of membrane reactor steam reformer that allows heat transfer so that quantities of high purity hydrogen could be generated in a small volume process by reforming 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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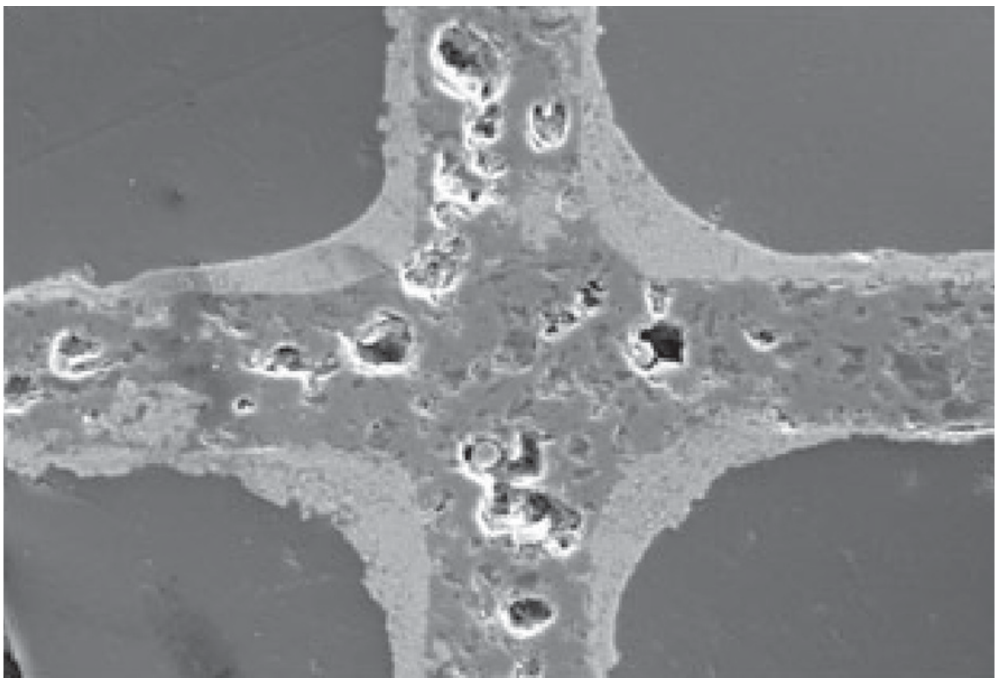
[1] For more information: http://www.rebresearch.com/me100.html

Nanoscale Water Gas Shift Catalysts

Commercial Technology

Nexceris, LLC, formerly 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, non-pyrophoric nature, and capability to operate over a wide temperature range. Nexceris 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). Nexceris began selling these catalysts commercially in 2005 and continues development work to improve functionality, increase durability, and reduce cost.[1]



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

[1] For more information: https://fuelcellmaterials.com/products/powders/nanoscale-powders/

Technology History

- Developed and commercialized in 2005 by Nexceris, LLC.
- Currently using the synthesis technology to develop other types of catalysts.

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 for WGS reactions at temperatures above 250ºC.[1]
- Does not require complex pre-reduction processes.[1]
- Modified formulation available for reforming of methane, ethanol and other hydrocarbons.[1]

Benefits

Efficiency

Allows the design and construction of compact, high performance and thermally integrated water-gas-shift reactors.[1]

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).[1]

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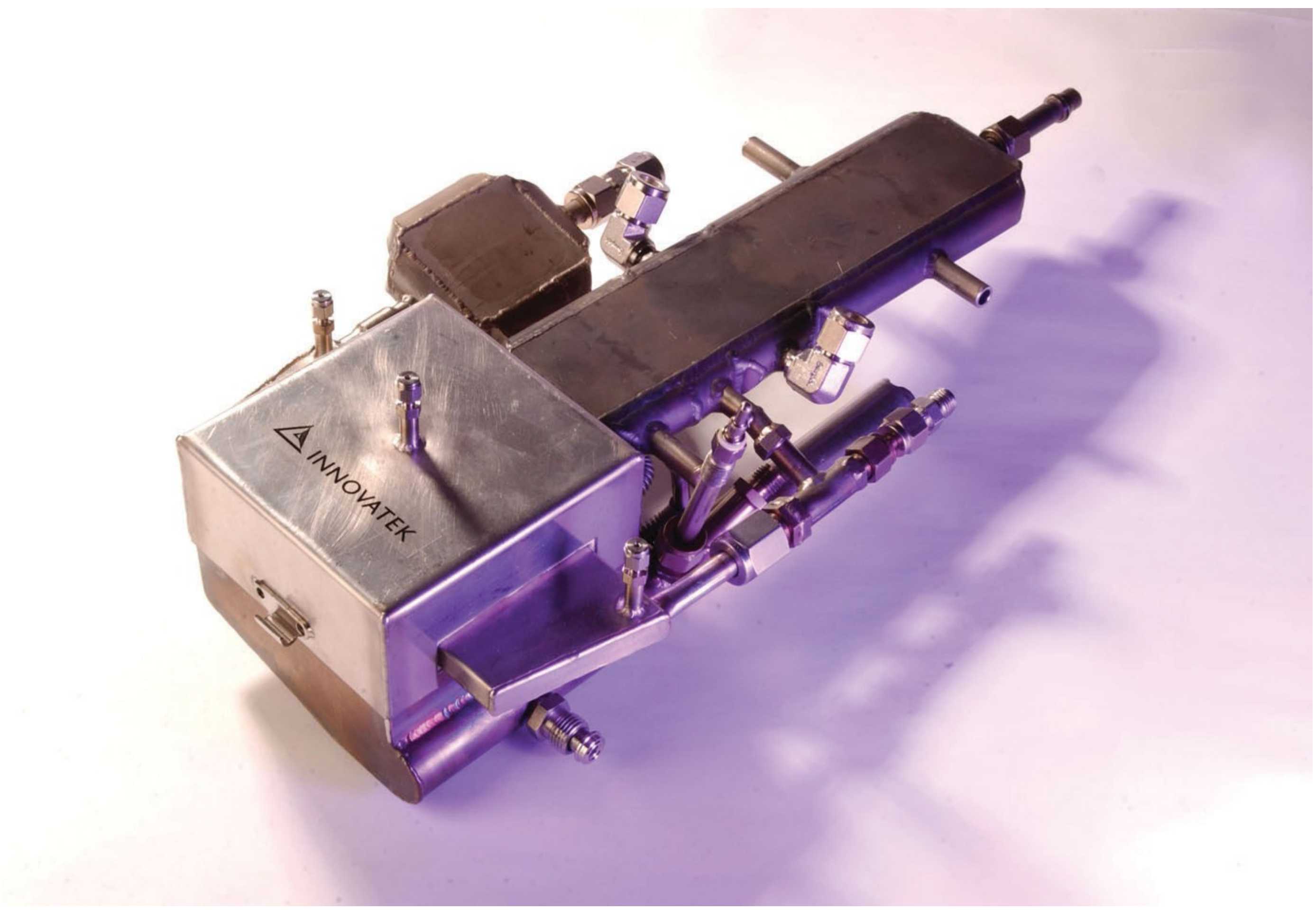
Novel Catalytic Fuel Reforming

Commercial Technology

InnovaTek, Inc., with FCTO funding, has developed a hydrogen generator that reforms multiple fuel types (natural gas, gasoline, diesel, and biodiesel) to produce hydrogen by integrating microreactor and microchannel heat exchanger technology with sulfur-tolerant catalysts. Microstructured components, especially an integrated system of catalytic and heat exchange microchannels, produce a compact, thermodynamically efficient fuel processor design. The InnovaGen® Fuel Processor produces up to 12 liters per minute of hydrogen that can fuel a 1- to 5-kW solid oxide (SOFC) fuel cell, or other auxiliary power unit.[1] Current work is focused on developing and delivering 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.

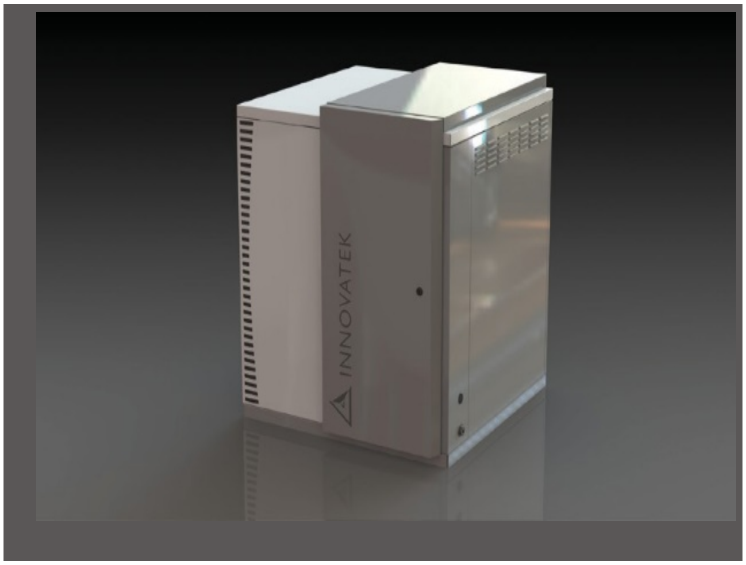
Technology History

- Developed by InnovaTek, Inc.
- Critical parts manufactured using 3-D printing of high temperature metals.
- Commercially available in 2015.



InnovaTek's Catalytic Fuel Processor

[1] For more information: http://www.innovatek.com/files/InnovaGen.pdf



InnovaTek's InovaGen™ Energy System

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.

Durability

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

Performance

Demonstrates system CHP efficiency of 76%.[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/annual_review14_fuelcells.html#systems

PEM Electrolyzer Incorporating a Low-Cost Membrane

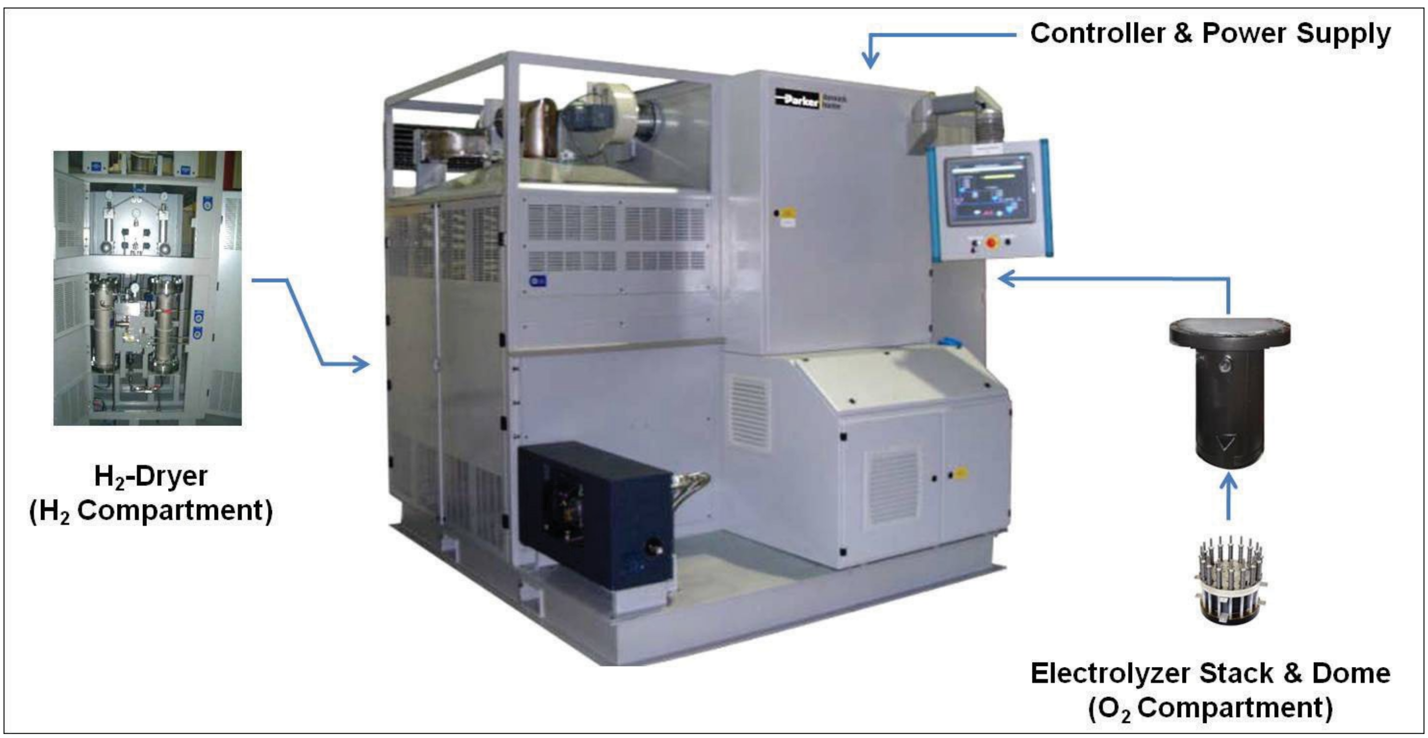
Commercial Technology

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-H2/hr at an operating pressure of 350 psig.[1]
- Uses a 27-cell electrolyzer stack with an active area of 290 cm2 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

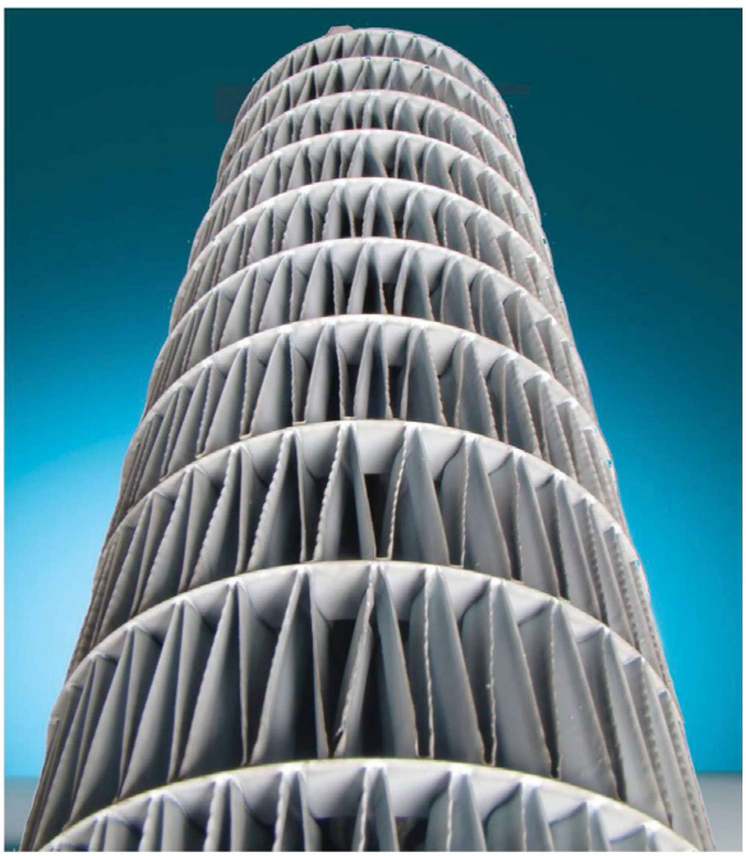
Stackable Structural Reactor (SSR®) for Low-Cost Hydrogen Production

Commercial Technology

Catacel Corporation, a wholly owned subsidiary of Johnson Matthey, 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.

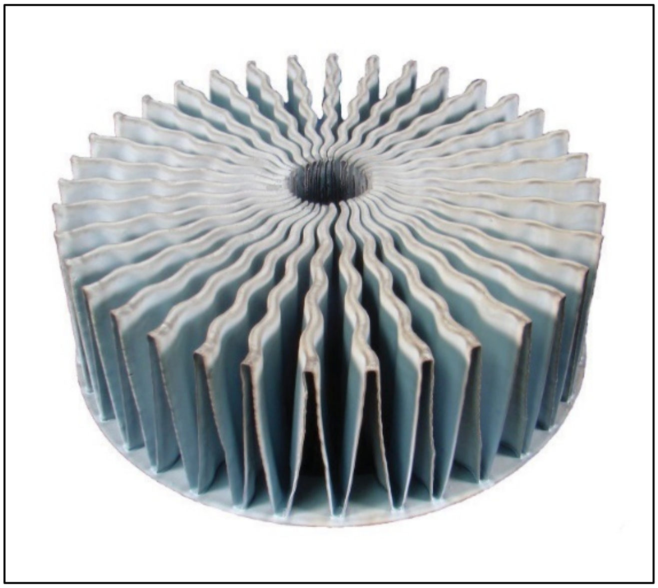
Technology History

- 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://www.catacel.com/CATACEL-SSR



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://www.catacel.com/CATACEL-SSR

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

Commercial Technology

Hexagon Lincoln, 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. Hexagon Lincoln's TITAN Module provides users with more than two times the compressed gas payload of steel tube trailers.

[1] Hexagon Lincoln 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.

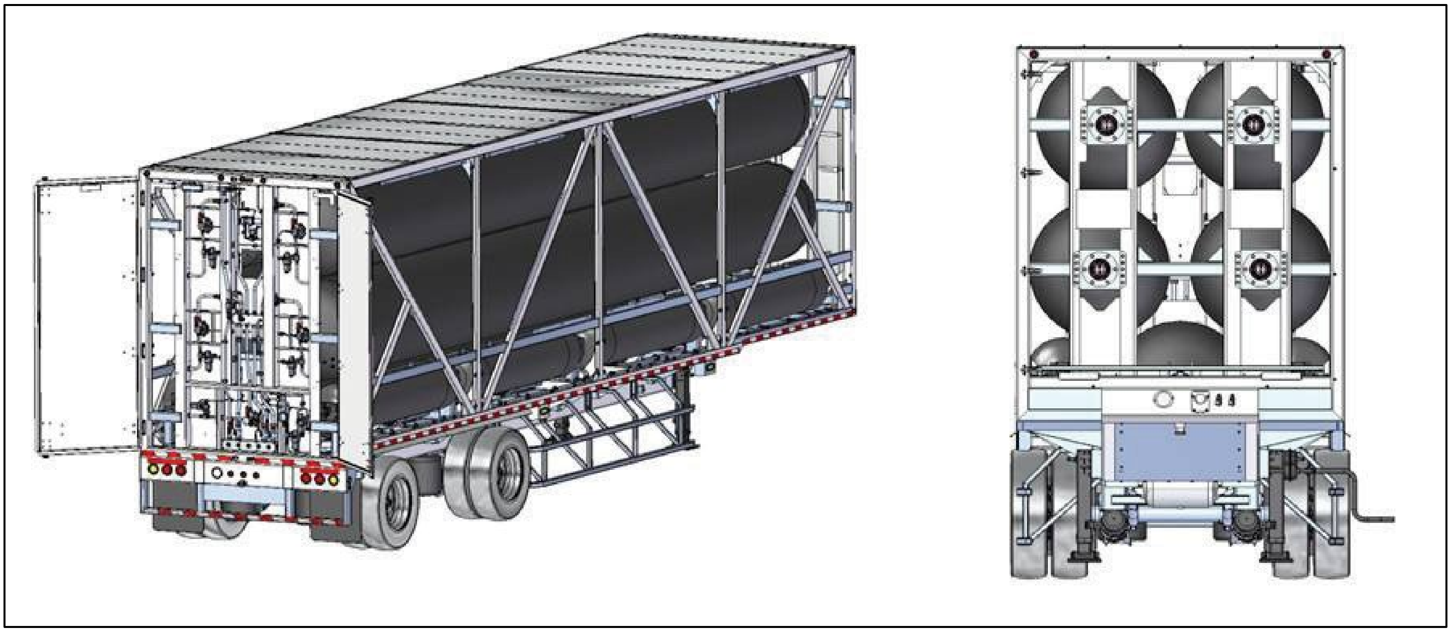
The capacity of the baseline TITAN5 Trailer can be increased to 1775 lb by adding smaller pressure vessels in the available internal spaces flanking the lower tank to create the TITAN5 Magnum configuration. Further capacity increases could also be achieved by increasing the system's operating pressure. Hexagon Lincoln 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 Hexagon Lincoln.
- Now available in standard and higher capacity magnum configurations.
- Commercialized in 2012 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.

Hexagon Lincoln's 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

Unitized Design for Home Refueling Appliance for Hydrogen Generation to 5,000 psi

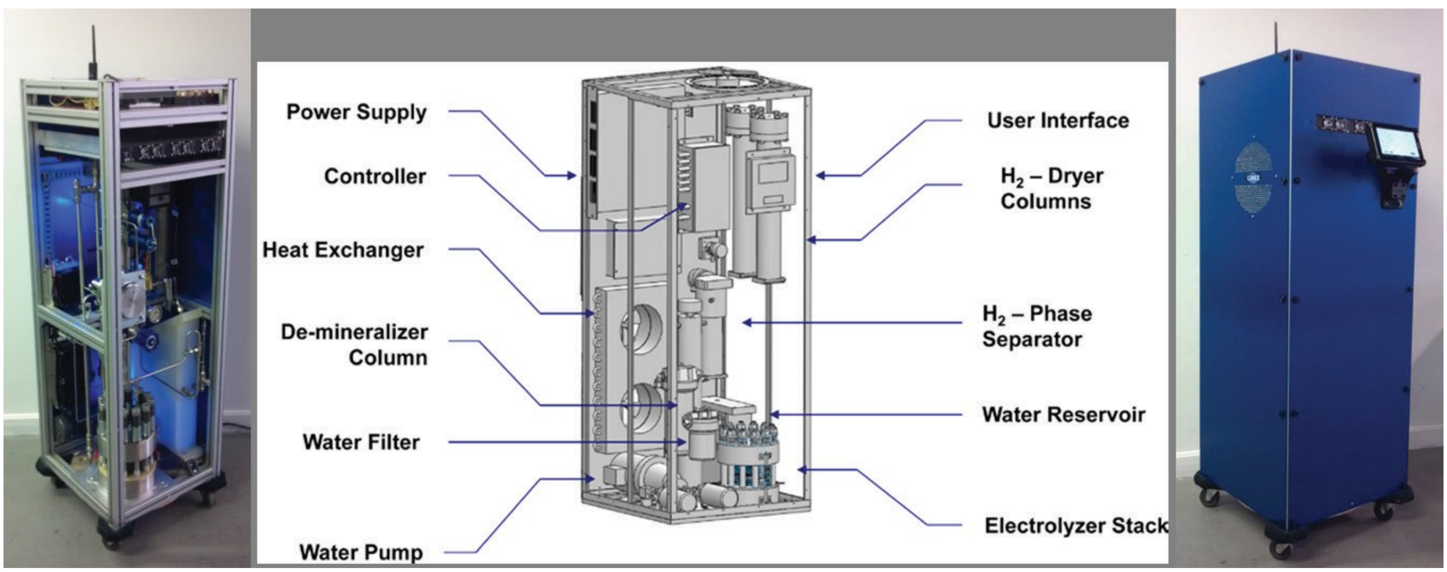
Commercial Technology

With funding from FCTO, Giner, Inc., developed a low-cost electrolyzer stack and balance of plant 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 initial focus was to reduce commercial electrolyzer costs while simultaneously raising the efficiencies of the PEM-based water electrolyzer units that operate at 400 psi. Giner further extended this technology to operate at greater than 5,000 psi 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 have enabled the achievement of a viable 5,000 psi PEM-based water electrolyzer system for home refueling applications. Giner found 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.

Technology History

- Developed by Giner, Inc.
- Commercialized in 2015.



Giner's Prototype Electrolyzer (Home Refueling Appliance) System

[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ii_h_1_norman_2012.pdf

Giner's High-Pressure Electrolyzer Stack with Reinforced Cell Frames

Applications

Can be used as a hydrogen refueling device for residential and a wide range of other applications that require pressurized hydrogen.

Capabilities

- Produces hydrogen at pressures of up to 6,000 psi.[1,2]
- Provides remote system monitoring and operation via Bluetooth™ connection up to 30 feet away.[2]
- Provides hydrogen at a cost per kilogram that is approaching DOE program 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 the end-user site.

Safety

Uses system safety features that meet 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

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C.3 Storage Innovations

Hydrogen Composite Tanks

Quantum Fuel Systems, LLC (formerly 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]

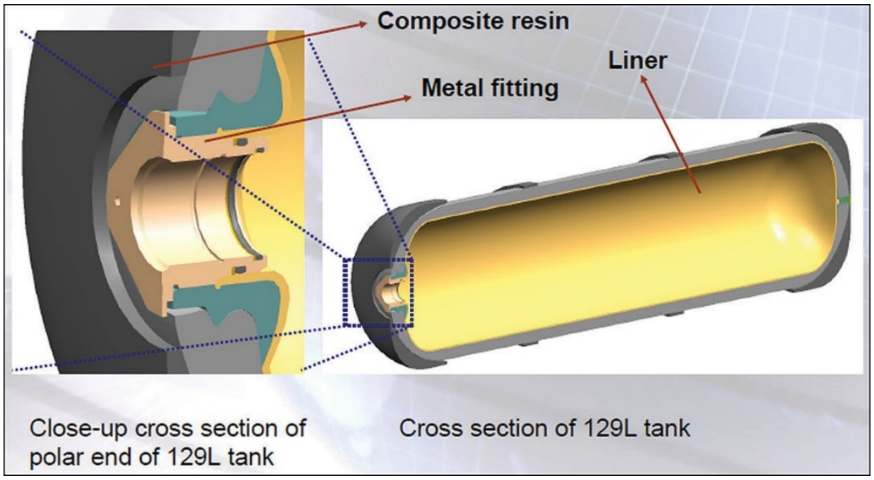
While the initial tanks have been a commercial success, Quantum continued to optimize the design with the aim of decreasing tank cost while maintaining structural performance. Current commercially available products use premium- grade materials to support challenging structural requirements for burst 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, LLC 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 Fuel Systems' 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

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Appendix D: Emerging Technology Innovation Descriptions

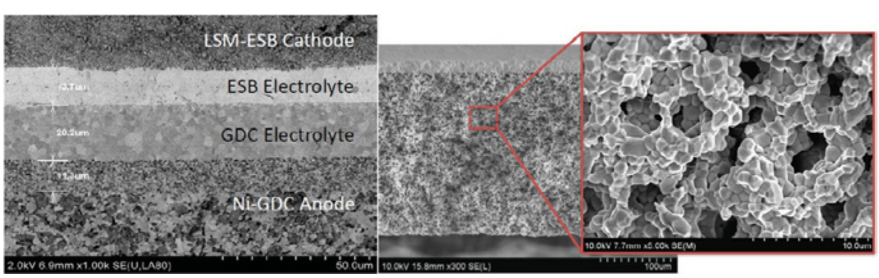
D.1 Fuel Cell Innovations

Affordable, High Performance, Intermediate Temperature Solid Oxide Fuel Cells

Emerging Technology

Solid Oxide Fuel Cells (SOFCs) use a solid oxide electrolyte layer to enable high electrical conversion efficiency with low emissions at a relatively low cost. However, because SOFCs tend to operate at high temperatures, mechanical and chemical issues may arise as a result, leading to decreased performance and reliability. Redox Power Systems (Redox), with funding from FCTO, is developing an alternative SOFC that operates at intermediate temperatures (IT) while maintaining efficiencies and performance of high operating temperature SOFCs.[1] Redox plans to achieve several goals with their design. These include having a high-energy conversion efficiency to reduce consumption of hydrocarbon fuels (e.g., natural gas), keeping their fuel choice flexible to allow for a diverse energy infrastructure, making high specific and volumetric power density stacks to reduce costs and improve fuel efficiency, thus resulting in a decrease of pollution and greenhouse gas emissions. Redox's design for their IT SOFC includes an optimized bilayer electrolyte. The compositions and microstructures for the cathode and the anode are optimized using a custom multi-physics model. The performance of the bilayer cells are then mapped and optimized to improve the performance of the designs, resulting in the demonstration of a ~1 kW stack for IT operation.

Redox succeeded in integrating the bilayer electrolyte mechanism into their custom multi-physics model for the fuel cell and stack.[2] This model has been validated using button and 10 x 10 cm cell data under different operating conditions (e.g. power, temperature). Redox also demonstrated button cells with open circuit potential (OCP) > 0.9 V at < 600°C using a gadolinium doped ceria (GDC)/erbium-stabilized bismuth oxide (ESB) bilayer electrolyte. The demonstrated button cells have power densities exceeding 1.25 W/cm^2. This configuration can effectively boost the open circuit voltage by as much as 20% at intermediate operating temperatures. Therefore, the efficiency of the SOFCs is similarly increased compared to single cerium oxide electrolyte cells. The addition of the bilayer electrolyte to Redox's multi-physics model makes it a valuable tool for optimizing designs at both cell and stack levels. Future work will include the optimization of the bilayer electrolyte at the 10 x10 cm cell size. Tests will be performed to increase the OCP > 0.9 V at < 600°C for this larger size. A further demonstration of 10 cm by 10 cm cells in a ~1 kW stack under combined heat and power conditions using natural gas is also planned.



Left: SEM Microscopy Micrograph of typical GDC/ESB Bilayer Cell
Right: Redox Power Systems' Porous Anode Scaffold for 10 x 10 cm cell

Technology History

- Developed by Redox Power Systems.
- Integrated bilayer electrolyte mechanism into custom Redox multi-physics model for cell and stack.
- Working to further optimize and demonstrate the bilayer electrolyte at the 10 cm by 10 cm cell size.

Applications

Can be used to improve performance, durability, and cost compared to other solid oxide fuel cell technologies.

Capabilities

- Provides > 1.25 W/cm^2 of power at 600°C for button cells with catalysts in the cathode and/or anode.
- Provides improved electrical conversion efficiency with the GDC/ESB bilayer electrolyte.

Benefits

Cost Savings

Reduces overall fuel cell stack cost by allowing the use of simpler materials due to lower intermediate temperature operation (~600°C). Additionally, fewer components are used due to the IT SOFC's higher power density compared to traditional SOFCs.

Emissions Reductions

Releases less CO_2/kWh as a result of higher efficiency.

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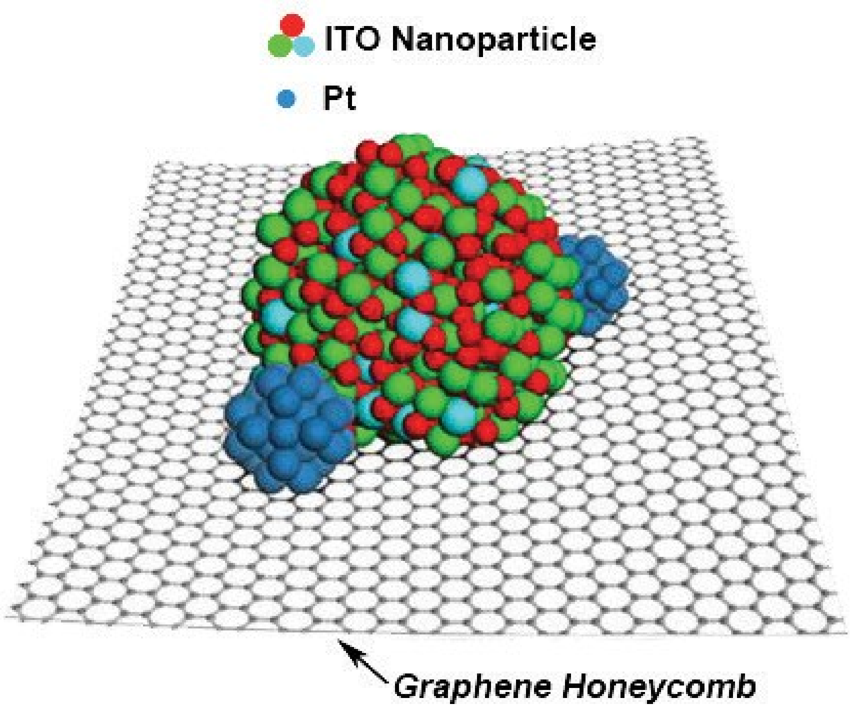
[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/v_f_8_blackburn_2015.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review15/fc115_blackburn_2015_o.pdf

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.
- Continuing work to improve metal oxide conductivity and carbon surface coverage uniformity to increase cathode performance and durability

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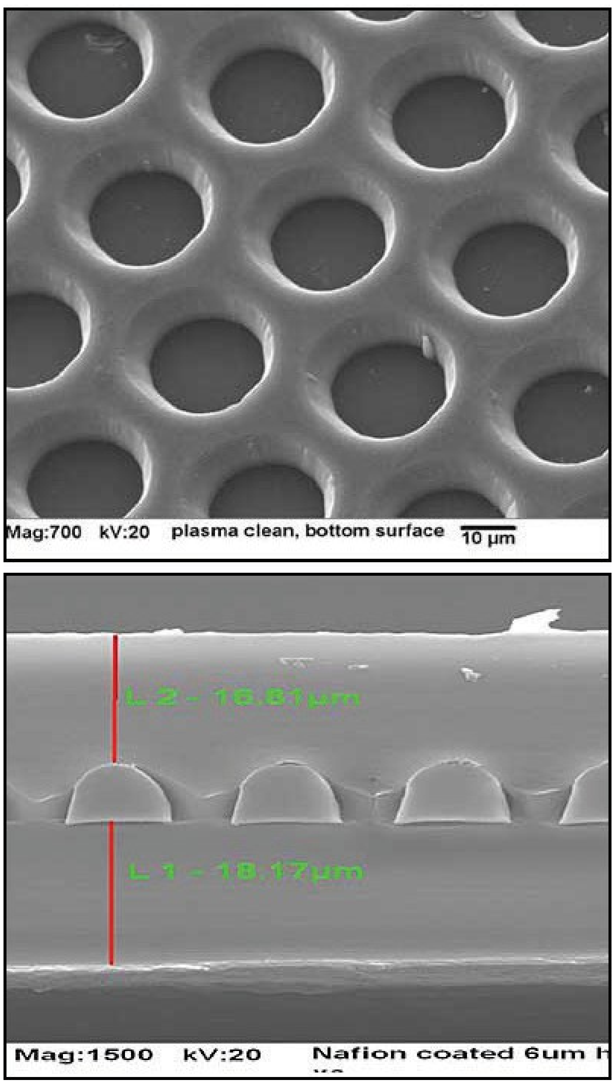
[1] For more information: http://www.princeton.edu/~cml/assets/pdf/pu_11_133kou.pdf
[2] For more information: http://sciencemag.org/content/211/4487/1121

Dimensionally-Stable High-Performance Membrane

Emerging Technology

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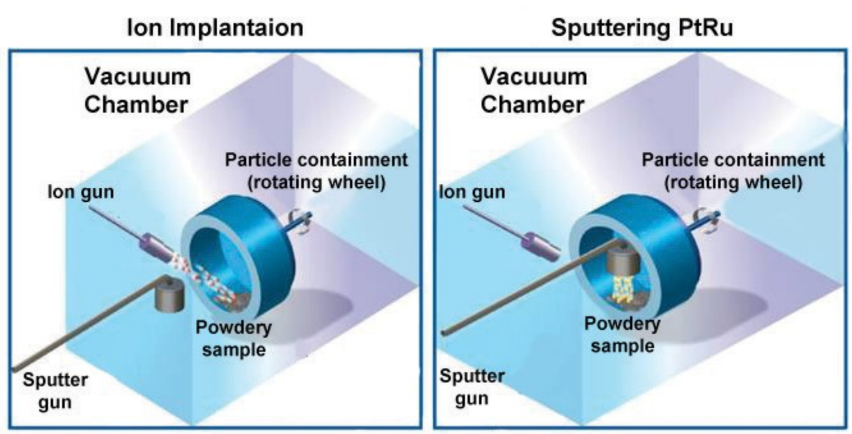
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/fc036_mittelsteadt_2013_o.pdf

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 methanol oxidation reaction (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.

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

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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[1] or 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

Direct Methanol Fuel Cell for Handheld Electronics Applications

Emerging Technology

MeOH Power, 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] MeOH Power 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]

MeOH Power's Mobion Technology

Technology History

- Developed by MeOH Power, 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.

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.

Versatility

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

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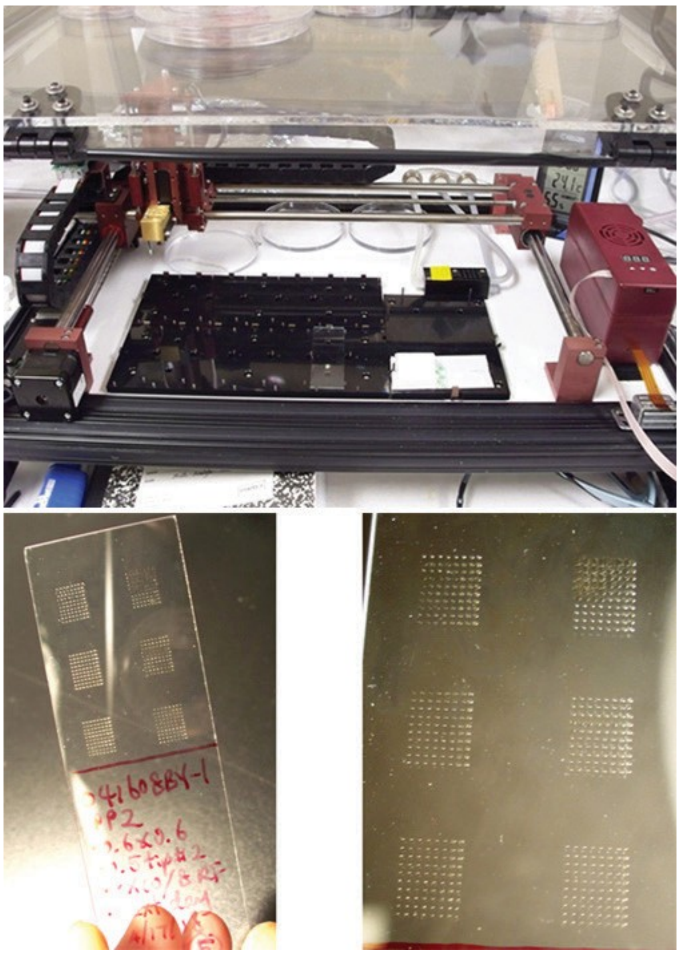
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review10/ar- rah2001_carlstrom_2010_o_web.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/xi_1_carlstrom.pdf

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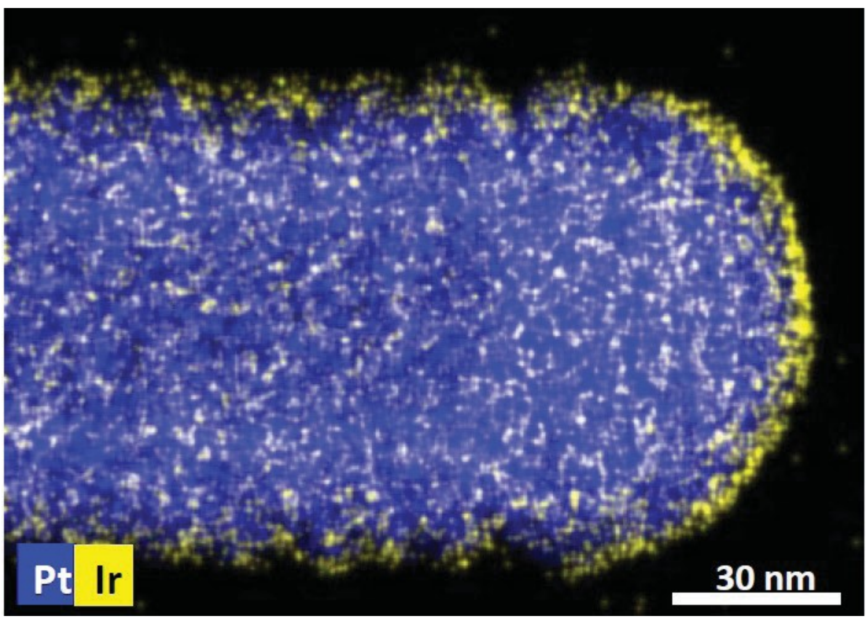
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress06/x_sbir.pdf

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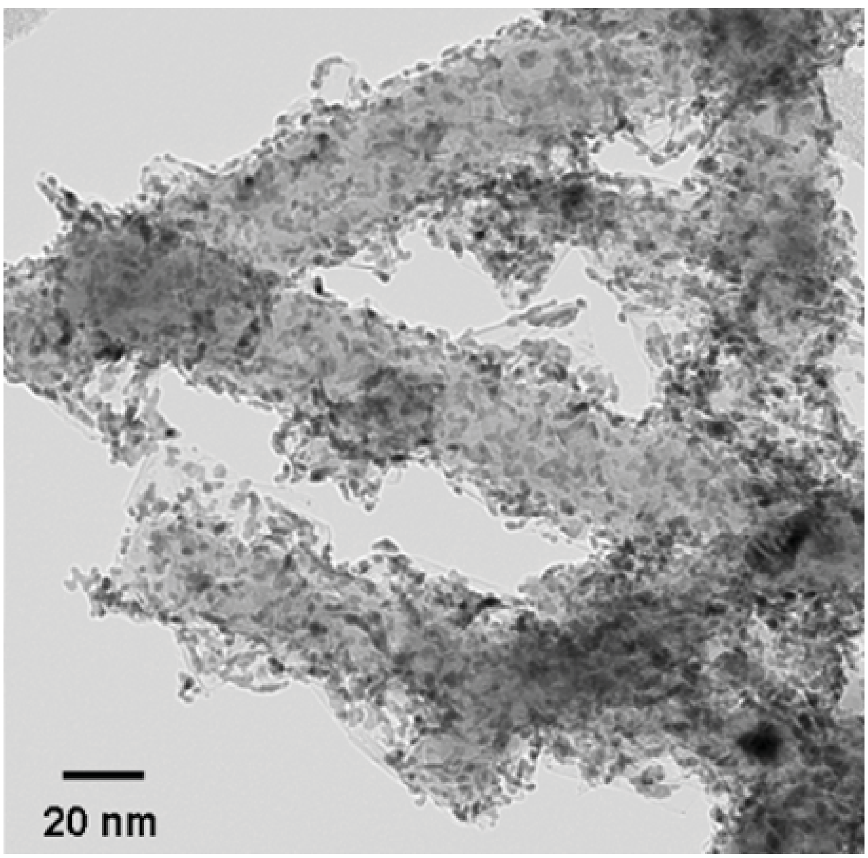
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_3_atanasoski_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review13/fc006_atanasoski_2013_o.pdf

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. and being commercialized by OneD Material, LLC.

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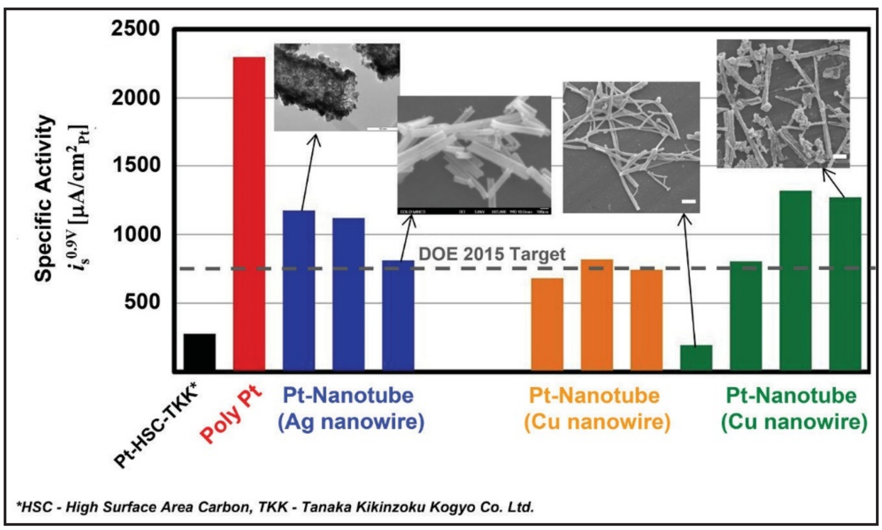
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review09/ fcp_09_zhu.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress09/ v_j_7_zhu.pdf
[3] For more information: http://www.osti.gov/scitech/biblio/959141

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: https://www.hydrogen.energy.gov/pdfs/progress12/v_d_4_pivovar_2012.pdf

Fuel Cell Membrane Measurement System for Manufacturing

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

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.2Achieves 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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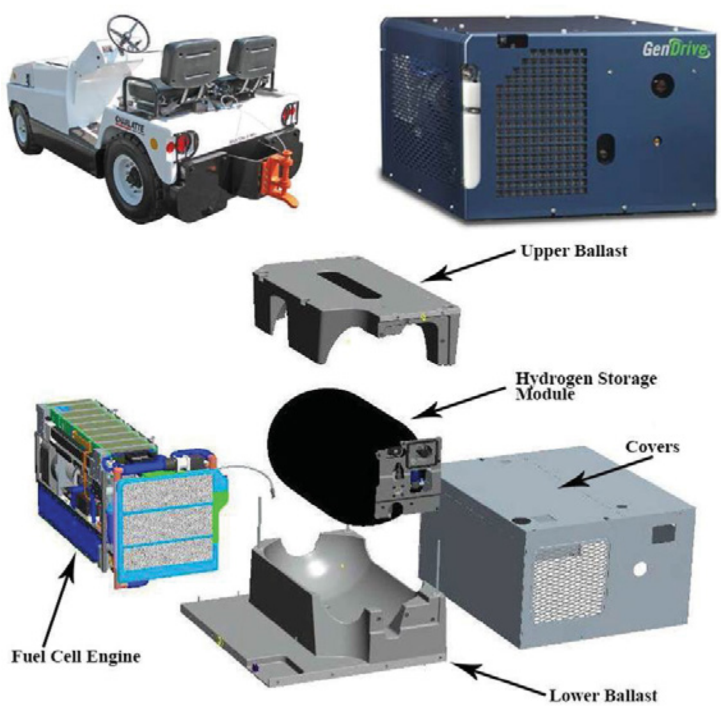
[1] For more information: https://share.sandia.gov/news/resources/news_releases/mobile_lights/#.VqenR1InnYF
[2] For more information: http://www.multiquip.com/multiquip/h2lt.htm
[3] For more information: http://www.hydrogen.energy.gov/pdfs/review11/mt010_klebanoff_2011_p.pdf

Ground Support Equipment Demonstration

Emerging Technology

Plug Power Inc., with FCTO funding, are developing a hydrogen-fuel-cell-based solution as a cost-competitive and energy-efficient power source alternative to internal-combustion-engine-powered baggage tow tractors (airport vehicles). The fuel cell solution will reduce consumption of petroleum based fuels and lower carbon emissions. A field trial will be conducted to demonstrate the viability of the expected decrease in energy expenditures when compared to diesel-powered airport vehicles.[1]

The Plug Power-led team is working with a hydrogen producer, airport authorities, the tractor manufacturer, and the end user. Plug Power will develop an 80V (~20 kW) fuel cell prototype power unit, based on Plug Power's GenDrive™ product line, that will be used on a Charlatte CT5E baggage tow tractor. The fuel cell units will meet Tier 4 emission standards. The Alpha prototype performance has been tested and certified for use in the application. A fleet of 15 units has been deployed at FedEx Express's facility in Memphis, TN as part of a two-year demonstration. Plug Power is providing onsite hydrogen fueling services using a GenFuel liquid hydrogen plant with compression, storage, and dispensing.[2]



Plug Power's Alpha Prototype for Baggage Tow Tractor

Technology History

- Developed by Plug Power Inc., in collaboration with FedEx Express and Charlatte.
- Acceptance testing work and preparing demonstration site for installation of hydrogen infrastructure.

Applications

Can be used as an alternative power system for ground support applications e.g. tow-tractors, baggage and materials handling.

Capabilities

- Provides a hydrogen-fuel-cell-based power source alternative to petroleum or battery power sources.[2]
- Provides towing capability of 5,000 lbs. (40,000 lbs. of pulling capacity).[2]
- Provides up to 10 hours per day operation.[2]

Benefits

Cost Savings

Provides fuel savings for fleets above 30 units and eliminates downtime when compared to diesel equipment which requires particulate filter regeneration.

Emissions Reductions

Eliminates CO_2 emissions when compared to petroleum based power units that in the case of diesel release 10.1 kg of CO_2 per gallon.

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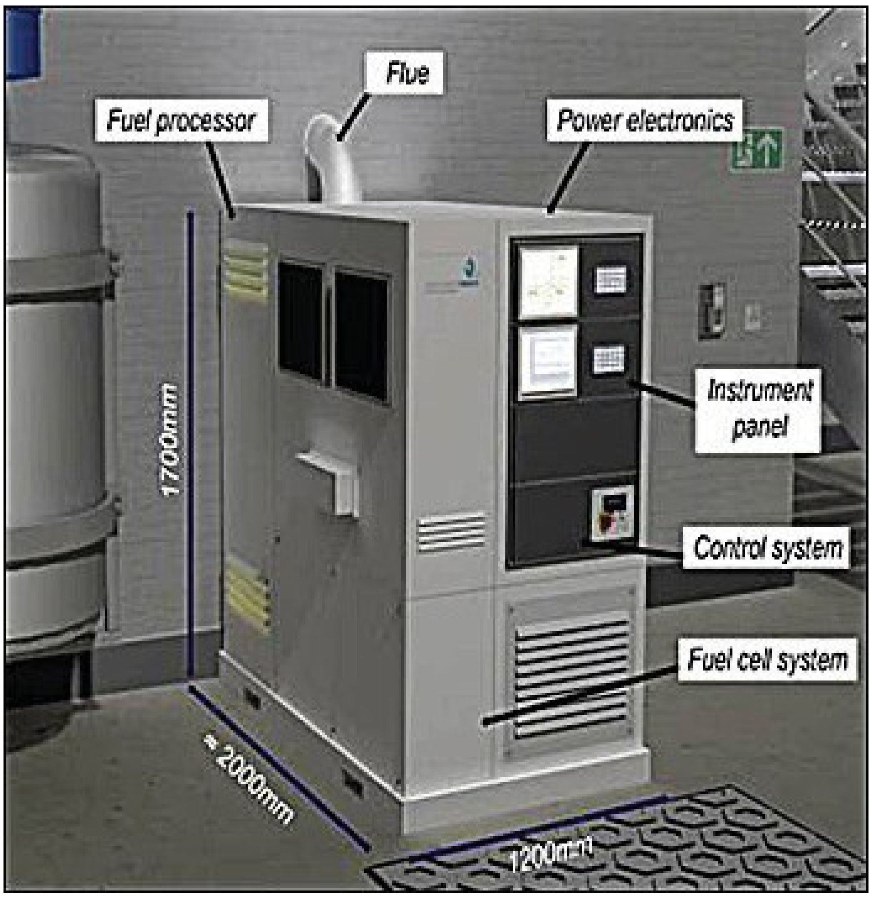
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress13/ix_5_petrecky_2013.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review14/mt011_petrecky_2014_o.pdf

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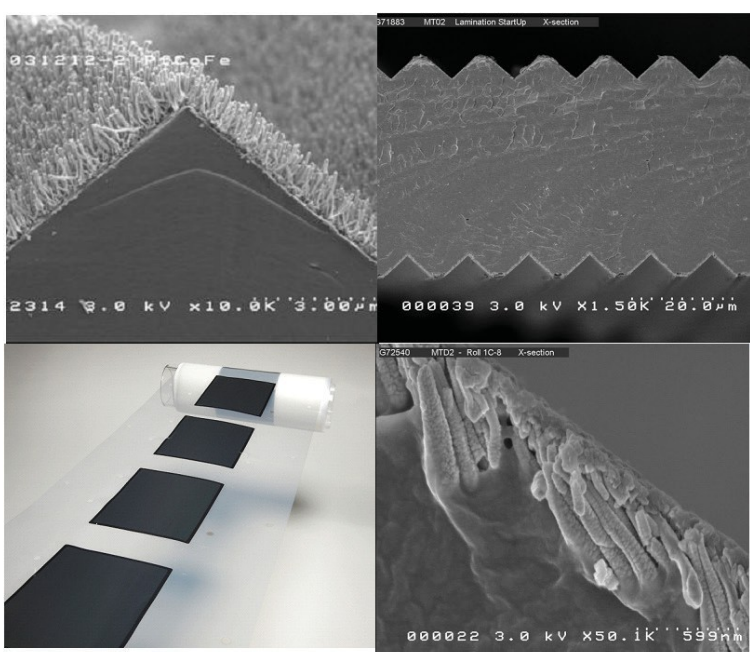
[1] For more information: http://www.iphe.net/docs/Meetings/Germany_11-11/presentations/(2)%20Hayter%20Intel%20Energy.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_j_1_tock_2012.pdf
[3] For more information:http://www.intelligent-energy.com/our-focus/distributed-power/overview/

High Performance, Durable, Low Cost MEAs for Transportation Applications

Emerging Technology

3M Company, with FCTO funding, is developing an improved membrane electrode assembly (MEA) for transportation applications. 3M's approach will optimize integration of advanced anode and cathode catalysts, based on their nanostructured thin-film (NSTF) catalyst technology platform to improve overall MEA performance, durability, robustness, and cost.[1] Specifically, 3M aims to meet or exceed near term and long term DOE goals for MEA specifications for reduced platinum (Pt) loading, power performance, durability, heat rejection, high volume manufacturing cost per kW, and system start-up response under cold or freezing conditions.

3M is working on post-processing of their Pt3Ni7 NSTF catalyst through annealing and dealloying to improve MEA rated power. Extensive integration studies of PEM – cathode catalysts and how they interact have uncovered several factors that influence performance (equivalent weight, thickness and support structure). Cold start performance improvement is being achieved by changing the anode gas diffusion layer (GDL) structure and composition as determined by modelling, materials characterization and understanding the mechanisms that anode GDL influences the MEA. Cost reduction is being accomplished by reducing the platinum group metal (PGM) content of the NSTF. 3M are continuing research to further improve MEA robustness and performance. Stack testing has been conducted at General Motors, and resultant performance and operational robustness was substantially below that obtained at single cell scale. Diagnostic experiments indicated insufficient break-in at stack scale, and new break-in procedures, developed and validated at single cell scale, are currently being evaluated for effectiveness in short-stack format.



3M's MEA using NSTF Catalyst

Technology History

- Developed by 3M Company.
- Continuing materials development, and performance improvement and fuel cell stack performance testing.

Applications

Can be used in hydrogen fuel cells for portable, stationary, and on-vehicle applications.

Capabilities

- Reduces catalyst PGM loading to 0.131 mg/cm^2 (DOE target is $\leq$ 0.125 mg/cm^2), including cathode interlayer for improved operational robustness.[2]
- Achieves heat rejection ($Q/\Delta T$) of 1.45 kW/ºC (DOE target is 1.45 kW/ºC).
- Achieves performance at 0.80V of 201mA/cm^2 (DOE target is 300 mA/cm^2).

Benefits

Cost Savings

Reduces MEA cost by using less PGM and processes that are scalable to high volume manufacturing.

Durability

MEA passes catalyst support cycle and MEA chemical tests, and achieves 2 out of 3 electrocatalyst cycle milestones.

Robustness

Improves robustness through material selection and optimization as predicted by computer modelling of MEA activity.

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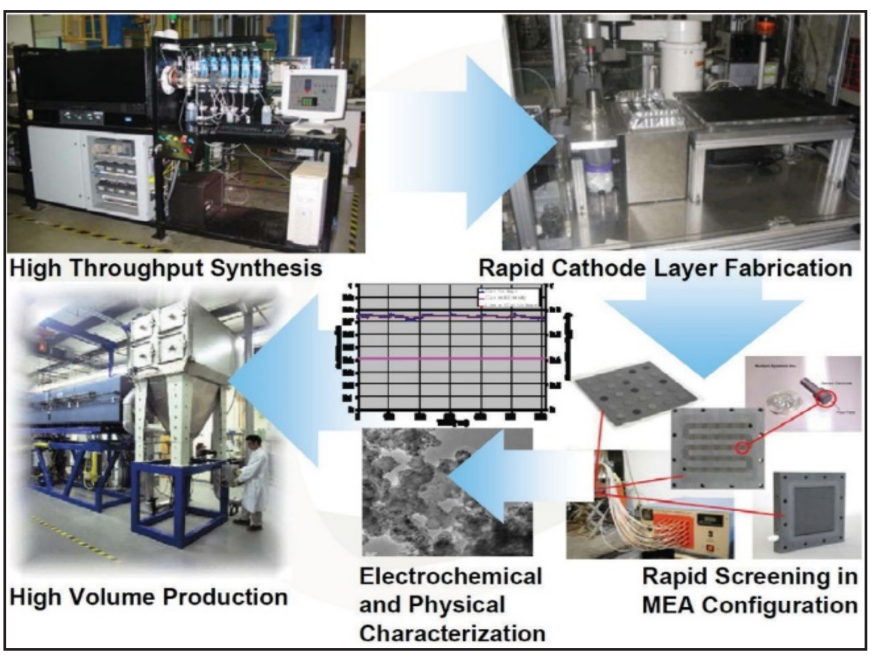
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress13/ v_c_1_steinbach_2013.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review14/fc104_ steinbach_2014_o.pdf

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, meeting the DOE target.[1] Single-cell MEA operation at lower voltages (0.7 V and 0.6 V) lead to performance of 0.3-0.4 mg Pt/kW, exceeding the DOE targets set at the beginning of the project.[2] Selected Pt-alloy compositions also demonstrate improved durability when tested under load cycling protocols.[1] 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

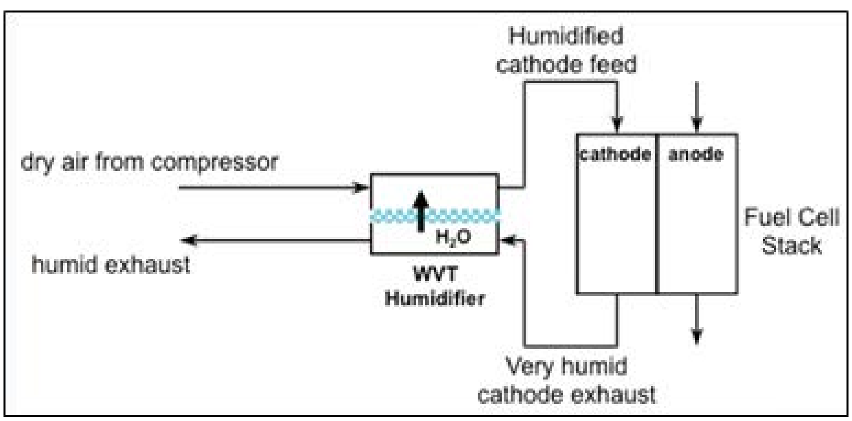
High-Performance Water Vapor Membranes to Improve Fuel Cell Balance of Plant Efficiency and Lower Costs

Emerging Technology

One of the challenges with the use of polymer electrolyte membrane (PEM) fuel cells is that PEM performs better in a moist environment, which improves the conduction of protons through the membrane. Maintaining proper humidification of the membrane is vital to the fuel cell's operating efficiency. One method for maintaining an adequate moisture level involves using a membrane-based humidifier that recovers the water vapor formed by the fuel cell's chemical reaction. Within a membrane humidifier, dry incoming oxidant gas (air) and moist cathode exhaust gas flow on opposite sides of a water-permeable membrane. The membrane transfers the water vapor to the cathode feed stream while preventing crossover of the gas streams. Currently commercialized humidification membranes are vulnerable to contamination during operation, resulting in membrane degradation and significant losses in membrane permeance.[1]

With funding from FCTO, Tetramer Technologies, LLC, and multiple project partners, including Dana Holding Corporation, General Motors Corporation, Ballard Power Systems, Inc., and Membrane Technology and Research, Inc. are developing new water vapor transfer membranes that can effectively transfer water with no chemical degradation. The aim is to focus on creating a membrane that provides multiple water transport paths while mitigating or eliminating any possible degradation reactions.

Tetramer Technologies has continued to optimize their membrane and down-selected a series of materials able to consistently achieve a water flux of > 3.0 $gs^{-1}m^{-2}$ under DOE-specified test conditions. Based on these materials, Tetramer is currently optimizing membrane configurations to further enhance performance and durability, particularly at the higher temperatures (>100°C). Tetramer developed and successfully demonstrated preliminary industrial roll coating parameters for the commercial production of water vapor membranes. Long-term durability tests are currently in progress in conjunction with post-test forensic analysis to aid further down-selection of membranes.



Tetramer's Membrane Humidification System for PEM Fuel Cells

[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress14/ v_h_1_wagener_2014.pdf

Technology History

- Developed by Tetramer Technologies, LLC, with assistance from multiple project partners.
- Currently conducting tests to optimize the water vapor transport membrane and reduce degradation.

Applications

Can be used for water vapor management within a fuel cell stack.

Capabilities

- Achieves a water flux of 3.17 g $sec^{-1}m^{-2}$ when operating at DOE-specified conditions.[1]
- Operates at > 100oC without an hydride degration.[1]

Benefits

Cost Savings

Achieves Tetramer Technologies' initial cost target of $20/m^2 and is on track to reach the DOE 2020 target of $10/m^2.

Durability

Resists chemical degradation, helping to enable the use of membrane humidifiers in demanding automotive applications.

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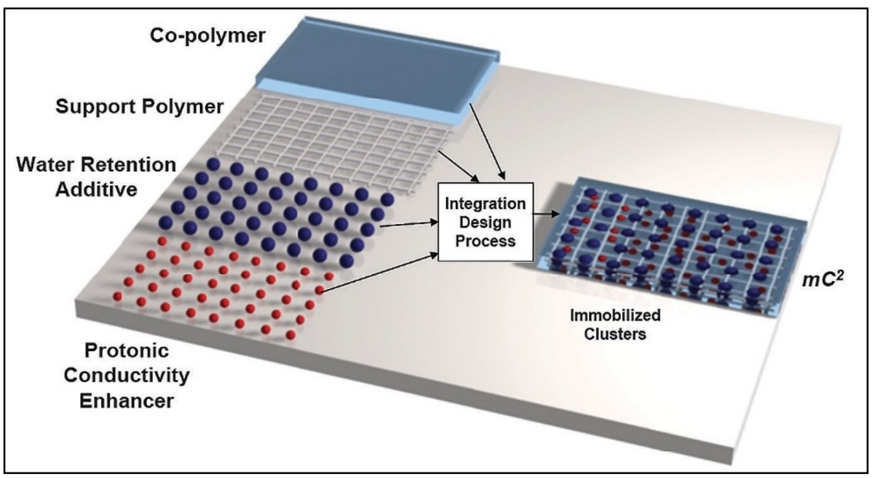
High-Temperature Membrane with Humidification-Independent Cluster Structure

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 (mC^2) 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 mC^2 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 mC^2 membrane to reach performance at rated power of 1247 mW/cm^2 (DOE 2017 target: 1000 mW/cm^2).[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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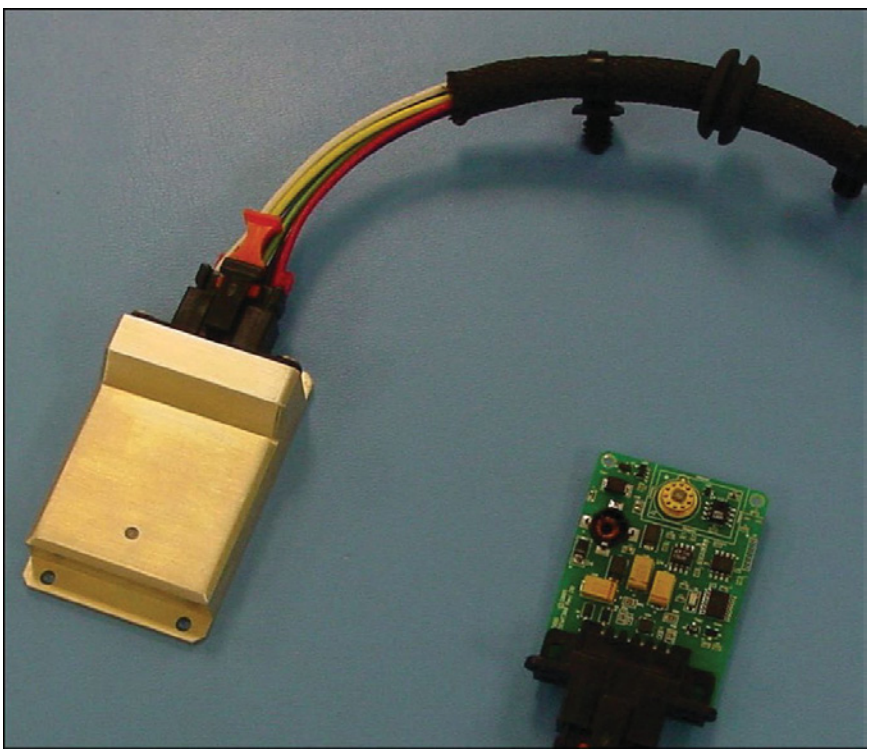
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ v_c_3_lipp_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review12/fc040_ lipp_2012_o.pdf

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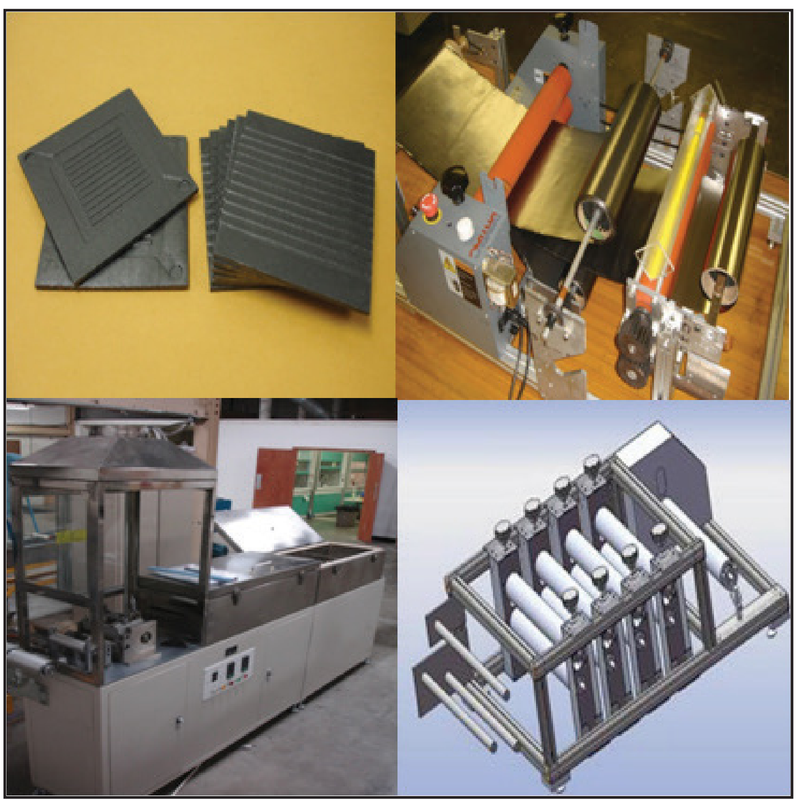
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review10/ pd043_martin_2010_p_web.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress07/ ii_k_5_martin.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress06/ v_h_3_martin.pdf

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 nanoscaled 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] 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. 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.



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.

Benefits

Productivity

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

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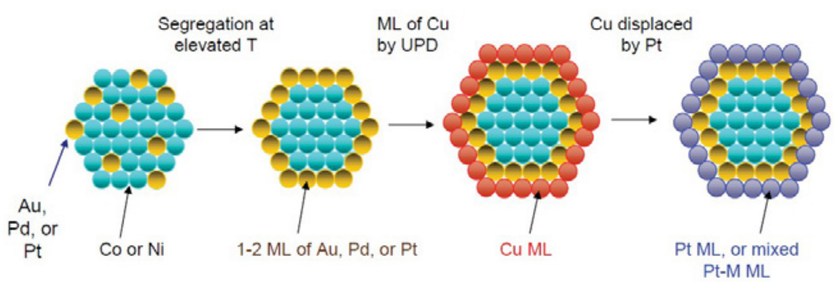
[1] For more information: http://www.freepatentsonline.com/8518603.html

Low Platinum Loading Fuel Cell Electrocatalysts

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.[2,3] 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

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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[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

Maritime Fuel Cell Generator Project

Hydrogen fuel cells have the potential to reduce emissions in maritime ports by supplying power for refrigerated containers and other auxiliary equipment (e.g., yard trucks, forklifts, and other specialty material handling equipment) that is currently powered by diesel generators. In order for hydrogen fuel cells to become more widespread in the maritime environment, their reliability in harsh marine operating conditions (e.g., large ambient temperature variations, exposure to corrosive marine air, salt water intrusion from waves, and repeated jostling from rough seas) must be validated.

Sandia National Laboratories (SNL) and its partners, Young Brothers, Ltd. (YB), Foss Maritime, Hydrogenics, Hawaii Natural Energy Institute, Hawaii Center for Advanced Transportation Technologies, American Bureau of Shipping, the US Coast Guard, and the Pacific Northwest National Laboratory, H_2 safety program, with co-funding from FCTO and the Department of Transportation's Maritime Administration, developed and demonstrated a 100-kW integrated fuel cell prototype for marine applications. In previous work, SNL identified several opportunities for demonstrating the technical and commercial viability of fuel cells in the maritime environment. One such opportunity is at the YB wharf in Honolulu harbor.[1] YB provides barge transport of goods between Oahu and the neighboring Hawaiian islands. Currently, YB is using diesel generators mounted inside mobile containers to power their refrigerated containers, used to keep perishable goods cold while on the dock and on the barge.

On-site deployment at the YB facility in Honolulu has concluded. Lessons learned from the deployment are being incorporated into an upgrade of the generator to improve reliability and operator usability. Future deployments at other host ports and companies are being arranged.[2]

SNL's Maritime Fuel Cell Generator

Technology History

- Developed by SNL, Hydrogenics, and several partners.
- Completed on-site deployment at the YB wharf in Honolulu Harbor, Honolulu, HI.

Applications

Can be used as a low-emission alternative to diesel generators for powering refrigerated containers and other auxiliary equipment used in maritime material handling applications, shorepower for marine vessels, and grid-independent port power.

Capabilities

- Produces 100 kW of electrical power.
- Stores 75 kg of compressed hydrogen.

Benefits

Emissions Reductions

Reduces fuel emissions replacing dedicated diesel generators with hydrogen fuel cells.

Versatility

Operates both on the dock and over the ocean on barges, providing power for refrigerated containers at the docks and during transit with several other applications possible.

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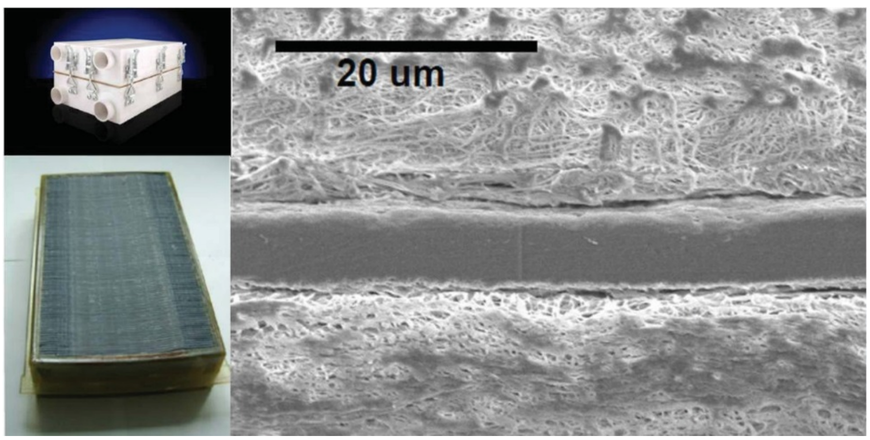
[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress14/ix_5_pratt_2014.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review16/ mt013_pratt_2016_o.pdf

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

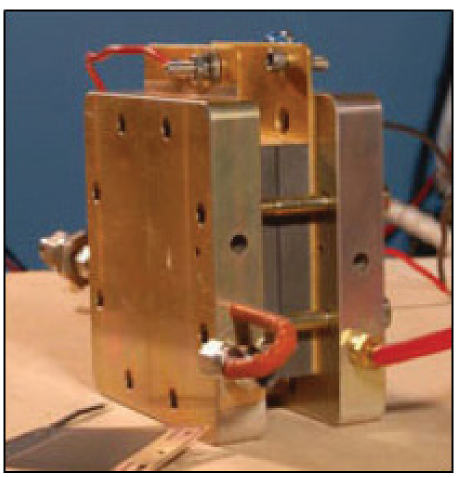
Nano Structured Metal Bipolar Plates for Low-Cost Fuel Cell Stacks

Bipolar plates represent a significant portion of the cost of a fuel cell stack, and play a key role in stack performance by directing the flow of reactant gases and conducting electric current from one cell to another in the stack. Bipolar plates with a low cost with and high performance will enable the increased use of fuel cells in automotive applications.

TreadStone Technologies, Inc., with support from FCTO, in the form an a SBIR grant, is developing a method of coating the stainless steel bipolar plates used in hydrogen fuel cell stacks with doped titanium oxide (TiOx).[1,2] TiO_2 doping forms Nb^{5+}, or Ta^{5+} within the TiO_2 lattice structure, resulting in higher electronic conductivities. To get around the challenges of TiOx being a semi-conductive material, the metal of the stainless steel plate is first coated with a titanium-niobium (Ti-Nb) or titanium-tantalum (Ti-Ta) alloy. The doped TiOx surface layer is then grown on the Ti alloy layer coating the stainless steel. With this method, TreadStone aims to identify the best composition of titanium alloy target as the coating material for PEM fuel cell applications, and demonstrate a full-size test of the coated plates in an automotive short stack (~10 cells).

TreadStone has demonstrated the superior performance of the doped TiOx coated stainless steel plates for fuel cell application in both *ex-situ* and *in-situ* tests.[3]

Both Nb- and Ta-doped TiO_X coatings meet the corrosion resistance targets, even under extreme corrosion testing conditions. There is no increase in the surface electrical contact resistance of the coated plates after the corrosion tests. Further work includes taking the fabrication process to a larger scale, process simplification, and performance demonstration in automobile stack durability tests to be conducted at the University of Hawaii with technical support and a short stack provided by Ford Motor Company.



Single-Cell Test with TreadStone's Nb-TiOx Coated Stainless Steel Bipolar Plates

Technology History

- Developed by TreadStone Technologies, Inc., with assistance from the University of Hawaii and Ford Motor Company
- Working to further develop and increase the scale of the fabrication process, and demonstrate results in durability tests.

Applications

Can be used to improve cost, resistivity, and corrosion resistance in hydrogen fuel cell stacks.

Capabilities

- Meets the corrosion resistance target of < 1 $\mu A/cm^2$.
- Achieves low electrical contact resistance (< 4 $m\Omega \cdot cm^2$).

Benefits

Cost Savings

Reduces fuel cell stack cost by using less expensive materials to make the bipolar plates while meeting performance targets.

Durability

Operates for 1,100 hours without performance degradation.

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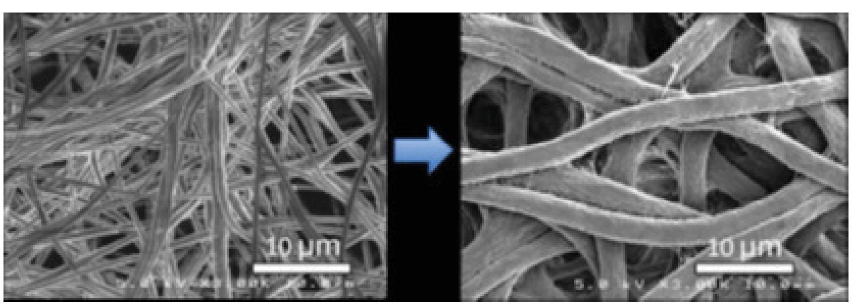
[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/ v_c_3_wang_2015.pdf
[2] For more information: https://www.sbir.gov/sbirsearch/detail/687113
[3] For more information: https://www.hydrogen.energy.gov/pdfs/review15/ fc105_wang_2015_o.pdf

New Fuel Cell Membranes with Improved Durability and Performance

Membrane resistance (i.e., poor proton conductivity) is a challenge for automotive applications where fuel cells have to operate under hot, dry conditions. Increasing the number of proton charge carriers by increasing the acid content of the membrane is one way to lessen resistance. Perfluorosulfonic acid (PFSA)- based membranes become water soluble when the acid content exceeds about 1.4 mmol/g or an equivalent weight (EW) of 700 g/mol.[1] By using multi-acid side chain (MASC) ionomers to make the membrane, membrane resistance can be decreased by increasing proton conductivity without the risk of the membrane becoming water-soluble. However, ultra-low EW membranes typically have poor mechanical properties when hydrated and therefore require a mechanical support. To counter the reduced strength and therefore durability of the MASC- based membrane, electrospun nanofibers can be used to provide support.

With funding from FCTO, 3M Company is developing new ionomers and nanofiber supports to create fuel cell membranes that have reduced resistance without compromising durability in accelerated stress tests at a commercially competitive cost. The membrane developed is a perfluoroimide acid (PFIA) ionomer, a polymer based off of 3M's PFSA polymer backbone that includes both an imide and terminal sulfonic acid group on the side chain. The nitrogen proton of the imide groups is highly acidic and functions as a proton charge carrier while the tetrafluoroethylene units in the backbone prevent the polymer from dissolving in water. The nanofibers are developed through combining 3M's traditional nanofiber cast and fill methods, and Vanderbilt University's dual fiber electrospinning of both support fibers and ionomer fibers at the same time.

The ionomers and nanofiber supports have undergone initial testing and an initial membrane has been constructed. Testing of fuel cell stacks with the PFIA membranes is currently underway, with postmortem analysis to better understand the degradation mechanisms for the membranes.



Vanderbilt Fiber Diameter Study Using 3M's Experimental PFIA Ionomer Cospun with PVDF (smaller fibers on left, larger on right)

Technology History

- Developed by 3M Company, with assistance from General Motors and Vanderbilt University.
- Currently testing the membranes in a fuel cell stack.

Applications

Can be used in PEM fuel cells for automotive or stationary applications.

Capabilities

- Exceeds DOE 2020 target for mechanical durability (>20,000 cycles until >15 mA/ cm^2 H_2 crossover).[1]
- Exceeds DOE 2020 target for chemical durability (>500 hours of operation until >15 mA/cm^2 H_2 crossover or >20% loss in open circuit voltage).[1]

Benefits

Durability

Enables ultra-low EWs (620-650 g/mol) without becoming water soluble.

Performance

Exhibits higher proton conductivity than standard PFSA-based membranes. Achives a maximum hydrogen crossover of 1.9 mA/ cm^2 (exceeding the DOE 2020 target of 2 mA/cm^2).[1]

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[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/ v_b_1_yandrasits_2015.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 interfacial contact resistance (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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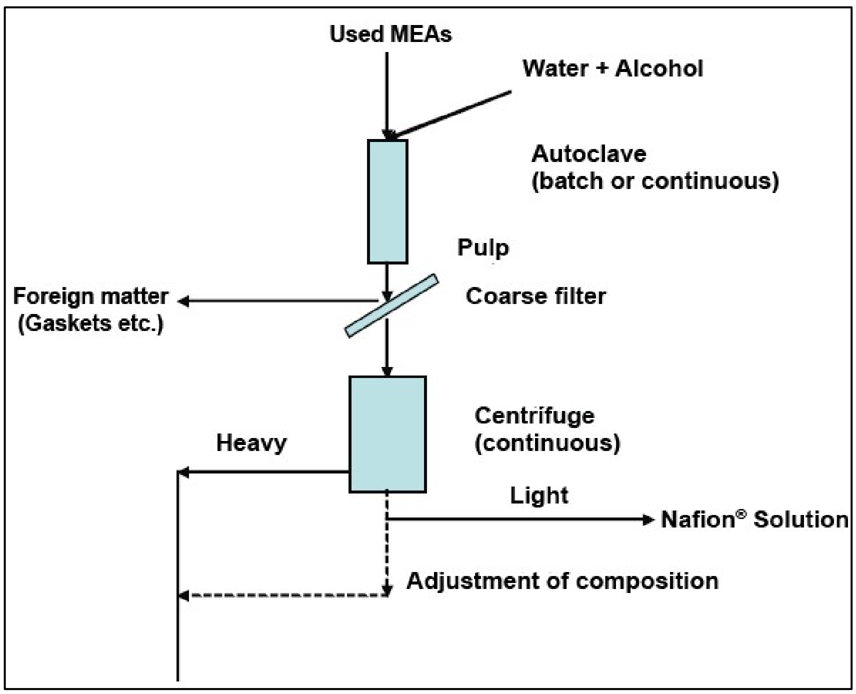
[1] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/merit03/86_ornl_mike_brady.pdf
[2] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/new_fc_tortorelli_ornl.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/ v_1_1_brady.pdf

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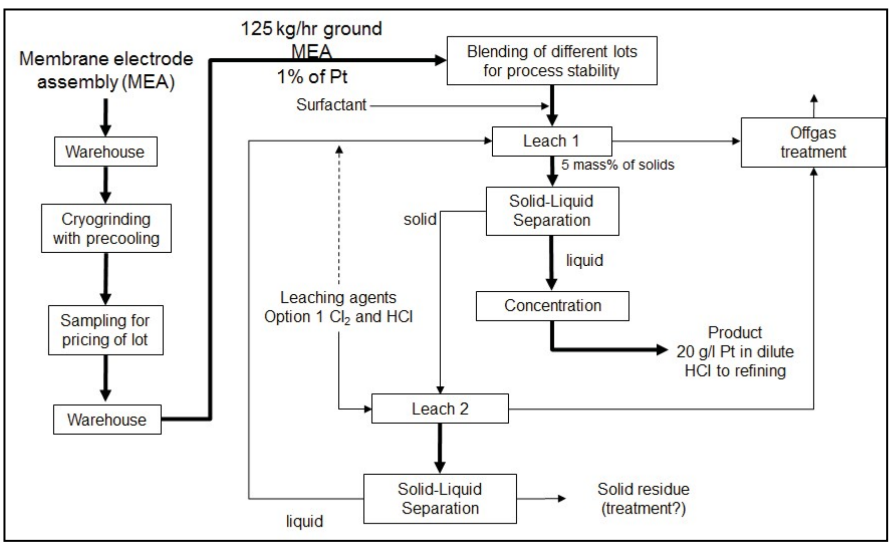
[1] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/iva7_grot.pdf

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 catalyst coated membrane (CCM) and gas diffusion electrode (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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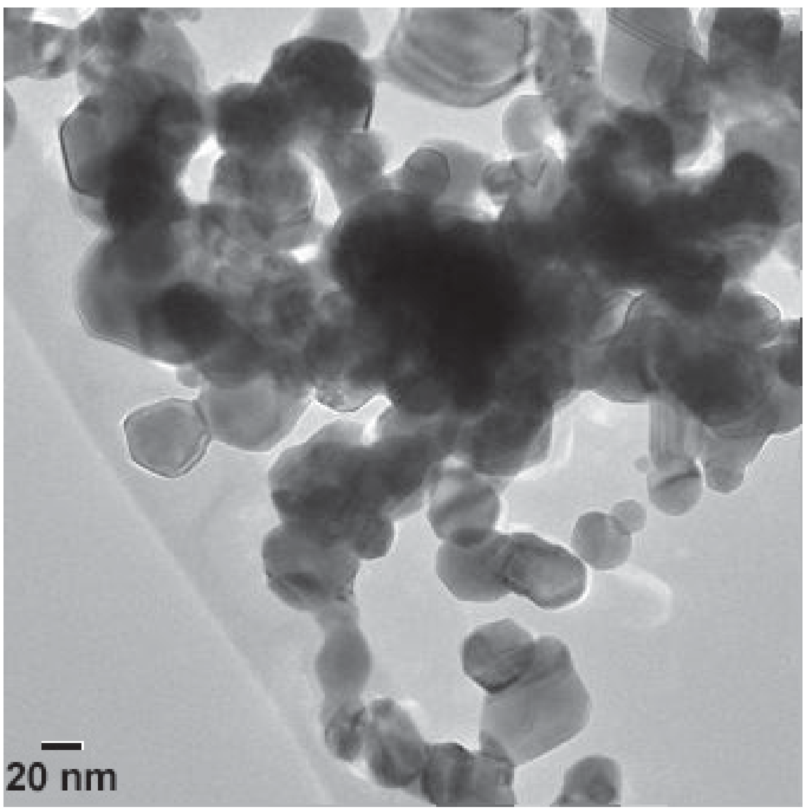
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review07/fc_30_shore.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress08/v_f_1_shore.pdf
[3] For more information: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/iva8_robertson.pdf
[4] For more information: 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 have 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 Brookhaven National Laboratory.
- 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.[3]
- Resists Pt dissolution under cycling conditions.[3]
- Reduces Pt loading.[3]

Benefits

Cost Savings

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

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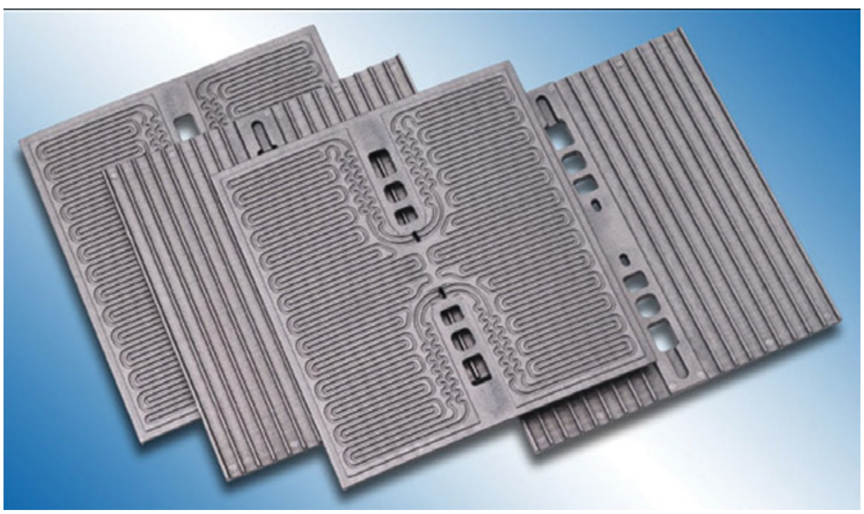
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress10/v_e_9_adzic.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/ v_d_6_adzic_2011.pdf
[3] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ v_d_6_adzic_2012.pdf

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

Roots Air Management Systems with Integrated Expander

Emerging Technology

Proton Exchange Membrane (PEM) fuel cells remain an emerging technology in the vehicle market with several cost and reliability challenges that must be overcome in order to increase market penetration and acceptance. DOE has identified the lack of cost-effective, reliable, and efficient air supply systems that meet the operational requirements of a pressurized PEM 80-kW fuel cell as a major technological barrier that must be overcome.[1]

With assistance from FCTO, Argonne National Laboratory, Strategic Analysis, and a team of industry partners, Eaton Corporation has developed the Roots Air Management System (AMS). The Roots System leverages the broad efficiency map of Eaton's Twin Vortices Series (TVS) compressor to improve overall drive cycle fuel economy. By integrating a net shape plastic expander with an aluminum compressor and motor, Eaton has reduced overall system costs and increased system efficiency. The expander was optimized through CFD modeling and collaboration with ANL. The compressor and motor were designed to minimize the part count and optimize the bearing arrangement. Low temperatures required by the expander allowed for the implementation of reduced-cost plastic components containing an integrated aluminum support structure within the expander. A cost analysis of the preliminary system design was performed by Strategic Analysis.

Final validation testing of Eaton's AMS on a fuel cell will be accomplished at Ballard Power Systems. The Roots AMS will be integrated into a Ballard PEM stack and benchmark testing will be performed to allow comparison to models developed by ANL.[2]

Eaton's Roots Air Management System

Technology History

- Developed by Eaton Corporation in partnership with Ballard Power Systems, Kettering University, Argonne National Laboratory, Strategic Analysis and Electricore, Inc.
- Currently modifying and testing Eaton's TVS Roots-type supercharger.

Applications

Can be used to improve PEM fuel cell performance on transportation applications, e.g. onboard vehicles.

Capabilities

- Reduces the compressor and expander speed to improve power consumption.
- Provides an overall higher drive cycle fuel economy via a broad efficiency map.
- Reduces AMS cost with an economic system design.

Benefits

Cost Savings

Reduces costs by reducing the number of parts and simplifying expander fabrication by using plastics.

Efficiency

Operates at lower speeds compared to incumbent technology and optimizes Roots expander design to match the optimized compressor map.

Performance

Improves system performance by using a TVS compressor and expander technology, which have a broad efficiency map.

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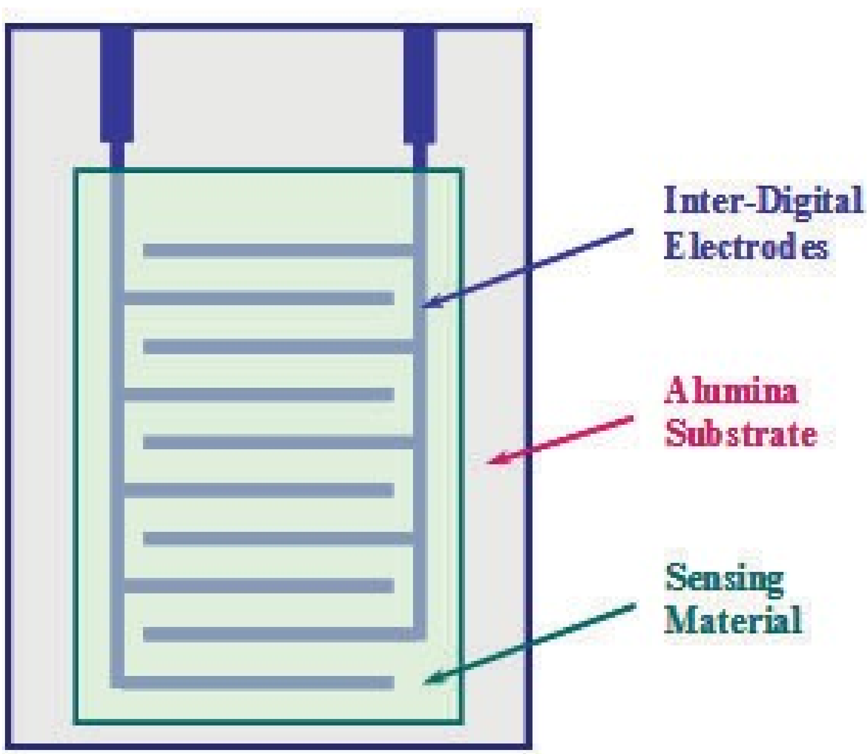
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress14/v_h_2_stretch_2014.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review14/fc103_ stretch_2014_o.pdf

Sensors for Automotive Fuel Cell Systems

Emerging Technology

In an FCTO-funded project, completed in 2005, Nexceris, LLC, formerly NexTech Materials, Ltd., developed gas sensors required for automotive fuel cell systems. As a subcontractor to UTC Fuel Cells, Nexceris 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]

Nexceris' 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 patented 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.



Nexceris' H_2S Sensor

Technology History

- Developed by Nexceris, LLC, starting in 2002 as part of DOE's Partnership for a New Generation of Vehicles Program.

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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[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

Solid Acid Fuel Cell Stack for Auxiliary Power Unit Applications

Emerging Technology

SAFCell, Inc., with funding from FCTO and DOE SBIR grants, 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 auxiliary power unit (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.[1] 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

[1] For more information: http://www.safcell.com/benefits/
[2] For more information: http://www.safcell.com/news

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.[2]

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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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, and 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 H2-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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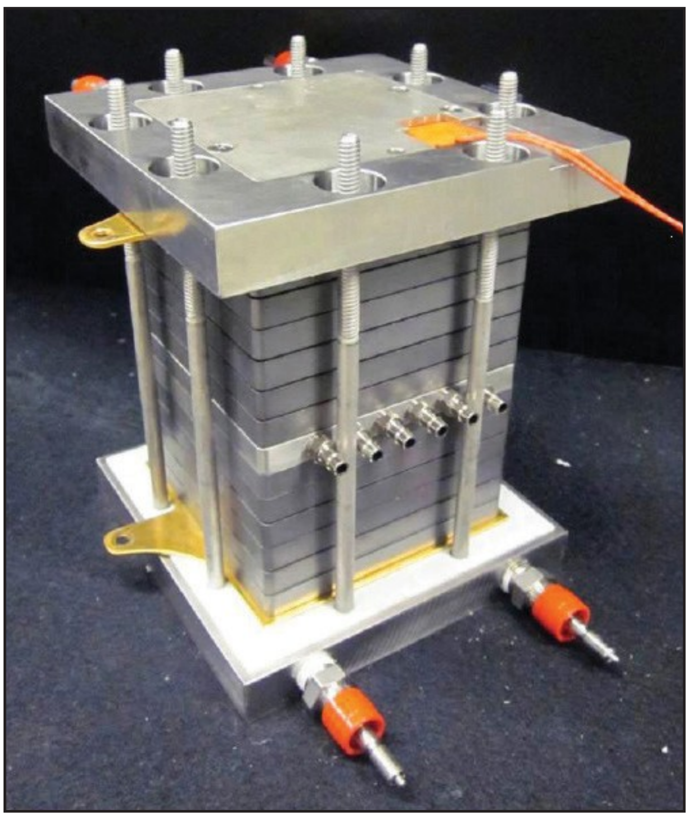
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/v_d_13_popov_2012.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review12/fc088_popov_2012_o.pdf

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 PEM fuel cell 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 matches MEAs made by traditional thermal pressing.[1] 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.
- Research was successful in 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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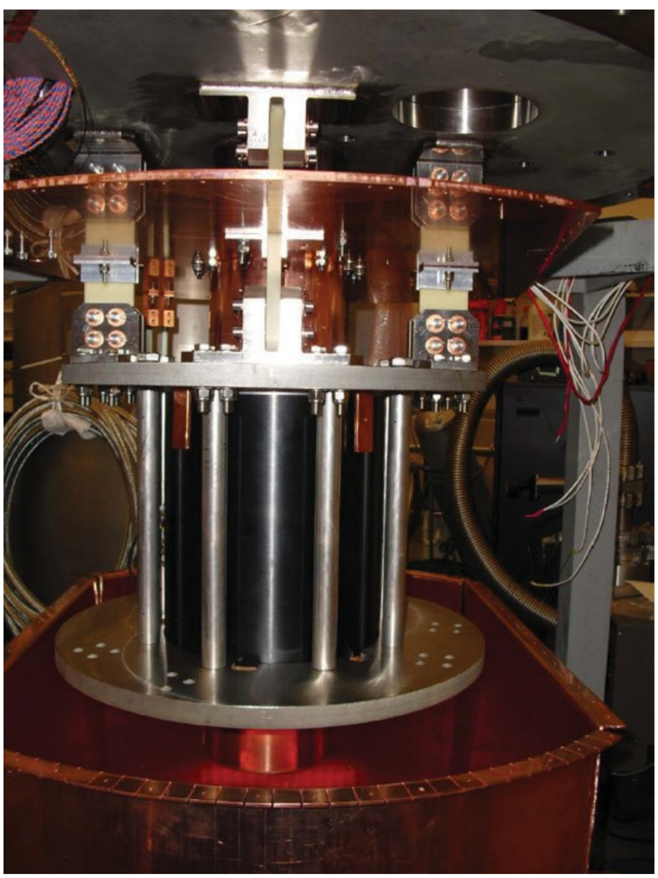
D.2 Production/Delivery Innovations

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

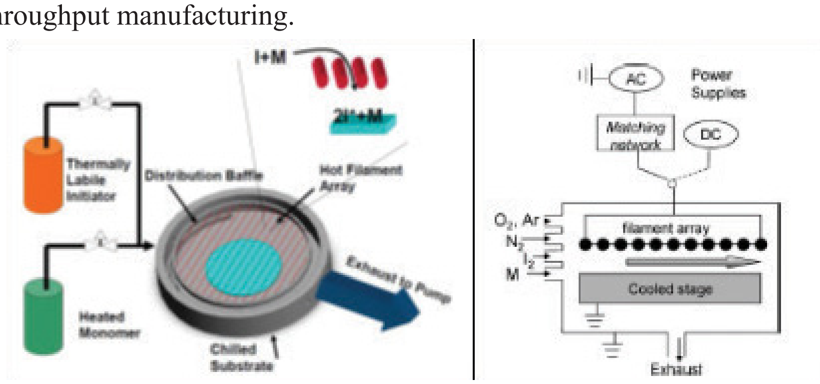
Advanced Barrier Coatings for Harsh Environments

Emerging Technology

Plastic and elastomeric seals are integral to all areas of hydrogen compression, storage, and dispensing (CSD). Seals degrade over time through use and eventually need to be replaced. This problem is further exacerbated when operating conditions for hydrogen CSD processes are carried out under extreme temperature or pressure, as the extreme conditions wear down the seals' integrity more quickly. Seal failure is not only a large cause of unscheduled maintenance for hydrogen CSD processes, it is also responsible for more than 25% of all hydrogen leaks; resulting in significant process downtime and extra operation cost.[1]

With funding from FCTO, in the form of SBIR grants, GVD Corporation, in collaboration with Greene, Tweed & Co., is developing a barrier coating for O-rings and other high-pressure hydrogen seals to prevent hydrogen from permeating out of the seal, even when operating at high temperatures and pressures. Using polymer vapor deposition, GVD Corporation is able to produce thin polymer coatings on almost any material. Two different types of coatings are used. Lubricious coatings of vapor-deposited polytetrafluoroethylene are used on rigid seals to reduce seal wear due to friction. Flexible barrier coatings comprised of alternating thin inorganic layers as a vapor barrier and polymer layers for flexibility are used for elastomeric seals to mitigate hydrogen vapor permeation. For each alternating inorganic/polymer bilayer, the gas permeability is reduced by up to an order of magnitude.[1] Advantages for the vapor deposition process include conformal coating of 3D seal geometries, depositing barrier layers in the same chamber using the same feed gas, and being more scalable and manufacturable compared to competitive solutions.

The initial barrier coating tests have finished. A barrier coating thickness of 4µm was chosen as an optimum coating thickness to pursue because it showed a 35% reduction in relative permeability during preliminary helium testing; helium had 7 times higher permeation than hydrogen. The next steps are to optimize the organic/inorganic barrier coatings using a scaled plasma-enhanced chemical vapor deposition (CVD) process. Future work will include barrier performance demonstration in relevant testing environments, (including conditions of high temperature and high pressure), demonstrating reduced wear for low friction coatings in an operational environment, and designing a tumble-coating system for high-throughput manufacturing.



GVD's modified standard deposition hardware to allow single chamber hot filament CVD (left) and plasma-enhanced CVD (right)

Technology History

- Developed by GVD Corporation in partnership with Greene, Tweed & Co.
- Finished initial testing of the barrier coatings.

Applications

Can be used as a barrier coating for O-rings and other high pressure hydrogen seals to mitigate hydrogen permeability and reduce seal wear due to friction.

Capabilities

- Improves Hydrogen CSD seal life from <1,500 hours to >8,000 hours.
- Reduces the relative permeability of helium by 35%.

Benefits

Cost Savings

Decreases hydrogen CSD cost.

Durability

Improves the lifetime of seals by 5 times

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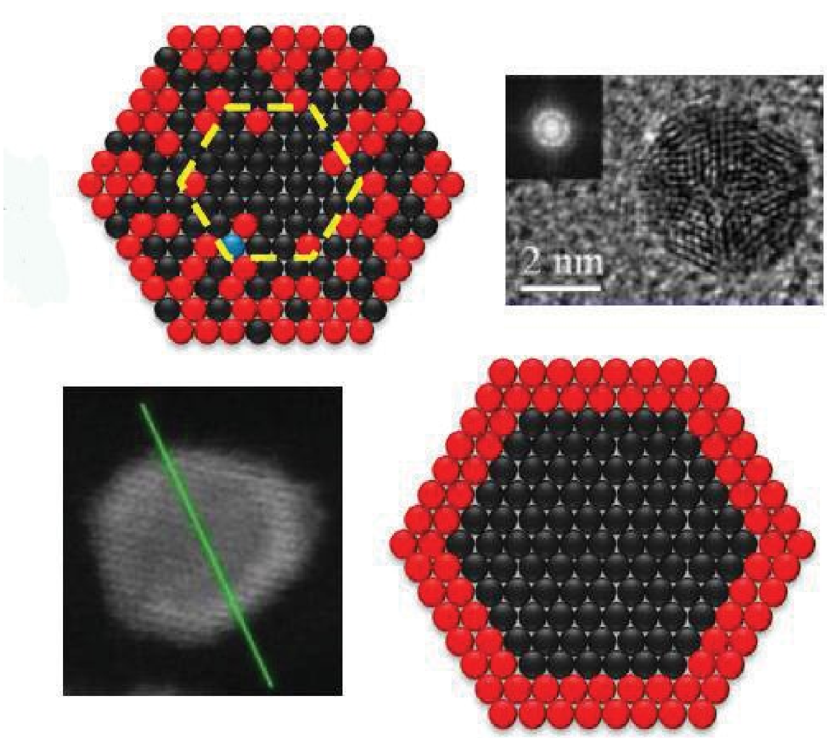
[1] For More Information: https://www.hydrogen.energy.gov/pdfs/review16/ pd132_oshaughnessy_2016_o.pdf

Catalyst/Electrodes for Hydrogen Production by Water Electrolysis

Emerging Technology

Proton OnSite, with funding from DOE SBIR grants and FCTO, is working to reduce the cost of hydrogen production via PEM electrolysis. Recent developments have lowered the cost of the flow field/bipolar plate assembly and the MEA is now the most expensive component of the electrolysis cell. The primary driver of the high MEA cost is the platinum group metals (PGMs) content and processing that can account for over half the cost. Cost reduction efforts are focusing on lowering catalyst loading of PGMs and improving deposition methods.[1,2]

Proton is investigating catalyst structures developed by Brookhaven National Laboratory for fuel cells to use in electrolysis. These materials have a high mass activity and enable reduced loading of PGMs for fuel cell MEAs. To withstand the more aggressive electrolysis reaction conditions, compared to a fuel cell, the materials are modified so that the electrodes (anode and cathode) are more durable and maintain equivalent performance. Proton aims to achieve this by increasing catalyst surface area combined with a gas diffusion electrode. Proton has selected a set of sample materials for durability testing in a commercial fuel cell stack. Proton is currently working on manufacturing processes for these electrodes and catalyst materials. Cost analysis modelling will be performed once fuel cell stack performance testing and manufacturing process scale-up is completed.[2]



Ru and Pt-Rich Optimized Catalyst (Bottom) Compared to Catalyst Made From Previous Methods(Top)

Technology History

- Developed by Proton OnSite in collaboration with Brookhaven National Laboratory.
- Continuing work to develop catalyst and electrode manufacturing processes.

Applications

Can be used to produce hydrogen using water electrolysis.

Capabilities

- Reduces catalyst PGM content by more than 90%.[2]
- Targets 2020 DOE electrolyzer system capital costs of $300 per kW.[2]

Benefits

Cost Savings

Reduces costs by using less expensive electrode and catalyst materials for MEA construction

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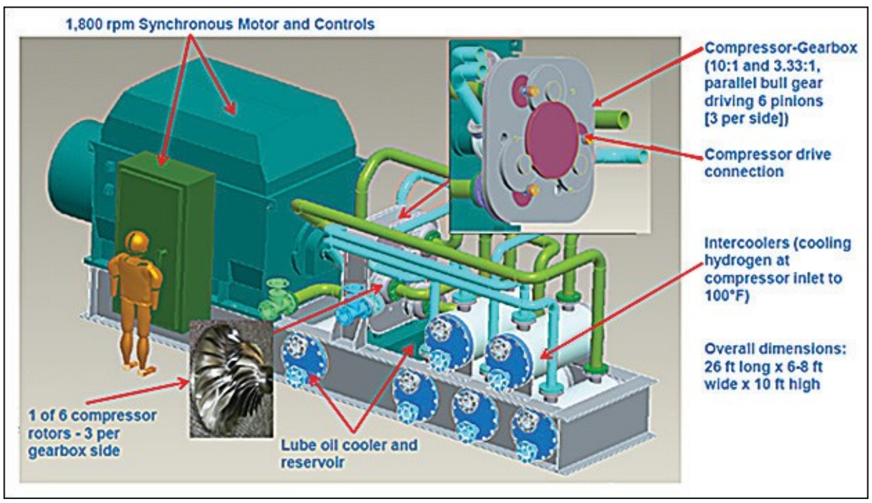
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress13/ii_a_8_ayers_2013.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review14/pd098_ayers_2014_o.pdf

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

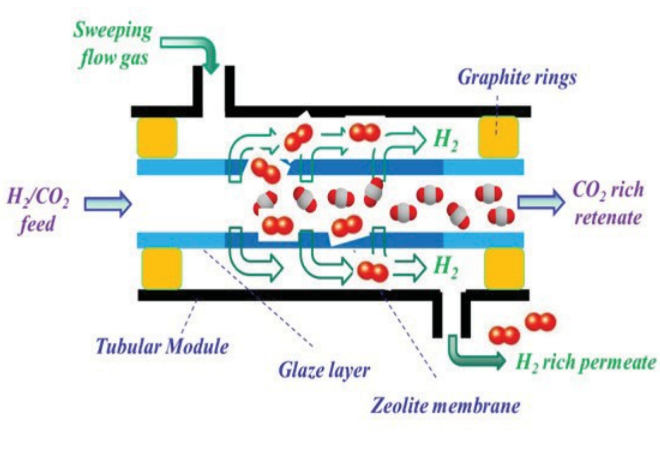
Composite Membrane for High Temperature Hydrogen Separation

Emerging Technology

Nationwide use of hydrogen produced at a DOE goal of $2.00-4.00/gasoline gallon equivalent (GGE) will require several improvements to both lower cost and increase production.[1] Currently, hydrogen is produced by using several methods that are energy intensive and complicated. Pressure swing adsorption (PSA) and cryogenic separation are two popular methods but represent large upfront costs and are relatively complicated to perform. Separation membranes offer a lower cost option that is capable of running continuously. Unfortunately, many separation membrane technologies suffer from lower selectivity and produce lower-purity hydrogen than PSA and cryogenic systems. These issues often lead to the selection of the other two systems over membranes for production of high- purity hydrogen.

Bettergy Corp., with assistance from FCTO and the University of Cincinnati, has developed a high-selectivity, thermally and chemically stable membrane for hydrogen separation. Bettergy's composite membranes offer a hydrogen separation option at lower cost than Pd or Pd-alloy membranes, with a selectivity ratio up to 70. The use of composite material also provides increased mechanical durability and allows the membrane to remain functional at high temperature, up to 500°C. The membrane can be coupled with a water-gas shift reaction to offer emissions mitigation while producing hydrogen. Bettergy has designed its composite membrane to be usable in industrial flue gas exhaust systems to both offer environmental protection and recover hydrogen for use in process streams.

Bettergy continues to develop the membrane to improve its volume/area ratio. Further work will include a project scale up for prototype production and use in demonstration facilities. Bettergy hopes to identify an industrial partner to assist with demonstration and scale up.



Bettergy's Composite Separation Membrane

Technology History

- Developed by Bettergy Corp. with the assistance of the University of Cincinnati.
- Currently working on membrane scale up to demonstration sizes.

Applications

Can be used to produce hydrogen when high selectivity and stability are needed.

Capabilities

- Offers high hydrogen separation selectivity (70) at operating temperatures of up to 500°C.
- Achieves high hydrothermal stability, chemical stability, and durability.
- Provides highly energy efficient separation.

Benefits

Cost Savings

Lowers upfront cost of hydrogen separation and recovery by replacing PSA and cryogenic systems with a low-cost composite membrane.

Productivity

Operates in high temperature and harsh environments.

Efficiency

Offers continuous hydrogen production capability for use as fuel or feedstock in industrial processes.

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[1] http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/hptt_roadmap_ june2013.pdf

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 FCTO 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.

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.

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

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

Economical Production of Hydrogen using High-Efficiency Electrocatalysts for Alkaline Membrane Electrolysis

Emerging Technology

Hydrogen production via electrolysis offers the potential of a zero-emission fuel source (when driven by renewable electricity) and can be performed at an end-user's location to eliminate the time/expense associated with hydrogen transportation. At present, there are two major types of commercially available electrolyzers: systems using liquid potassium hydroxide as the electrolyte and solid-state systems using a proton exchange membrane (PEM) as the electrolyte. The PEM-based electrolyzers offer advantages (higher current density and improved safety) over the liquid-based systems but have high material costs.[1] The largest contributors to the high cost are the noble-metal catalysts (e.g., platinum) and titanium flow field plates that are required for operation in the acidic environment of PEM electrolyzers.

With funding from DOE SBIR grants, Proton OnSite is developing an anion exchange membrane (AEM) electrolyzer that will address the cost concerns of the PEM systems. The use of an alkaline (as opposed to an acidic) electrolyte membrane enables the use of lower cost stainless steel flow field plates and less- expensive catalysts. Proton OnSite investigated the use of pyrochlore catalysts (compounds of the form $A_2B_2O_{6-7}$, where A is bismuth or lead, and B is ruthenium or iridium) for the oxygen evolution electrode and observed improved efficiency over baseline noble metal oxide catalysts.

Proton OnSite developed a prototype AEM electrolysis system and is currently conducting durability testing on the system. Future work includes electrode and stack scale-up and additional optimization of the system.

Proton's Prototype AEM Electrolysis System

Technology History

- Developed by Proton OnSite, with assistance from multiple universities.
- Currently conducting durability testing on an initial prototype system.

Applications

Can be used to reduce the cost of hydrogen production for a variety of end-use applications (e.g., high-purity gas for laboratory instruments or as a storage medium for renewable energy).

Capabilities

- Achieves a levelized hydrogen production cost of \$3.46/kg (DOE 2015 target: \$3.90/kg; DOE 2020 target: \$2.30/kg).[2]
- Achieves an electrolyzer stack energy efficiency of 67% (DOE 2015 target: 76%; DOE 2020 target: 77%).[2]

Benefits

Cost Savings

Reduces electrolyzer stack costs by using non-noble metal catalysts and stainless steel flow field plates.

Environment

Enables full utilization of renewable energy sources during off-peak hours (e.g., nighttime wind energy) by storing energy in the form of hydrogen.

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[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress13/ ii_a_5_ayers_2013.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/progress14/ ii_b_2_ayers_2014.pdf

Efficient Solid-State Electrochemical Hydrogen Compressor Emerging Technology

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

Flexhose: Cryogenically Flexible, Low Permeability Thoraeus Rubber Hydrogen Dispenser Hose

Widespread adoption of hydrogen-based transportation in the United States requires the implementation of safe, reliable, and low-cost hydrogen refueling stations. Cryogenic high-pressure storage will be needed to maintain the volumes of hydrogen required for integration of hydrogen vehicles in the U.S. vehicle fleet. Unfortunately, refueling hoses that use stainless steel support components are incompatible with high-pressure cryogenic storage due to hydrogen-induced cracking in the steel components.[1] Adoption of a hydrogen-based infrastructure will necessitate the development of new materials for refueling stations.

NanoSonic, Inc., with assistance from FCTO, in collaboration with NREL and industry partners has developed a cryogenically flexible, low-permeability, high- pressure delivery hose - Flexhose. NanoSonic's Flexhose was designed to offer flexible use with cryogenic hydrogen at 875 Bar. HybridSil, a fiber-reinforced low-permeance resin, is braided into the hose to prevent embrittlement from infiltration of hydrogen.[2] A low glass transition temperature (T_g) polymer was also developed and used in the hose to create fold tolerance and to be electrically non-conductive even after bending 180 degrees at cryogenic temperatures. MetalRuber™ is also added to the hose materials to provide EMI shielding and textile reinforcement against mechanical stresses. The hose is rated to perform constantly at a pressure of 875 Bar for over 50,000 hydrogen fills.

NanoSonic is working with its project partners to evaluate the Flexhose against industry guidelines and verify the compatibility of the hose with domestic hydrogen delivery specifications. Following qualification, Flexhose will be transferred to hydrogen dispensing stations in California and refueling equipment manufacturers for system integration and cost analysis.

Nanosonic's Flexhose

Technology History

- Developed by NanoSonic, Inc., CSA Group, NREL, Fittings Partner, WEH USA, and Giles County Government.
- Currently testing hose capabilities and specifications.

Applications

Can be used in cryogenic hydrogen fueling stations to dispense fuel.

Capabilities

- Provides hose flexibility at cryogenic temperatures.
- Achieves high pressure hydrogen fueling requirements at 875 Bar.
- Provides 25,550 annual refueling cycles.
- Electrically nonconducting.

Benefits

Cost Savings

Reduces hydrogen losses to evaporation during fueling using a low hydrogen permeability resin layer within the hose.

Durability

Thoraeus Rubber™ and low T_g resins maintain hose integrity even when bent to 180° and eliminate hydrogen embrittlement.

Safety

Achieves a maximum pulse pressure more than twice the 875 Bar required by fueling safety codes.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review14/pd101_lalli_2014_o.pdf

[2] For more information: http://www.hydrogen.energy.gov/pdfs/review15/pd101_lalli_2015_o.pdf

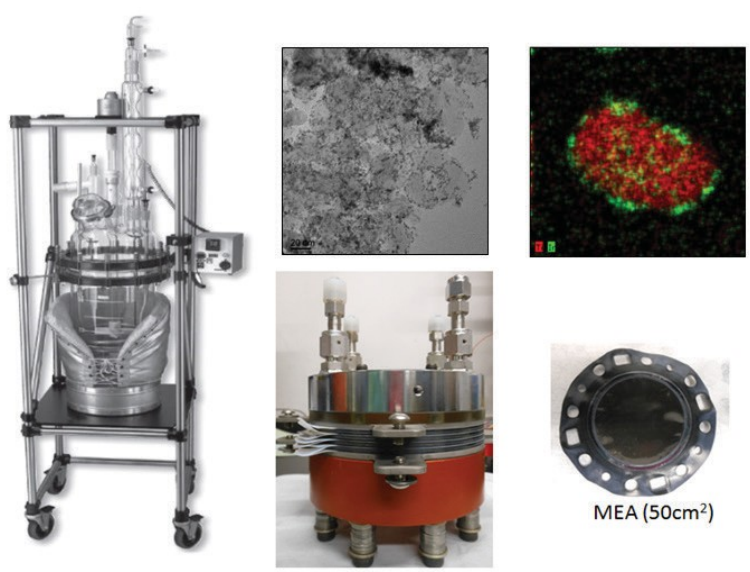
High-Performance, Long-Lifetime Catalysts for Proton Exchange Membrane Electrolysis

Emerging Technology

FCTO's Multi-Year Research, Development, and Demonstration Plan identifies water electrolysis via hydrogen production capital cost, system efficiency and electricity cost as technical barriers that must be overcome to attain hydrogen production 2020 goals. Currently, the high capital cost prohibit widespread adoption of electrolysis for hydrogen production, development to improve efficiency, durability and larger systems is needed. The commercial viability of electrolysis hydrogen production is also dependent on system energy efficiency which requires electricity cost below \$0.04/kWh to meet FCTO targets.[1]

Giner, Inc., with assistance from FCTO and a team of partners, are developing low platinum group metal (PGM) catalysts to improve the efficiency and lifetime of proton exchange membranes (PEMs) for water electrolysis. Giner are investigating iridium (Ir) nanotube supports and nanowires at a reduced Ir loading per unit area of 0.5mg/cm^2 compared to over 5.0mg/ cm^2 typically. The activity of a tungsten doped titanium oxide (W-TiO_2) catalyst developed specifically for this project with the 3M Company when combined with the Ir based nanotube supports and nanowires increased 2 – 3 times compared to the baseline Ir catalyst.[2]

A 6 cell electrolyzer stack that was constructed using Ir/W-TiO_2 based membranes exhibited promising performance test results and has successfully surpassed 1000 hours of durability testing. Future work will include extended durability testing in harsh conditions and improving the catalyst performance by varying Ir deposition. Giner and 3M have also successfully developed a roll-roll production process for producing the nanostructured thin film (NSTF) catalysts, further enabling reduced electrolyzer system cost.



Giner's Ir/$W_XTi1\text{-}_XO_2$ based Catalyst Reactor, Catalyst Images and Test Cells and 6-Cell Stack

Technology History

- Developed by Giner, Inc. with collaboration from the 3M Company and NREL.
- Currently investigating further enhancing catalyst performance and conducting durability tests.

Applications

Can be used for hydrogen production by water electrolysis.

Capabilities

- Provides enhanced catalyst performance by increasing the oxygen evolution reaction (OER), mass and specific activities compared to baseline Ir black catalyst.
- Achieves catalyst performance with reduced PGM and Ir loading (up to 8x less).

Benefits

Cost

Reduces capital electrolyzer system cost by using a roll-roll processing to produce high performance catalysts using less costly materials (PGMs and Ir loading).

Efficiency

Increases electrolyzer system efficiency using nanotechnology to enhance catalyst performance and durability.

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[1] For more information: http://energy.gov/sites/prod/files/2015/06/f23/fcto_myrdd_production.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/progress14/ii_b_4_xu_2014.pdf

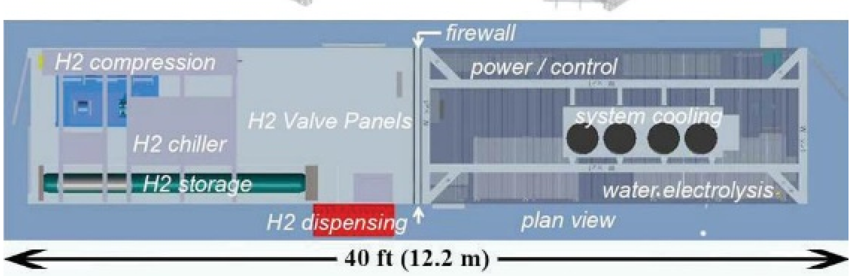
High-Pressure PEM Electrolyzer and Composite Tube Hydrogen Storage

Emerging Technology

To address some of the technical barriers of establishing a hydrogen fueling infrastructure, Proton OnSite, with FCTO funding and in collaboration with SunHydro LLC, are developing containerized hydrogen fueling stations. To demonstrate the viability of these infrastructure components, Proton will use recently developed higher pressure hydrogen generation with compression and composite storage technologies combined with new packaging concepts for a reduced on site station footprint. Technology demonstrations will be conducted at two SunHydro hydrogen fueling stations.[1]

The containerized station is designed to meet initial demand for a small, manufactured hydrogen fueling infrastructure such that it is scalable and can be deployed quickly. The design integrates all the necessary hydrogen generation, storage and fueling components in an intermodal transport ISO container. This design concept will ease permitting issues because the smaller footprint with novel, integrated component arrangements minimizes code-directed clearances and enhances safety. Station performance will be monitored quarterly for hydrogen produced, stored, and dispensed as well as energy consumption by major station subcomponents.[1]

Proton and SunHydro started technology validation in early 2011 at a SunHydro site, Station #1 in Wallingford, CT and have dispensed over 10,000 kg of hydrogen and performed over 3,500 high-pressure hydrogen fills as of early 2015. Proton's near term work has increased (doubled) this site's storage capacity and demonstrated 55 bar H_2 generation resulting in reduced compression energy. The containerized system to be installed at a second SunHydro site, Station #2 in Braintree, MA, is currently under construction and is scheduled to be deployed in Washington DC.



Proton OnSite's "Containerized" H_2 Generation, Storage and Fueling

Technology History

- Developed by Proton OnSite in collaboration with SunHydro LLC.
- Continuing work to complete pilot station system upgrades and installation, and to commercialize and expand hydrogen fueling services and systems.

Applications

Can be used to provide hydrogen fueling services and establishing a hydrogen infrastructure.

Capabilities

- Provides high pressure hydrogen generation (30 bar and 55 bar).[1]
- Provides modular and scalable hydrogen generation, storage and fueling consumption.

Benefits

Cost Savings

Provides simple installation with compact footprint that is intended to be compliant with hydrogen code and safety regulation requirements.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress13/vii_5_moulthrop_2013.pdf

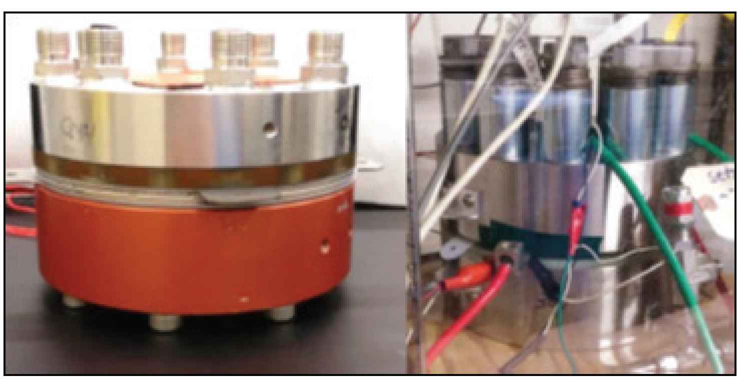
High Temperature, High Pressure Electrolysis

Emerging Technology

Electrolysis of water is an important tool for energy storage in wind and solar applications. DOE has identified a need for electrolyzer efficiencies to reach 77% Lower Heating Value (LHV) by 2020. High-pressure direct electrolysis is a desirable method for energy storage and hydrogen generation, due to the reduced need for high-pressure pumps and compressors. Direct electrolysis at elevated pressure permits hydrogen and/or oxygen tanks to be refilled directly, and reduces the overall mass, complexity, and cost of the electrolysis system.

With funding from FCTO, Giner, Inc., is developing a non-perfluorinated-ionomer polymer electrolyte membrane (PEM) that has conductivity to permeability (C/P) ratios above two times that of Nafion® membranes, which were used for baseline durability testing.[1] Membrane efficiency can be increased by operation at a higher temperature, which increases both conductivity and oxygen kinetics. However, increasing temperature increases a membrane's permeability. Higher pressure operation also increases gas crossover which decreases overall efficiency and accelerates membrane degradation while leading to potentially dangerous levels of hydrogen in oxygen and vice versa. Increasing the membrane thickness or lowering the operating temperature can decrease crossover, but also decreases efficiency. To circumvent these issues, Giner plans to increase efficiency by increasing the C/P ratio while operating at as high a temperature as possible without compromising the membrane.

Initial testing was conducted on 15 different ionomers: one unmodified Nafion, six perfluorinated sulfonic acid (PFSA) membranes (three modified N1100 membranes and three low equivalent weight membranes), and eight hydrocarbon-based membranes made by Virginia Tech. The initial stage of the project has been completed, with three of the hydrocarbon membranes exceeding the C/P goal ratio of 2. One of the PFSA membranes, the Solvay Aquivion 790, comes close with a C/P ratio of 1.7. In the interest of keeping a PFSA membrane in the study along with increasing the C/P ratio with novel treatments, the Solvay ionomer will be included in the next stage of testing. Further testing will focus on medium pressure testing for durability and performance.[2]



Giner's Fuel Cell Stack Hardware

Technology History

- Developed by Giner, Inc., with assistance from Virginia Polytechnic Institute and State University (Virginia Tech).Four promising membranes have been identified at the end of Phase I testing.

Applications

Can be used to increase the efficiency of the PEM while providing hydrogen at a pressure of 350 bar.

Capabilities

- Developed three hydrocarbon-based membranes that have a C/P ratio greater than 2.0 times that of Nafion.
- Withstands a differential operating pressure of 350 bar on the electrolyzer stack.

Benefits

Durability

Operates at high temperatures and pressures.

Efficiency

Achieves the 2015 DOE goal of 76% LHV electrolyzer efficiency.

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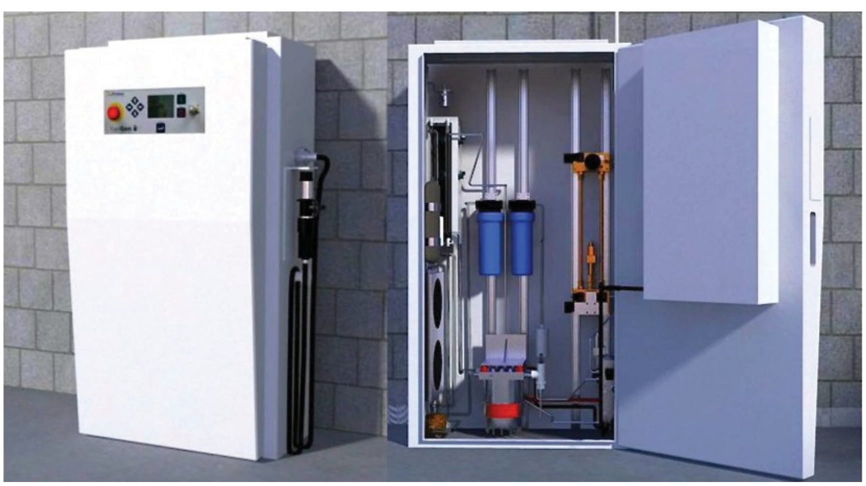
[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/ii_b_4_mittelsteadt_2015.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review15/pd117_mittelsteadt_2015_o.pdf

Hydrogen by Wire — Home Fueling System

Emerging Technology

Proton OnSite, 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

Technology History

- Developed by Proton OnSite.
- 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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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/pd067_dalton_2013_p.pdf

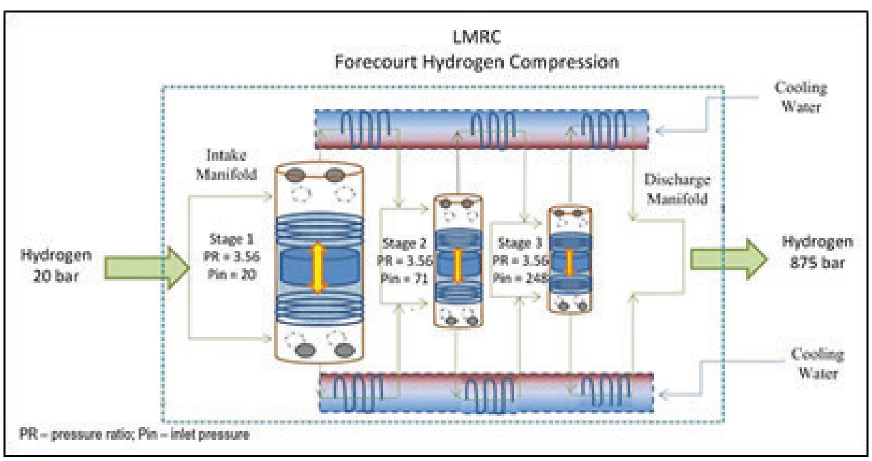
Hydrogen Compression Application of the Linear Motor Reciprocating Compressor (LMRC)

Emerging Technology

With funding from FCTO, Southwest Research Institute (SwRI) and ACI Services, Inc., are developing a linear motor reciprocating compressor (LMRC) system with the goal of increasing the efficiency and reducing the cost of forecourt hydrogen compression. The LMRC replaces a conventional reciprocating compressor (electric motor, crankshaft, and one or more pistons) with a system in which a disc-shaped permanent magnet acts like a piston by being driven back and forth inside an electromagnetic coil. Gas introduced at the ends of the cylinder is compressed by the reciprocating motion of the magnet.

The LMRC does not have metal-to-metal contact between the piston and cylinder walls, which reduces friction and eliminates the need for lubrication oil. The reduced friction and other design features (low piston speeds, low-pressure- drop, contoured valves, and intercooling between compression stages) improve compression efficiency.[1] SwRI anticipates that the LMRC will be able to achieve a compressor specific energy of ~1.3 kWh/kg H_2 compressed from 100 bar to 950 bar.[1] (For comparison, the DOE 2020 target for small [100 kg H_2/ hour peak flow] forecourt compressors under these conditions is 1.6 kWh/kg.)[2]

SwRI completed the design and finite element analysis modeling of the LMRC. Future work includes parts fabrication, assembly of a complete LRMC unit, and testing of the assembled unit.



SwRI's Three-Stage LMRC System

Technology History

- Developed by Southwest Research Institute with assistance from ACI Services, Inc.
- Currently transitioning from completed design to assembling and testing of the LMRC.

Applications

Can be used to provide low-cost, high-efficiency compression of hydrogen at forecourt fueling stations.

Capabilities

- Achieves a compressor specific energy of ~1.3 kWh/kg H_2 compressed from 100 bar to 950 bar (DOE 2020 target for these conditions is 1.6 kWh/kg).[1]
- Maintains ceramic seal life for up to 48 months (assuming an operation time of around 6 hours per day).[1]

Benefits

Cost Savings

Reduces capital costs compared with conventional reciprocating compressors by minimizing part count.

Durability

Reduces wear-related maintenance compared with conventional reciprocating compressors by reducing friction and reducing the number of wear components.

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[1] For more information: https://www.hydrogen.energy.gov/pdfs/review16/pd108_broerman_2016_o.pdf
[2] For more information: http://energy.gov/eere/fuelcells/doe-technical-targets- hydrogen-delivery

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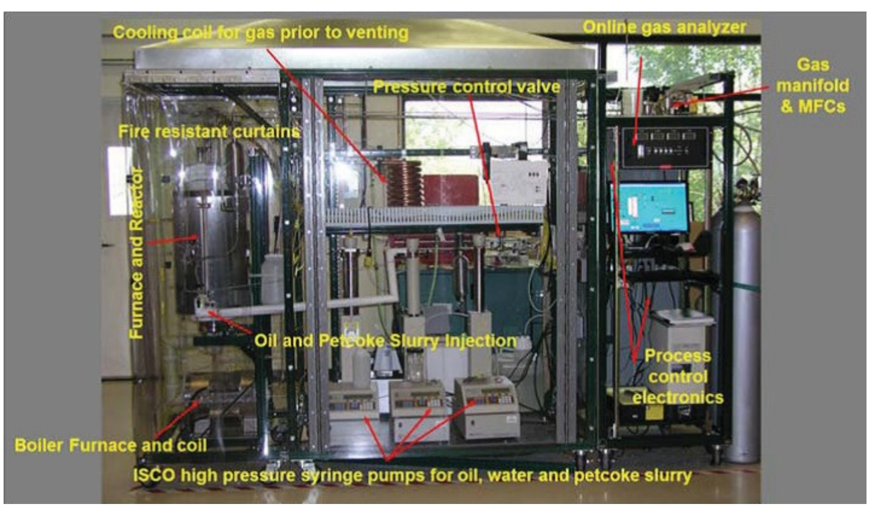
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/ viii_14_lieberman_2011.pdf
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review10/scs014_lieberman_2010_o_web.pdf

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

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.
- Converts 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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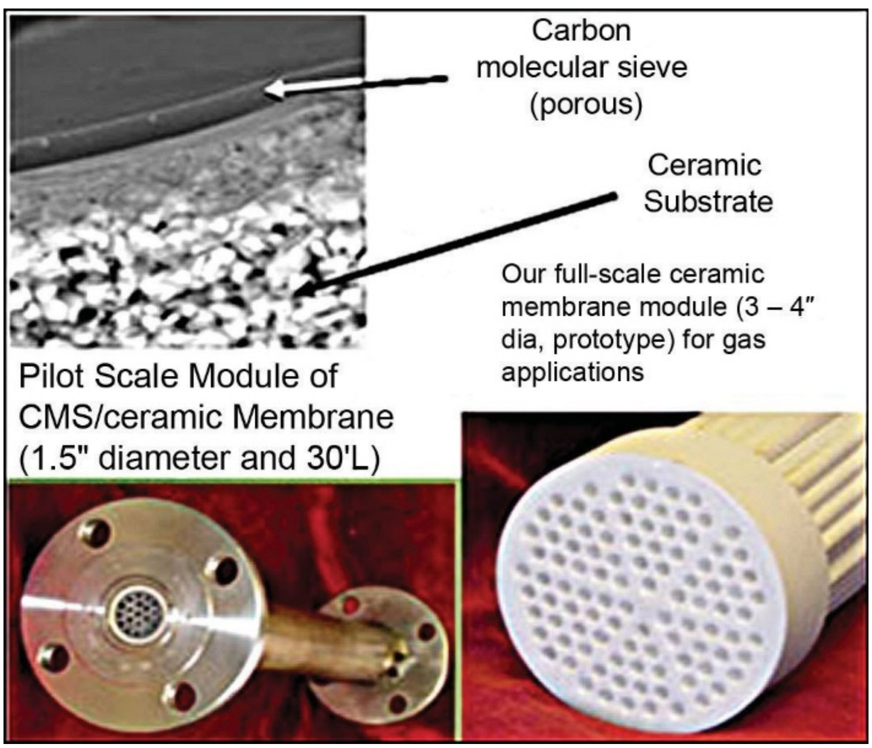
[1] For more information: https://aiche.confex.com/aiche/s12/webprogram/Pa- per245516.html

Hydrogen Production via a Commercially Ready Inorganic Membrane Reactor

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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Hydrogen Station Equipment Performance (HyStEP) Device

Emerging Technology

Hydrogen vehicles and fueling stations are starting to see more use in the automotive industry. However, the current practice of accepting hydrogen stations involves vehicle original equipment manufacturers (OEMs) evaluating each station before the station is accepted for their vehicle platform. Because each OEM conducts their own testing and evaluations, it can take months to get approval for a single hydrogen station. In areas like California, where 51 hydrogen stations are scheduled to be in operation by the end of 2016, with subsequent funding expecting to result in 86 stations by 2021, the timeline for station acceptance can be exceptionally long and requires a different solution.

With funding from FCTO, Sandia National Laboratories (SNL) and multiple project partners have developed the Hydrogen Station Equipment Performance (HyStEP) Device to assist with station certification.[1] The HyStEP is able to verify station fueling protocol following tests defined in the Canadian Standards Association (CSA) HGV 4.3 test method to ensure safe and reliable operations. This test method includes general fault detection, communication and fueling protocol tests. General fault detection testing verifies that a dispenser will not dispense fuel or stop fueling a vehicle if any of the test requirements are not met. Communication tests verify that the dispenser responds correctly to vehicle fueling status signals, and that fuel dispensing stops fueling or switches to non-communication fueling when communications are lost or signal values are out of range. Fueling protocol testing verifies that the dispenser selects the correct fueling protocol per the fueling protocol standard SAE J2601. This protocol is based on the pressure category, pre-cooling temperature, communications mode, and the size of compressed hydrogen storage system (CHSS). Additionally, the CHSS initial pressure and ambient temperature are used to verify that the dispenser chooses the correct average pressure ramp rate and target pressure (if applicable). A matrix of fueling protocol tests is defined such that all dispenser functions are evaluated with a minimum number of tests.

The HyStEP device is currently being deployed by CARB through a loan agreement with SNL. Stations are actively being tested to determine compliance with fueling protocol standards.[2]

Interior of HyStEP Trailer Showing Major Subsystems (left)
On Site at Powertech's H_2 dispenser (right)

Technology History

- Developed by Sandia National Laboratories and multiple project partners (Powertech Labs, National Renewable Energy Laboratory, Air Liquide, Boyd Hydrogen, California Air Resources Board (CARB), Toyota, and Pacific Northwest National Laboratory)
- Device design completed and approved for fabrication in Q1 2015; currently being deployed by CARB through a loan agreement with SNL, with additional field tests underway.

Applications

Can be used to decrease time required to commission new hydrogen fueling stations from weeks to days.

Capabilities

- Compatible with most trailer mounts.
- Includes 3 Type IV 70 MPa H_2 tanks with a total capacity of 9kg H_2 and pressure and temperature sensors.
- Performs all CSA HGV 4.3 tests within the under test fueling station's limitations.

Benefits

Efficiency

Validates hydrogen refueling stations more efficiently compared to current methods. The HyStEP test matrix can be completed within three days.

Mobility

Uses a trailer-mounted platform, which enables movement of the device to the most convenient location for station validation.

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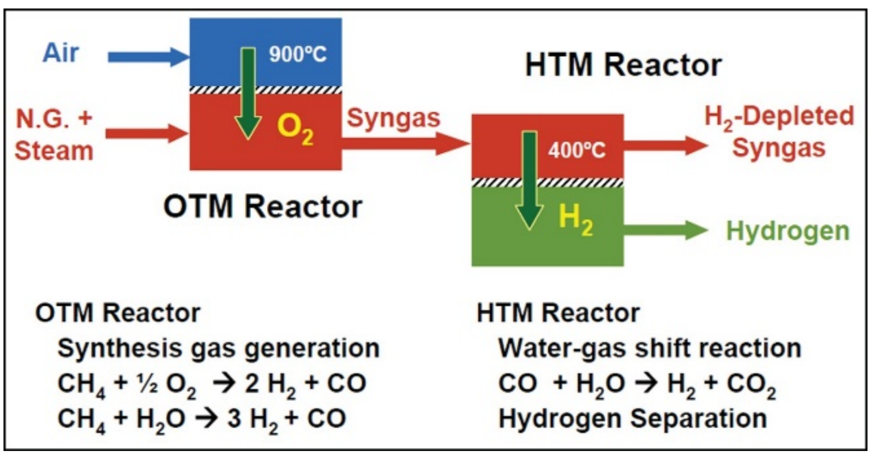
[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/vii_7_johnson_2015.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review16/ tv026_johnson_2016_o.pdf

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.
- Increases production of high-purity hydrogen from syngas.

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

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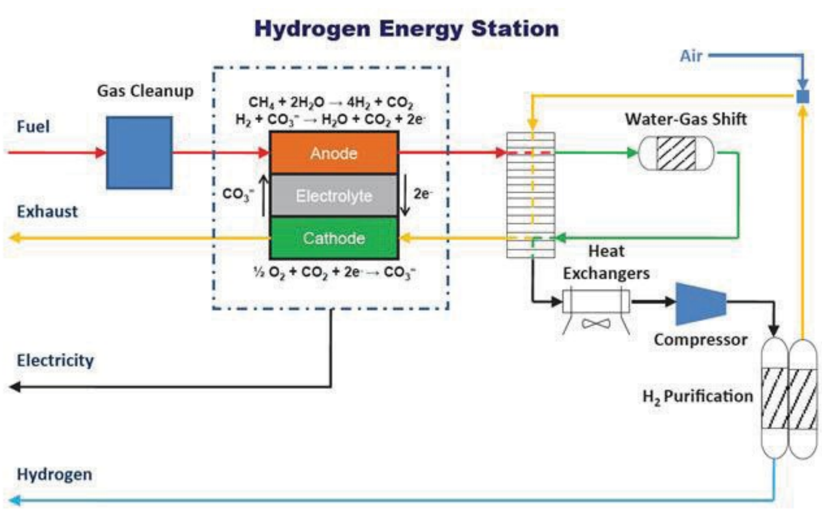
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/ ii_d_1_schwartz_2011.pdf

Integrated Hydrogen Energy Station

The development of hydrogen as a transportation fuel will require a hydrogen fueling infrastructure. Air Products and Chemicals, Inc., with FCTO funding, is developing and demonstrating the technical and economic viability of a hydrogen energy station using a high-temperature fuel cell designed to produce power and hydrogen from natural gas and other feedstock sources.[1] The co- production of power and hydrogen was chosen to improve the economics and liability of a stand-alone hydrogen fueling facility. Air Products designed and fabricated a high-temperature fuel cell co-production concept with safety the top priority in the system's design and operation.

Air Products chose a commercially available fuel cell, FuelCell Energy's DFC®- 300 molten carbonate fuel cell and modified it to allow for the recovery and purification of hydrogen from the fuel cell anode exhaust using an Air Products- designed hydrogen purification system.[1] The DFC technology works by internal reforming of hydrocarbon fuels inside the fuel cell via an endothermic reforming reaction with the exothermic fuel cell reaction. The reformer-fuel cell integration leads to approximately 50% electrical efficiency. The power plant (electricity only) is designed to operate at 75% fuel utilization in the stack with the remaining 25% fuel representing an opportunity for low-cost hydrogen recovery once separated and purified from the dilute anode effluent gases.

In 2010, design, fabrication, and shop testing were completed and operation began using renewable feedstock at the Orange County Sanitation District in California. The system completed its 3 year demonstration program in May of 2014.[2]



Flow Diagram of Air Products' Integrated Hydrogen energy Station

Technology History

- Developed by Air Products and Chemicals Inc. in collaboration with FuelCell Energy and Orange County Sanitation District.
- Continuing operations at demonstration site with sponsorship from the California Air Resources Board and the South Coast Air Quality Management District.

Applications

Can be used to co-produce hydrogen and electric power and provide hydrogen fueling services.

Capabilities

- Produces hydrogen (100kg/day) and electricity from a variety of feedstock sources including anaerobic digester gas.[2]
- Achieves hydrogen co-production at an overall system efficiency of 53.5% (50% goal).[1]

Benefits

Environmental

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

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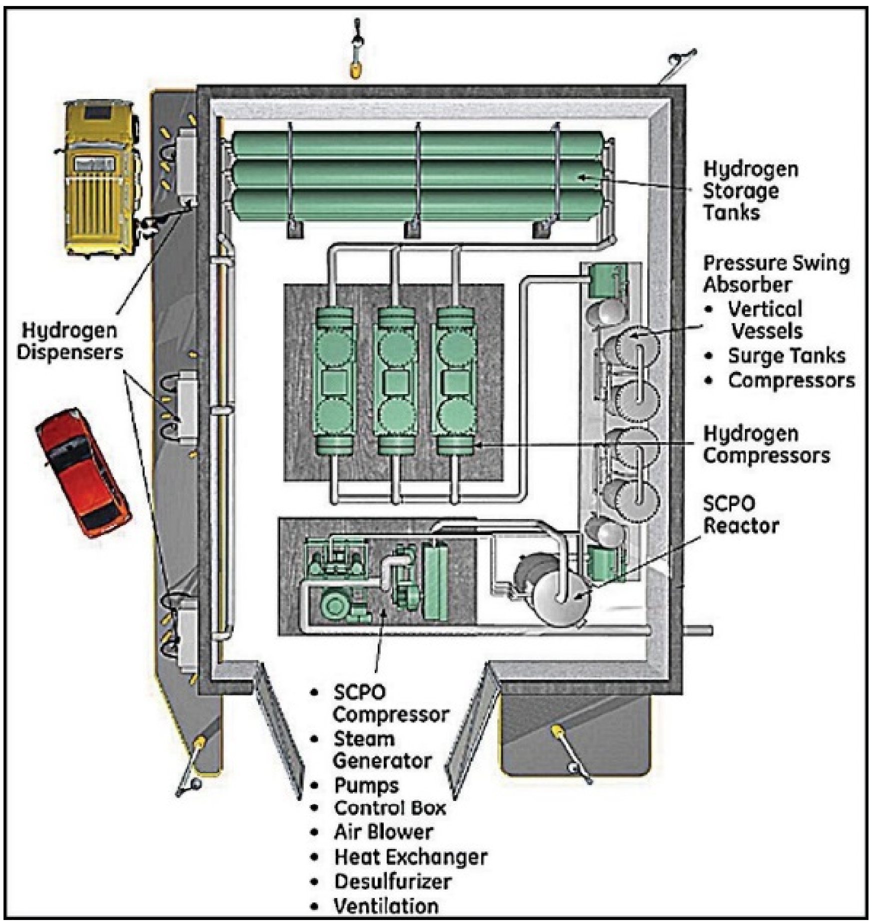
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ vii_2_heydorn_2012.pdf

[2] For more information: http://www.hydrogen.energy.gov/pdfs/review12/tv006_ heydorn_2012_o.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 staged catalytic partial oxidation (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.
- Evaluating potential application opportunities.

Applications

Can be used in different industries when syngas and hydrogen production are needed use of biofuels, gasoline, or diesel as feedstock.[1]

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 desirable response time, stability, and resistance to aging and degradation from thermal cycling. LANL is now field testing the technology at a commercial California Hydrogen filling station working to demonstrate the technology in real-world H_2 applications. Improvements to the electrode materials by LANL – brought about through cross validation with other DOE labs - facilitate commercialization through cost-conscious, reproducible manufacturing methods.

Packaged Electrochemical H_2 Safety Sensor Deployed for Field Trials Testing

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

Technology History

- Developed by LANL and LLNL.
- Preparing for field trials of the sensor system at California hydrogen filling stations. 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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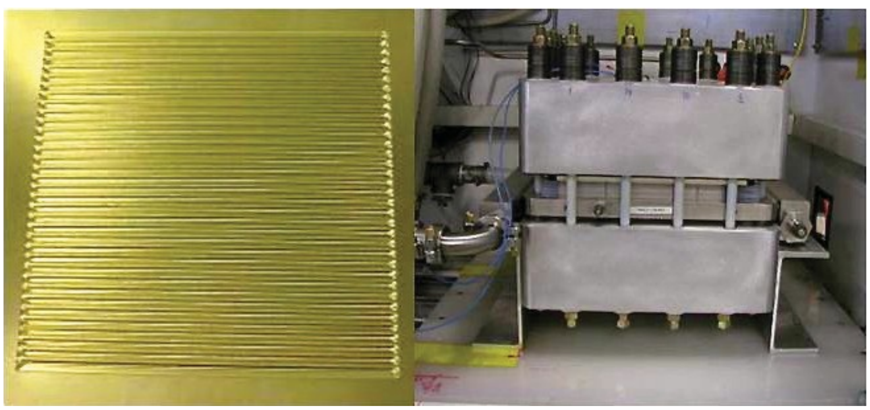
Low-Cost Hydrogen Generation from Renewable Energy

Proton OnSite, 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 OnSite.
- 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

Low Cost Hydrogen Storage at 875 Bar Using Steel Liner and Steel Wire Wrap

Emerging Technology

Hydrogen storage is an important issue for a hydrogen-based fuel economy. Improvements for storage are always desirable; being able to store hydrogen gas at higher pressures allows for more hydrogen to be available for use at refueling stations. However, the usual issue of making high-pressure hydrogen storage vessels are either that the cost is too high or that the durability of the system is inadequate.

With funding from FCTO, Wiretough Cylinders, LLC, in collaboration with Oak Ridge National Laboratory, Sandia National Laboratories, and the State of Virginia, is developing low cost, high-pressure hydrogen storage systems for use in hydrogen refueling.[1] The vessels are constructed using commercially available type I metal cylinders that have been used for compressed natural gas and hydrogen storage. These cylinders initially could only handle pressures up to 55 MPa, but they are then strengthened with ultra-high-strength steel wires (3 GPa in strength) using Wiretough's wrapping process to approximately double the pressure capability of the cylinders. The wire-wrapped cylinders are further subjected to an autofrettage process where pressures are high enough to plastically deform the inner liner, but the wire jacket remains elastic. The autofrettage pressure is then released, leaving the inner liner with high residual compressive hoop stresses. This process decreases the maximum tensile loop stress in the liner under the operating pressure and can thus enhance the fatigue life of the vessel significantly.

Four metal liners for 1.9 m length cylinders have been acquired; two of them have been successfully wire wound and subjected to burst testing. The vessels have sustained pressures up to 3 times the design pressure. The third liner has been used for material testing, and the fourth liner was used to optimize reinforcements in the transition regions between the cylinder body and the domes on the two ends. The 1.9 m long cylinders are now complete and the cylinder length is being extended to 9.5 m for further proof of concept. This design concept and the related materials have received ASME Code approval.[2]

Wiretough's Liner After a 262.7 MPa Burst Pressure Test

[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/iii_9_prakash_2015.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review16/pd110_prakash_2016_o.pdf

Technology History

- Developed by Wiretough Cylinders, LLC.
- Successfully completed burst testing on two of the 1.9 m length cylinders.

Applications

Can be used to store gaseous hydrogen at high pressures for a relatively low cost.

Capabilities

- Achieves the DOE recommended safety factor of 3 or higher on the burst pressure.
- Achieves ASME U3 (High Pressure Vessel) certification.
- Stores up to 30 kg of gaseous H_2 at an operating pressure of 875 bar, with a maximum pressure of 1000 bar.

Benefits

Cost Savings

Constructs vessels with a cost value of <$1,000/kg H_2 per vessel.

Durability

Maintains a product life of more than 30 years per vessel.

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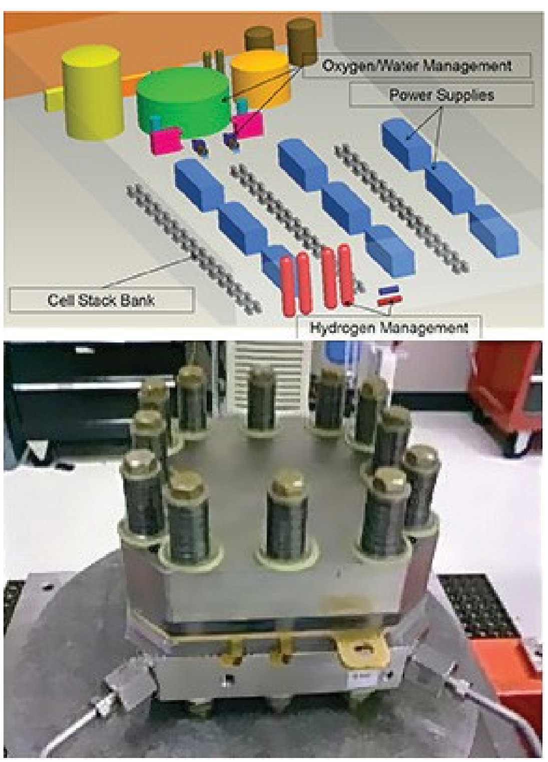
Low-Cost, Large-Scale PEM Electrolysis for Renewable Energy Storage

Emerging Technology

Proton OnSite 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% will be required by developing new catalyst and membrane materials to reduce efficiency losses arising from oxygen evolution over-potential and membrane ionic resistance.[1] 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 bottom)

Technology History

- Developed by Proton OnSite.
- 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 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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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ ii_d_5_ayers_2012.pdf

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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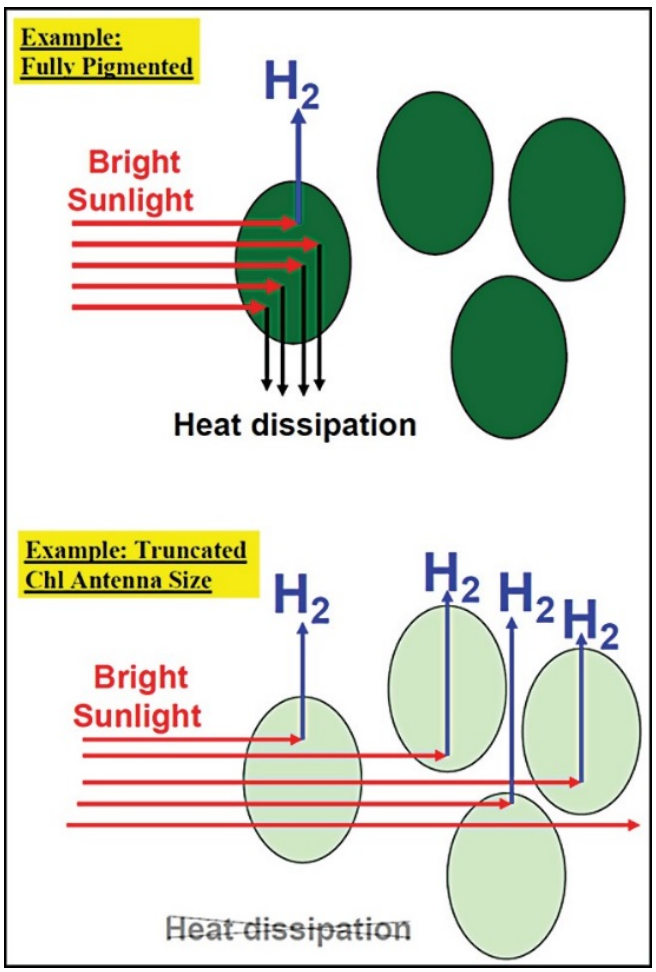
Maximizing Light Utilization Efficiency and Hydrogen Production in Microalgal Cultures

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

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

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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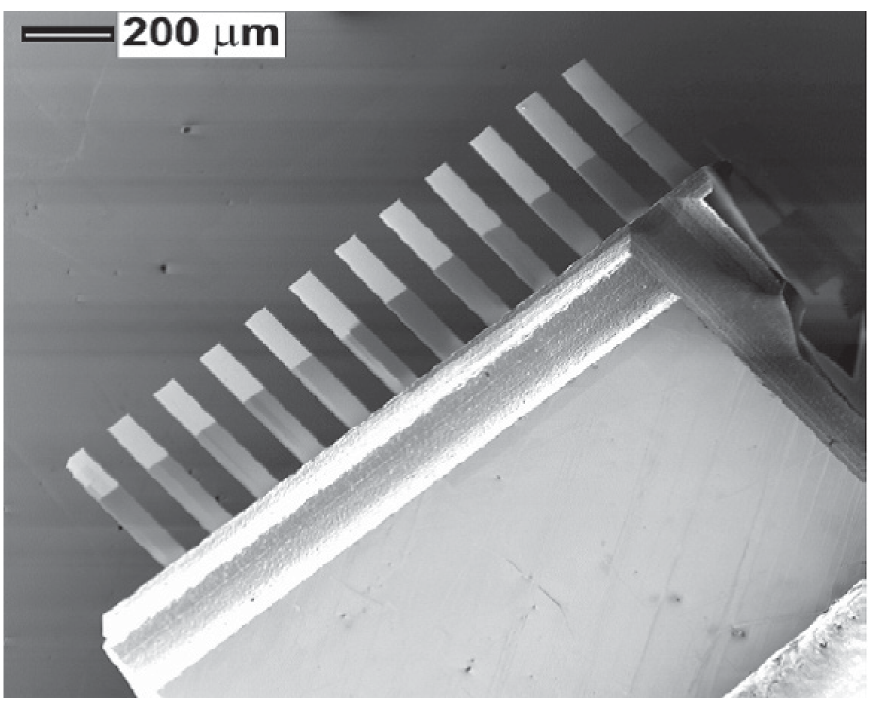
MEMS Hydrogen Sensor for Leak Detection

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

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% H_2 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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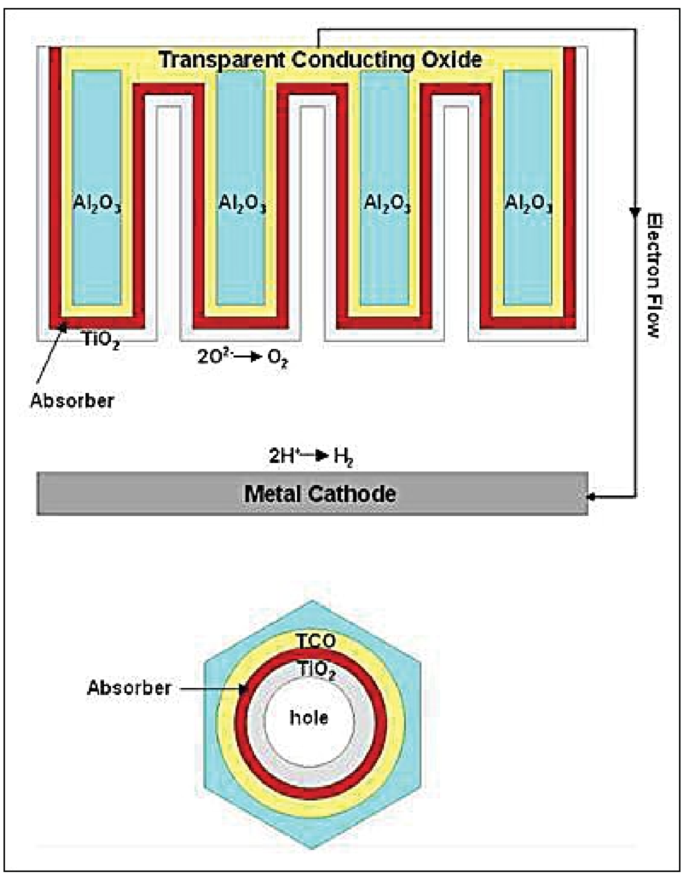
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/viii_16_smith_2011.pdf

Nanotube Array Photocatalysts

Emerging Technology

Synkera Technologies, Inc., a wholly owned subsidiary of Integrated Device Technology, 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

[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

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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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]

Mockup of MiTi Hydrogen Compressor (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

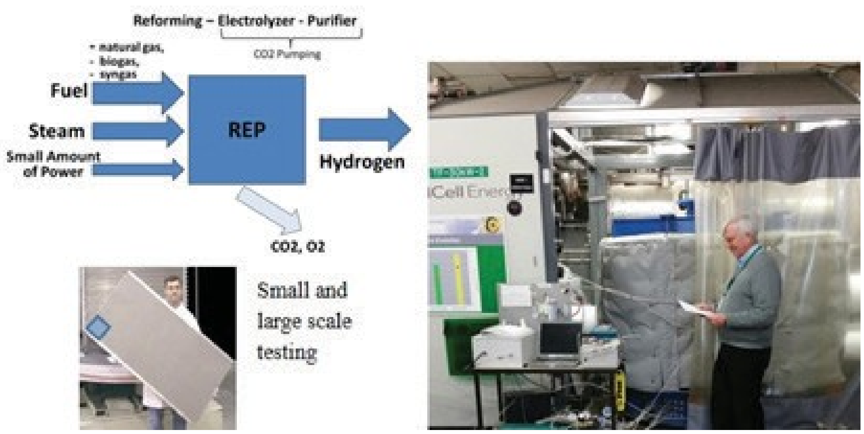
Reformer-Electrolyzer-Purifier (REP) for Production of Hydrogen

Emerging Technology

FuelCell Energy Inc. (FCE), with assistance from FCTO, is developing a reformer- electrolyzer-purifier (REP) unit to produce and deliver hydrogen at a target cost aligned with FCTO's Multi-Year Research, Development, and Demonstration plan.[1] FCE and the University of California. Irvine's National Fuel Research Center have evaluated and confirmed the feasibility of the REP technology on a single cell (300 cm^2) and large scale (10,000 cm^2) 30 cell stack. The REP is based on FCE's molten carbonate fuel cell (MCFC) technology. The single cell testing was used to optimize the various operating parameters and develop a model accurate under various operating conditions. Long-term testing was used to confirm that the expected operating lifetime is acceptable. A detailed REP system configuration and process flow diagram were developed to estimate the system cost and economic viability data for third party analysis.[2] The 30 cell stack produced 100 kg/day of hydrogen, meeting the final milestone of the FCTO program.

The REP system operates with high production efficiency, especially when using a waste heat source to assist with the low-pressure steam generation and low temperature reforming (<1150°F) steps. It produces high-purity hydrogen by electrochemically pumping almost all of the CO_2 from the system. CO_2 is removed as $CO_3^{=}$ by reacting CO_2 and H_2O, producing additional H_2. The key cell components of the system are the same as FCE's commercial MCFC technology, Direct Fuel Cell (DFC®) technology. FCE tested and validated the REP cell technology, in a 4,000+ hour single cell test and produced over 100 kg/day of 97%+ H_2 from a short stack of large DFC® cells. During single cell testing, we confirmed the REP H_2 can be used without purification to generate power in a low temperature (PEM) fuel cell and/or to feed an EHC (electrochemical hydrogen compressor) to generate fuel cell vehicle (FCV) quality, high pressure H_2 for the hydrogen infrastructure.

Future work will include testing of the 100 kg/day stack over a long period, followed by a field demonstration of the technology.



FuelCell Energy's Large Scale REP TestSystem produced over 100 kg/day using DFC® cell components

Technology History

- Developed by FuelCell Energy, Inc.
- Continuing single-cell operating condition testing, long-term testing and construction and evaluation of commercial scale REP.

Applications

Can be used to produce hydrogen from various feedstocks, including natural gas, methane and biogas.

Capabilities

- Provides durable fuel stack life with lifetimes in the range 3 – 5 years.
- Achieves hydrogen production cost aligned with FCTO long-term cost targets.
- Provides scalable production of 1 tov16,000 kg/day H_2.
- Provides small footprint on-site H_2.

Benefits

Cost Savings

Reduces system costs through detailed system optimization, configuration and materials cost analysis.

Emissions

Reduces CO_2 emissions up to 50% lower than a typical steam methanol reformer using low-power, high-temperature electrolysis combined with near 100% conversion of methane and CO to hydrogen.

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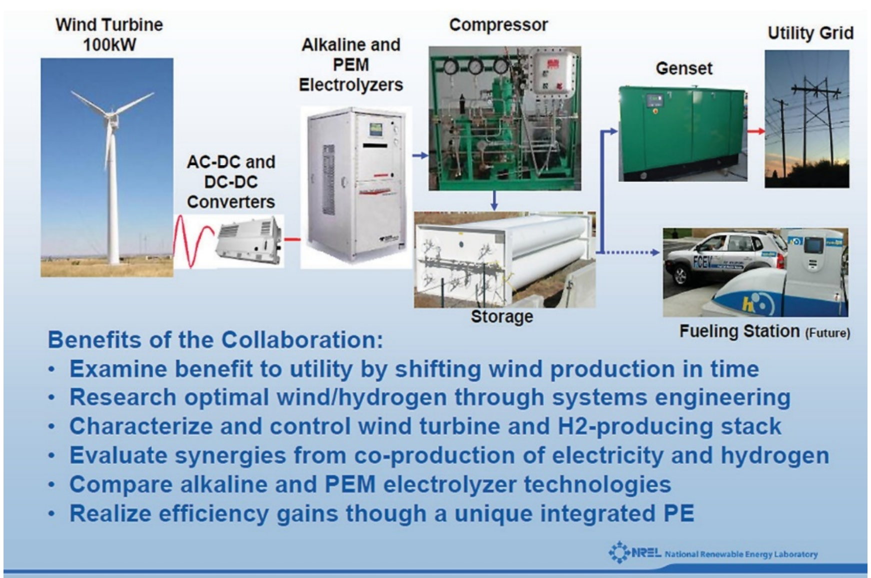
[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/ii_f_2_jahnke_2015.pdf
[2] For more information: http://ecst.ecsdl.org/content/71/1/179.full.pdf

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.



Xcel Energy/NREL Wind-to-Hydrogen system configuration

Technology History

- Developed by NREL in partnership with Xcel Energy, Proton OnSite, 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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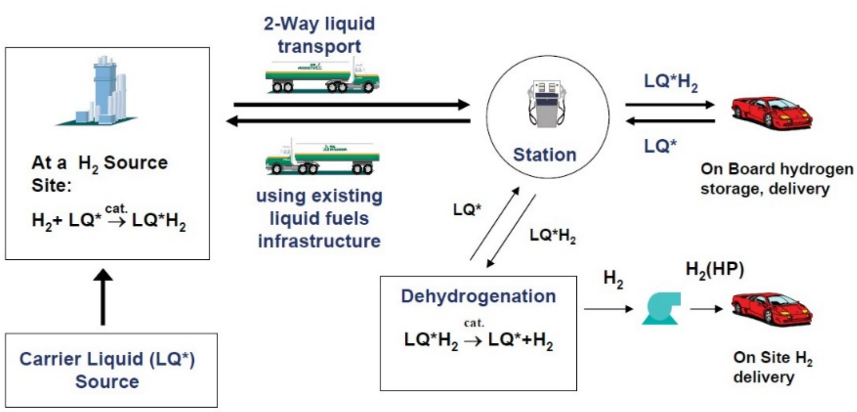
Reversible Liquid Carriers

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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D.3 Storage Innovations

Achieving Hydrogen Storage Goals through High-Strength Fiber Glass

Emerging Technology

Hydrogen storage is a key enabling technology for fuel cell vehicles (FCVs). FCVs must be able to store sufficient hydrogen for a driving range of at least 300 miles in order to offer a competitive driving range with other types of vehicles.1 In addition, it is desirable for the onboard storage tank to occupy as little volume as possible (in order to leave more space for passengers and cargo storage). Increasing the pressure at which gaseous hydrogen is stored increases the volumetric energy density (energy per unit volume; a.k.a. volumetric capacity), but requires sturdier vessels that can withstand the higher pressures. As a result, the cost of the storage vessels increases. If the cost of the storage vessels can be decreased without sacrificing volumetric capacity, FCVs will become more desirable for market adoption.

With funding from FCTO, PPG Industries, Inc., (PPG) and project partners (Hexagon Lincoln and Pacific Northwest National Laboratory [PNNL]) are developing a Type IV composite overwrapped pressure vessel reinforced with glass fiber. PPG is developing a glass fiber that can match the tensile strength of the fibers used in existing T-700 carbon fiber vessels, but is expected to reduce the composite contribution to the system cost by around 50%.2

Two new high-strength fiberglass chemistries have been developed. The initial fiberglass tank evaluation showed the tanks developed from the new fiber glass outperformed the reference fiber tanks on burst pressure and cyclic pressure, and also significantly outperformed the reference tanks on the stress rupture tests. Though there was some significant tensile strength loss for the new fibers in the small-scale pilot production, there are plans to investigate other methods in order to mitigate this loss. Future work will focus on finishing the evaluations of the tanks built in the first phase and the completion of cost modeling/analysis.

PPG's Pilot Fiber Production Process.

Technology History

- Developed by PPG Industries, Inc., with assistance from Hexagon Lincoln and PNNL.
- Currently conducting stress corrosion and stress rupture tests.

Applications

Can be used to store compressed hydrogen gas in FCVs or stationary applications.

Capabilities

- Achieves a volumetric capacity of 0.86 kWh/L (26 g H2/L).2 DOE 2020 targets: 1.3 kWh/L (40 g H2/L).
- Achieves a gravimetric capacity of 1.3kWh/kg (4 wt% H2).2 DOE 2020 targets: 1.8 kWh/kg (5.5 wt% H2).

Benefits

Cost Savings

Reduces the cost of the fibers for vessel reinforcement by about 50%. This lowers the fiber costs down to < $6/lb.

Durability

Improves the ability of hydrogen storage tanks to withstand high pressures without bursting.

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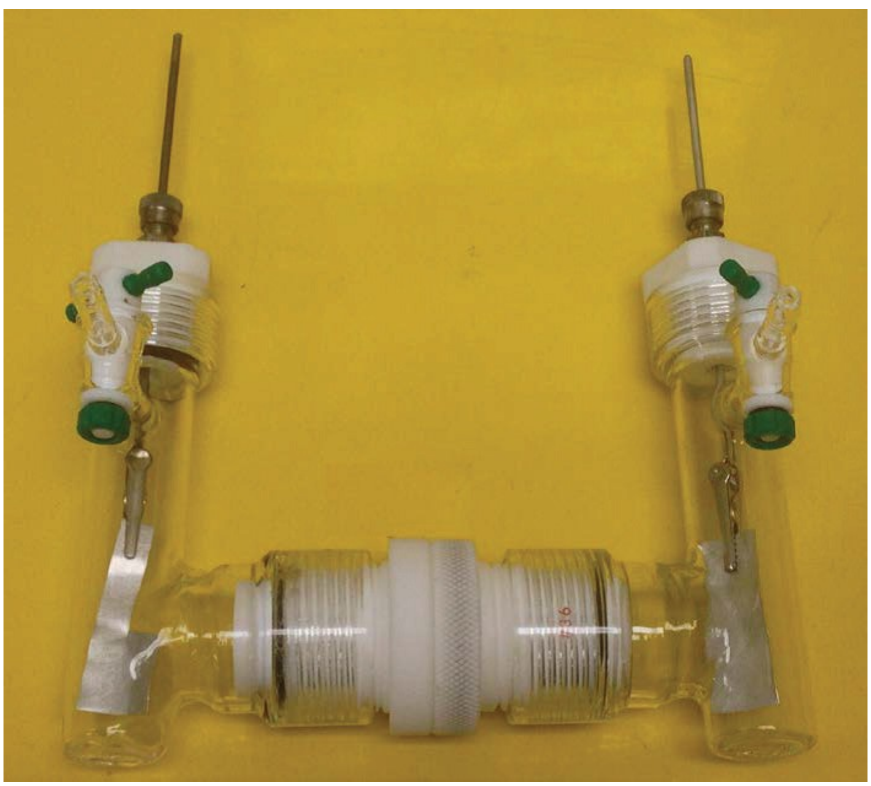
[1] For more information: http://energy.gov/eere/fuelcells/hydrogen-storage
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review16/st115_li_2016_o.pdf

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 - AlH3), 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 AlH3 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 LiAlH4 etherates (e.g. Et2O 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 H2 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 AlH3 production.



SRNL's Nafion® Film Electrochemical Cell for Producing Alane

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 - AlH3).
- Provides gravimetric capacity of 10 wt.% and volumetric capacity of 149 g/L H2, 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

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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[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress11/iv_a_7_zidan_2011.pdf

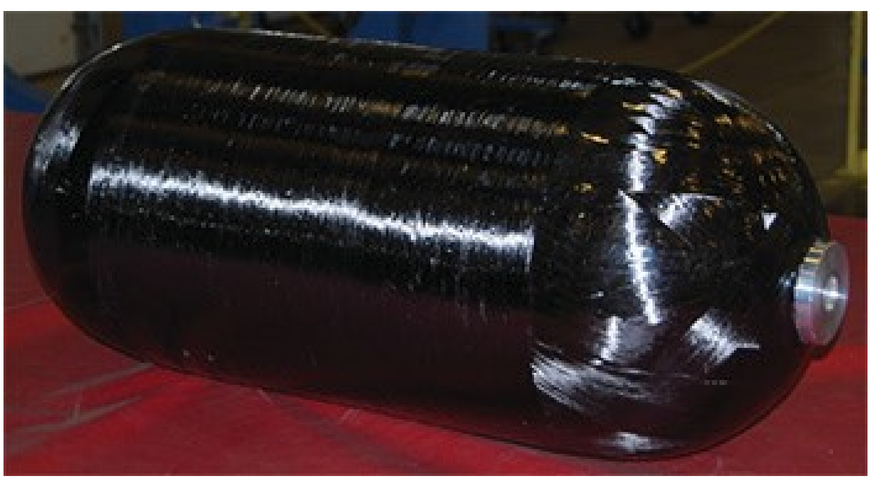
Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks

Emerging Technology

Hydrogen storage is a key issue that must be addressed to enable the adoption of hydrogen vehicles over standard fossil-fueled cars. High-density onboard hydrogen storage is required to sufficiently fuel vehicles for operating ranges necessary to compete with fossil-fueled counterparts. For ambient systems, this requires the pressure vessels be capable of operating above 500 bar.[1] Such vessels must be formed from composite materials because steel is subject to hydrogen embrittlement which can potentially cause failure. Unfortunately, composite materials such as epoxy resin are expensive and, to expedite market adoption of hydrogen vehicles, low-cost, safe, and efficient tanks are needed.

Pacific Northwest National Laboratory (PNNL), with assistance from FCTO and industry partners, has demonstrated a reduced-cost composite pressure vessel that is capable of operating at ambient temperatures. PNNL's tank is formed with polyvinyl ester resins to yield up to 60% cost reductions when compared to epoxy resins. Lower viscosity also reduces tank mass by allowing more resin to be squeezed out during the winding process. Several winding patterns were used to identify an optimal winding method. Burst pressure testing of these reduced mass tanks confirmed that the new tank design performed equal to or better than epoxy tanks. Samples of the resin produced by PNNL show increased material stability and can be stored for up to 45 days without phase separation.

PNNL's development work involved creating a new failure mode model to design and produce the new, optimized-composite tank. The model has correctly predicted failures when a high shear component is introduced. Industry partner, Hexagon Lincoln performed testing to correlate observed results with the improved failure model. This correlation allowed a clearer understanding of optimized tank design behavior using novel winding patterns. Cryogenic test results of the new design were also performed and evaluated for further cost reduction. Ongoing burst testing is aimed at evaluating the full-scale tank design to further correlate materials, mass, and cost savings. Follow-up testing will be performed to ensure the new tanks conform to industry standards.



PNNL's Hydrogen Storage Tank

[1] For more information: http://www.hydrogen.energy.gov/pdfs/review15/st101_gotthold_2015_o.pdf

Technology History

- Developed by PNNL, Hexagon Lincoln, Toray Carbon Fibers America, AOC LLC, and Ford Motor Company.
- Continuing work to evaluate full-scale tank performance.

Applications

Can be used for hydrogen storage, e.g., onboard storage in transportation applications.

Capabilities

- Provides tank design optimized for strength, weight, and cost reduction.
- Achieves reduced tank mass by up to 50%.[1]
- Achieves reduced cost per tank by up to 60%.[1]
- Achieves equal or better burst pressures when compared to standard composite tanks.

Benefits

Efficiency

Can be used at cryogenic temperatures to Increase hydrogen storage capacity.

Reliability

Optimized design provides high-pressure, cryogenic hydrogen storage with insulation dormancy of up to 18 days.

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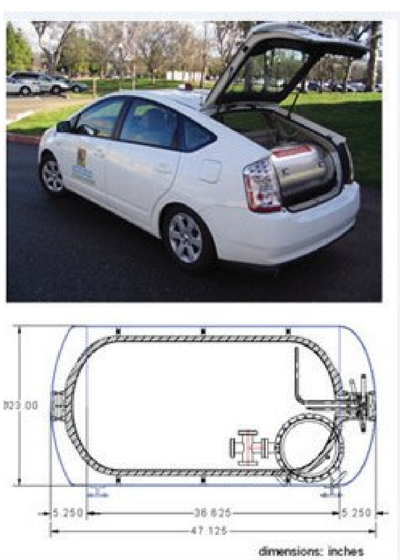
Hydrogen Storage in Cryo-Compressed Vessels

Emerging Technology

A compact high-pressure cryogenic storage system could be a solution to the storage challenge associated with hydrogen-powered vehicles. Cryogenic pressure vessels consist of an inner vessel designed for high pressure (350 bar) insulated with reflective sheets of metalized plastic and enclosed within an outer metallic vacuum jacket. When filled with pressurized liquid hydrogen, cryogenic pressure vessels become the most compact form of hydrogen storage available.

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 gravimetric 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.

A recent prototype hydrogen vessel for automotive applications has met both DOE's 2020 weight and volume targets. This vessel, when installed onboard an experimental hydrogen-powered vehicle, demonstrated a 1,050-km driving distance on a single fill. The vessel also demonstrated a thermal endurance of 8 days while stationary with no evaporative losses and a thermal endurance of up to a month if the vehicle is driven 8 km per day. Analysis performed by LLNL indicates that cryogenic vessels are comparable in terms of safety and cost to other hydrogen storage technologies. Long-term (~10 years) vacuum stability is the key outstanding technical challenge. LLNL's testing work continues to establish technical feasibility and safety.



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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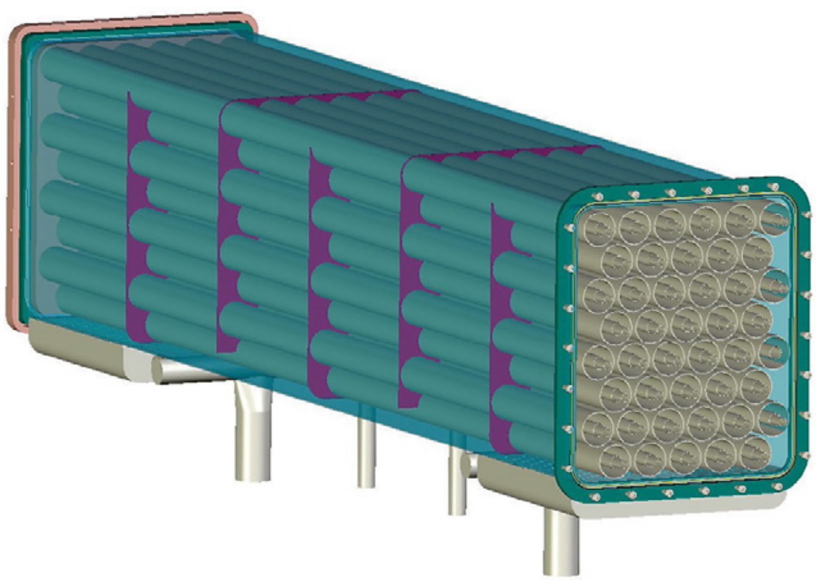
[1] For more information: http://www.hydrogen.energy.gov/pdfs/progress12/ iii_11_aceves_2012.pdf

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 proton exchange membrane fuel cell (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 hydrogen-powered (HP) and battery-powered (BP) 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 testing the prototype with forklift units.

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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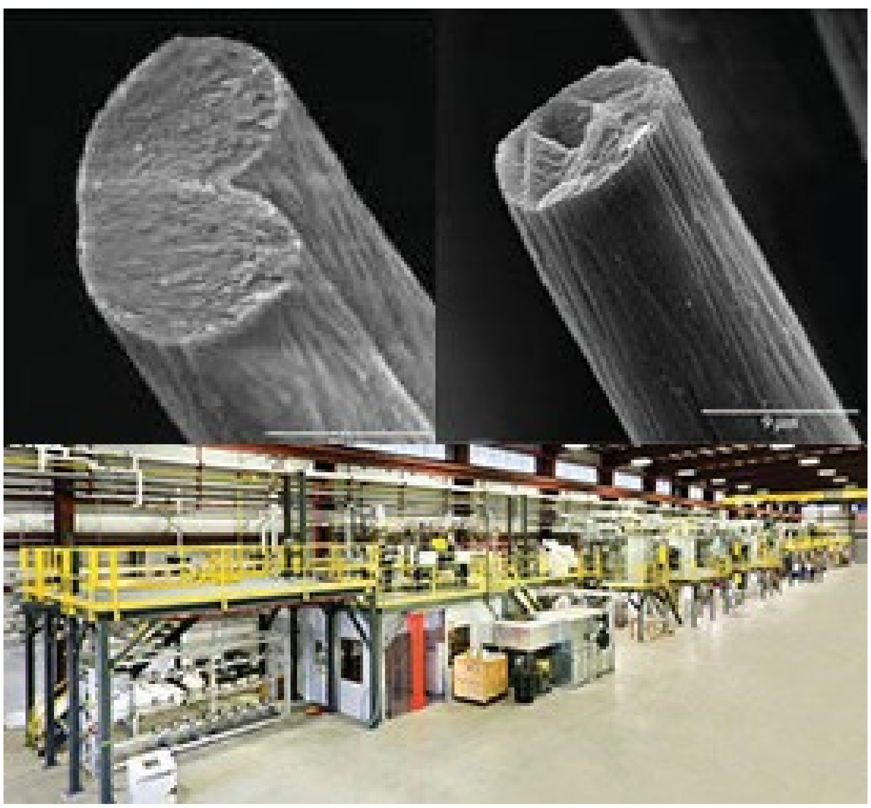
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review11/st095_jensen_2011_p.pdf

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.



Textile Produced PAN Fibers (LHS),
Carbon Fiber Grade PAN Fibers (RHS)
ORNL Carbon Fiber Technology Facility (Bottom)

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 2017 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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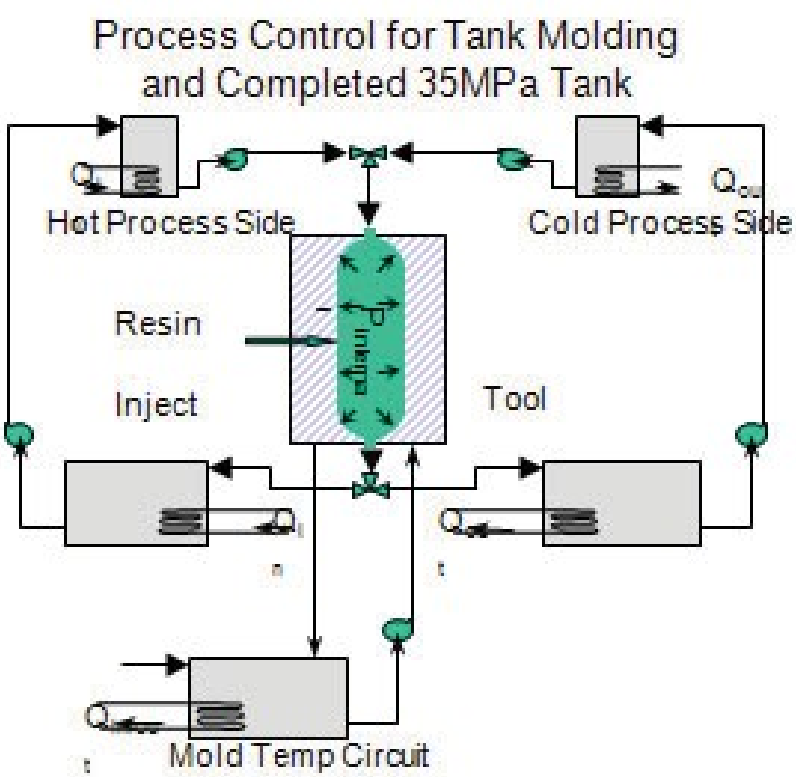
[1] For more information: http://www.hydrogen.energy.gov/pdfs/review13/st099_warren_2013_0.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/progress13/iv_f_3_warren_2013.pdf

Rapid Manufacturing of Vehicle-Scale, Carbon-Composite, High-Pressure Hydrogen Storage Cylinders

Emerging Technology

To support the commercial introduction of hydrogen vehicles, a faster and easier method to fabricate tanks is needed. Materials need to be developed that will support a new method of manufacturing that improves the fabrication cycle time yet maintains structural integrity. The goal is to produce tanks at a rate approaching vehicle production. Ideally, the method and materials must be equally applicable to conformal tanks and scalable to larger-size transportation cylinders.

To satisfy these requirements, Profile Composites Inc., with funding from 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

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 Material Science 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 Savings

Reduces users' cost through high-volume production of cylinders.

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[1] For more information: http://www.hydrogen.energy.gov/pdfs/review08/mf_4_wood.pdf

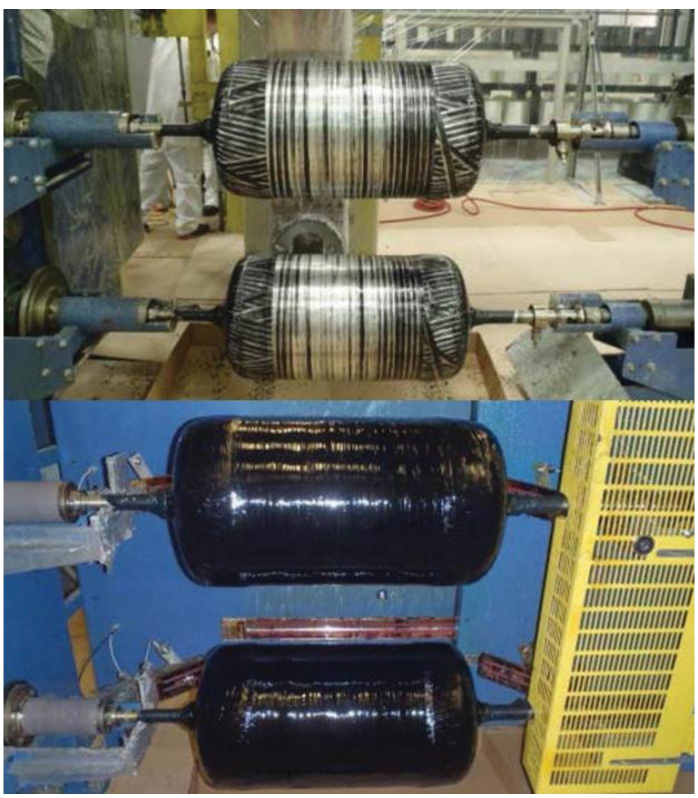
Ultra-Lightweight High Pressure Hydrogen Fuel Tanks Reinforced with Carbon Nanotubes

Emerging Technology

To address the higher cost of manufacturing high pressure carbon fiber tanks for hydrogen applications, Applied Nanotech, Inc., with FCTO funding, is developing methods for effectively reducing the amount of carbon fiber used to construct a carbon-fiber-reinforced polymer (CFRP) tank. Applied Nanotech will use nano- reinforcement, carbon nanotubes (CNTs) to improve the mechanical properties of the CFRP composite resin matrix.[1,2]

By using the resin matrix itself as a source of composite strength, along with the carbon fiber reinforcement, a storage tank can be produced that requires less carbon fiber material, weighs and costs less while preserving or even increasing its performance. Applied Nanotech has successfully demonstrated improvements in compression strength and compression modulus in the epoxy matrix using NH_2-functionalized CNTs.[2]

Future work will further reduce the weight by reducing the viscosity of the CNT reinforced resin using surfactants. Further enhancement of the mechanical properties of the CNT reinforced epoxy resin and improving the tank fabrication process for both 5,000 and 10,000 psi pressures are also planned.[2]



Glassfiber Layer Wound with CNT Epoxy (Top) and After Epoxy Resin is Smoothed (Bottom)

Technology History

- Developed by Applied Nanotech, Inc., in collaboration with industry partners.
- Future work includes continuing to improve the CNT reinforced CFRP materials, associated manufacturing processes and other applications of the technology (pipelines).

Applications

Can be used to cost effectively construct high pressure hydrogen storage tanks while maintaining mechanical integrity and performance.

Capabilities

- Reduces tank weight by up to 30% when compared to conventional CFRP.[2]
- Improves tank mechanical performance using CNT reinforced CFRP when com- pared to conventional CFRP.[2]
- Operates in the pressures range of 5000 -10,000 psi.[2]

Benefits

Cost Savings

Lowers tank cost by reducing the amount of carbon fiber material which accounts for~75% of overall tank cost.

Manufacturability

CNT reinforced epoxy resin has a broad spectrum of applications, including pipelines, where lightweight and mechanical strength are required.

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[1] For more information: http://sbir.gov/sbirsearch/detail/390121
[2] For more information: http://www.hydrogen.energy.gov/pdfs/review14/st105_mao_2014_p.pdf

Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage

Emerging Technology

Low-cost infrastructure, such as off-board bulk stationary hydrogen storage, is critical to successful market penetration of hydrogen-based transportation technologies. Stationary storage is needed in many locations ranging from hydrogen production plants, to refueling stations. The design capacity and pressure of stationary storage vessels are expected to vary considerably depending on the intended usage, the location, and other economic and logistic considerations. Therefore, it is important to develop vessel designs that are scalable to different pressures and capacities. Moreover, since storage vessels provide the surge capacity to handle hourly, daily, and seasonal demand variations, they endure repeated charging/discharging cycles. Thus, the hydrogen embrittlement (HE) in structural materials, especially the accelerated crack growth due to fatigue cycling, needs to be mitigated to ensure the safety of the vessel.

With funding from FCTO, Oak Ridge National Laboratory (ORNL), and several project partners (Global Engineering and Technology, Ben C. Gerwick, Inc., Foterra Pressure Pipe, Kobe Steel, Harris Thermal Transfer, Temple University, MegaStir Technologies, ArcelorMittal, and the U.S. Department of Transportation), are developing and demonstrating a modular steel/concrete composite vessel (SCCV) specifically designed and engineered for stationary high-pressure gaseous hydrogen storage applications[1]. The SCVV is designed to address two critical concerns for high-pressure hydrogen storage: the high capital cost, and the safety concerns with HE of high-strength steel vessels. In addition to its modular design, the SCVV integrates the following features: a composite design that shares the load 50/50 between an inner steel vessel and an outer concrete reinforcement, pre-stressed using ORNL's wire-wrapping technology. The layered steel vessel walls have vent holes designed to mitigate HE, and an integrated sensor system to monitor the structural integrity and operation status of the storage system.

Construction and validation of a full-scale demonstration SCCV, and hydrostatic testing of the demonstration SCCV per ASME's Boiler & Pressure Vessel code requirement have been successfully completed. A long-term evaluation of the demonstration model SCCV's performance under cyclic hydrogen pressure loading simulative to service pressure cycling is currently underway[2]

ORNL's Demonstration SCCV Undergoing Long-term Evaluation

[1] For more information: https://www.hydrogen.energy.gov/pdfs/progress15/ iii_2_feng_2015.pdf
[2] For more information: https://www.hydrogen.energy.gov/pdfs/review16/pd088_feng_2016_o.pdf

Technology History

- Developed by ORNL with assistance from a number of project partners.
- Currently conducting a long-term evaluation of the full-scale demonstration SCCV under cyclic hydrogen pressure loading.

Applications

Can be used to design stationary hydrogen storage vessels, with a focus on optimizing safety and costs.

Capabilities

- Mitigates HE by using small hydrogen vent holes in the multi-layered steel vessel.
- Has a modular design that is flexible for scalability and cost optimization.

Benefits

Safety

Improves safety by eliminating HE and sharing pressure load across multiple layers

Cost Savings

Reduces vessel cost by using combined steel/concrete load sharing design.

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Appendix E: Technology Innovation Developers

E.1 Resultant Fuel Cell R&D Innovations

E.2 Resultant Production/Delivery R&D Innovations

E.3 Resultant Storage R&D Innovations

E.4 Emerging Fuel Cell R&D Innovations

E.5 Emerging Production/Delivery R&D Innovations

E.6 Emerging Storage R&D Innovations

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