FTA Report No. 0246

FTA RESEARCH
FEDERAL TRANSIT ADMINISTRATION

University of Delaware Fuel Cell Transit Vehicle Program, Phases 1-5

PREPARED BY

University of Delaware
Department of Mechanical Engineering

JUNE 2023

U.S. Department of Transportation
Federal Transit Administration

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Courtesy of UD Fuel Cell Bus Program

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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14. ABSTRACT
The University of Delaware's Fuel Cell Transit Vehicle Program was initiated in September 2005 and ended in November 2022. The Program consortium was led by the University of Delaware and included the Electric Power Research Institute (EPRI), Ballard Inc., Ebus, Air Liquide, and Delaware Transit Corporation. The primary goal of the Program was to research, build, and demonstrate a fleet of fuel cell powered buses and hydrogen refueling infrastructure in Delaware. Additional goals included the research and development of fuel cell components for improved performance and durability, modeling and simulation of fuel cell systems and fuel cell/battery hybrid buses, thermal management of lithium-ion batteries, production of renewable hydrogen from a solar-powered thermochemical reactor, storage of hydrogen in metal hydrides, development of intelligent power management strategies for fuel cell hybrid buses, and determining the impact of connectivity on electric vehicle energy consumption and battery life. The Program also led to the development of the University of Delaware's Center for Fuel Cells and Batteries, and helped to launch a startup company, Sonijector LLC.

15. SUBJECT TERMS
Fuel cell/battery hybrid bus; hydrogen refuelling station; hydrogen generation; hydrogen storage; lithium-ion battery thermal management; fuel cell/battery vehicle modeling and simulation; fuel cell membranes; fuel cell catalysts; fuel cell gas diffusion layers; fuel cell bipolar plates; fuel cell modeling and simulation; fuel cell durability; connected vehicles

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Abstract

The University of Delaware's Fuel Cell Transit Vehicle Program was initiated in September 2005 and ended in November 2022. The Program consortium was led by the University of Delaware and included the Electric Power Research Institute (EPRI), Ballard Inc., Ebus, Air Liquide, and Delaware Transit Corporation. The primary goal of the Program was to research, build, and demonstrate a fleet of fuel cell powered buses and hydrogen refueling infrastructure in Delaware. Additional goals included the research and development of fuel cell components for improved performance and durability, modeling and simulation of fuel cell systems and fuel cell/battery hybrid buses, thermal management of lithium-ion batteries, production of renewable hydrogen from a solar-powered thermochemical reactor, storage of hydrogen in metal hydrides, development of intelligent power management strategies for fuel cell hybrid buses, and determining the impact of connectivity on electric vehicle energy consumption and battery life. The Program also led to the development of the University of Delaware's Center for Fuel Cells and Batteries, and helped to launch a startup company, Sonijector LLC.

Executive Summary

Program Background

The University of Delaware's Fuel Cell Transit Vehicle Program was initiated in September 2005 and ended in November 2022. A total of five phases were executed during this 17-year period. Phase 1 was initiated in September 2005 with a consortium led by the University of Delaware (UD). Additional members included the Electric Power Research Institute (EPRI), Ballard Inc., Ebus, Air Liquide, and Delaware Transit Corporation (DTC). UD, EPRI and DTC were signatories to the consortium agreement, and Ballard Inc., Ebus, and Air Liquide were consortium partners. Subsequently, Phase 2 was initiated in September 2006; Phase 3 in September 2007; Phase 4 in September 2008; and Phase 5 in September 2010.

Purpose

The primary goal of the Program was to research, build, and demonstrate a fleet of fuel cell powered buses and hydrogen refueling infrastructure in Delaware. The specific objectives were to:

1. Conduct basic research to improve fuel cell performance, efficiency, and durability through experiments and modeling;
2. Perform design analysis and configuration of the fuel cell stack, hydrogen storage system, delivery and refueling infrastructure, batteries for hybrid operation, control systems and hybrid operation, and sensors for real-time monitoring;
3. Participate in vehicle build and integration of systems;
4. Deploy buses in Delaware and develop infrastructure for maintenance and refueling;
5. Collect data on vehicle performance, efficiency, emissions, reliability, serviceability, and maintainability; and
6. Conduct public education and outreach as well as technology transfer to DTC.

Major Accomplishments

Phase 1

The Phase 1 fuel cell/battery hybrid bus was delivered and deployed on the UD campus in April 2007. It was a 22-foot, 22-passenger bus, equipped with a 20-kW Mark 9 SSL Ballard stack, 60 kWh of Nickel-Cadmium batteries, 12.8 kg of hydrogen in twin composite tanks (5000 psi), and with a 140-mile range. The Phase 1 Bus was operated on our campus until September 2016 with a ridership of hundreds of students per day. The Phase 1 Bus also participated in the first-ever demonstration of vehicle-to-grid (V2G) technology, which subsequently became a landmark achievement of the University of Delaware.

Phase 2

The Phase 2 Bus was identical to the Phase 1 Bus, except that it was equipped with twin Mark 9 SSL Ballard stacks for a total of 40 kW of propulsive power. The Phase 2 Bus was in operation from October 2009 through March 2020, and also transported hundreds of students across campus every day.

Phase 3

The Phase 3 Bus was delivered in 2015 and was used primarily as a test vehicle. It was a 40-foot Gillig glider equipped with a triple-Mark 9 SSL Ballard stack (total of 60 kW), 33 kWh of Lithium-Titanate batteries, and 19.2 kg of hydrogen storage (5000 psi). In addition, a hydrogen refueling station was built at Air Liquide's R&D Innovation Campus in Newark, DE in 2007 and served as the filling station for the UD fuel cell buses throughout the duration of the Program.

Phase 4

A major accomplishment of Phase 4 was the launch of a start-up company, Sonijector LLC, which provides fuel cell balance-of-plant solutions to automotive companies worldwide, based on the patents developed during the Program.

Phase 5

Phase 5 continued with vehicle testing and demonstration, research tasks aimed at improving fuel cell component life and reliability, and the development of intelligent power management strategies to improve the fuel economy and lifetime of fuel cell vehicles through vehicle modeling and simulation.

The Program was also instrumental in helping to create the Center for Fuel Cell Research (CFCR) on the UD campus in 2009, whose mission was to promote basic and applied research to improve fundamental understanding of fuel cells; provide students with the opportunity to participate in fuel cell research and demonstration projects; support companies in the region that are engaged in the development of fuel cells, as well as firms engaged in hydrogen production, storage and distribution; and create an opportunity for national and international recognition and a platform for economic growth. The Center for Fuel Cell Research was renamed the Center for Fuel Cells and Batteries in 2017. Through this center, over 50 undergraduate and graduate students, and post-docs were trained in fuel cell science and technology, and over 80 book chapters, patents, and papers were published in top scientific journals.

Section 1

Background and History

The University of Delaware's Fuel Cell Transit Vehicle Program was initiated in September 2005 and ended in November 2022. A total of five phases were executed during this 17-year period. Below is an overview of the activities and major accomplishments of each phase of the Program.

Phase 1

Phase 1 was initiated in September 2005 with a consortium led by the University of Delaware (UD). Additional members included the Electric Power Research Institute (EPRI), Ballard Inc., Ebus, Air Liquide, and Delaware Transit Corporation (DTC). UD, EPRI and DTC were signatories to the consortium agreement, and Ballard Inc., Ebus, and Air Liquide were consortium partners. The major accomplishment of this period was the design, fabrication, delivery, and deployment of UD's Phase 1 Fuel Cell/Battery Hybrid Bus. Additionally, a hydrogen refueling station was built on Air Liquide's campus in Newark, DE. Several fuel cell research projects were also initiated during this period. Phase 1 ended in August 2008.

Phase 2

Phase 2 was initiated in September 2006. The major accomplishment of Phase 2 was the design, delivery, and deployment of the UD Phase 2 Fuel Cell/Battery Hybrid. The Phase 2 Bus was the workhorse of the fleet and stayed in service until the pandemic disrupted operations in 2020. The UD Center for Fuel Cell Research (CFCR) was launched during Phase 2 in 2009. Several major research project results were achieved during Phase 2, including the first-ever demonstration of V2G technology. Phase 2 ended in December 2009.

Phase 3

Phase 3 was initiated in September 2007. The primary objective during this period was to conduct research on fuel cells, batteries, renewable hydrogen generation, bus hardware improvements, and bus modeling and simulations. The Phase 3 grant period ended on March 31, 2012 after two no-cost extensions. The Phase 3 Bus was delivered in December 2015, and was used primarily as a test vehicle until March 2020 when all operations ceased due to the COVID-19 pandemic.

Phase 4

Phase 4 was initiated in September 2008. Due to significant delays in the delivery of the Phase 3 Bus, it was decided that there would not be sufficient time and funds to adequately demonstrate Bus 4 after its delivery. Hence, an amendment to the Phase 4 Statement of Work was submitted to FTA to cancel the Phase 4 Bus and reallocate its capital costs to deploy and demonstrate the Phase 3 Bus and to conduct the remaining research and development tasks. To maximize the deployment and demonstration objectives of the UD Fuel Cell Bus Program, an extension of Phase 4 to September 30, 2019 was also requested. Both requests were approved by FTA. Accordingly, Phase 4 ended in September 2019. Many major research tasks were accomplished during this period. A start-up company, Sonijector LLC, was also launched to provide fuel cell balance-of-plant solutions to automotive companies worldwide.

Phase 5

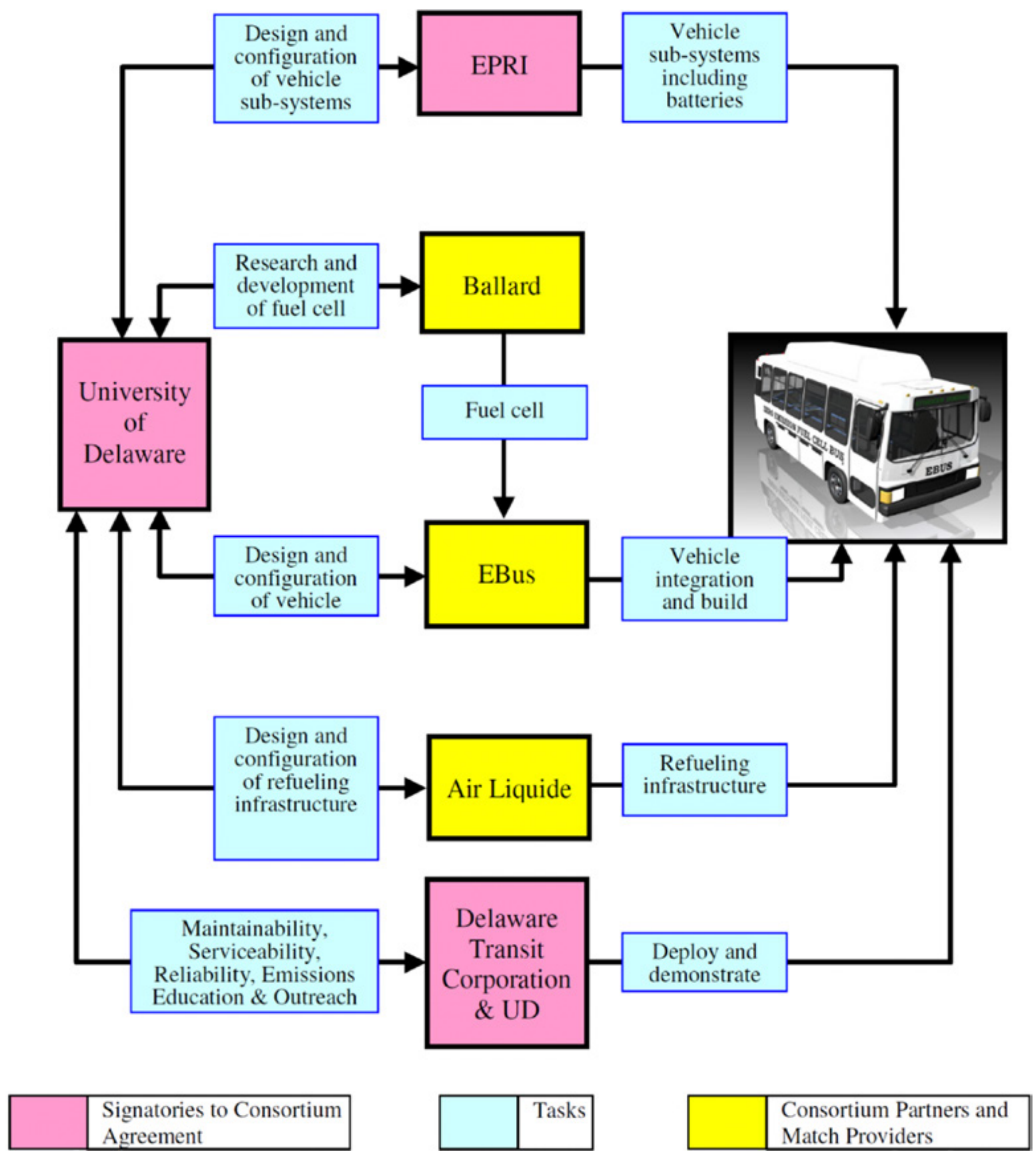
Phase 5 was initiated in September 2010. Due to delays in Phases 3 and 4, Phase 5 tasks were also delayed. The revised project milestones for Phase 5 were to continue the research tasks that focused on improving the performance, efficiency, and durability of automotive fuel cells; developing novel materials for catalysts, membranes, and flow fields; hydrogen storage; solar hydrogen; battery thermal modeling; vehicle modeling and simulation. Phase 5B and 5C grant periods ended in September 2019; however, an additional extension was requested for Phase 5A, which ended in November 2022.

Section 2

Major Accomplishments

Phase 1

Phase 1 was initiated in September 2005 with a consortium led by the University of Delaware (UD). Additional members included the Electric Power Research Institute (EPRI), Ballard Inc., Ebus, Air Liquide, and Delaware Transit Corporation (DTC). Figure 2-1 depicts the structure of the consortium and the major tasks as envisioned during the kick-off.



Source: UD Fuel Cell Bus Program

Figure 2-1 *UD Fuel Cell Bus Program Consortium, Structure and Overview of Tasks*

The primary accomplishment of this period was the design, fabrication, delivery, and deployment of UD's Phase 1 Fuel Cell/Battery Hybrid Bus. Figures 2-2 and 2-3 provide some details about the Phase 1 Bus. The Phase 1 Bus was in operation from April 2007 to September 2016. In addition, a hydrogen refueling station was built at Air Liquide's R&D Innovation Campus in Newark, DE in 2007, as shown in Figure 2-4.

Source: UD Fuel Cell Bus Program

Figure 2-2 *UD's Phase 1 Fuel Cell/Battery Hybrid Bus*

Length	22 ft
Width	92 in
Gross Weight	20,500 lbs
Curb Weight	15,500 lbs
Maximum Speed	45 mph*
Traction Motor	174 hp AC Induction
Transmission	1 speed Chain Drive
Batteries	300V Nominal NiCd
Fuel Cell	Ballard Mark9 SSL 19.4kW
Hydrogen Storage	12.8 kg at 5000 psi
Range	140 miles
Fuel Economy	12 mpgge*

Source: UD Fuel Cell Bus Program

Figure 2-3 *Specifications for UD's Phase 1 Fuel Cell/Battery Hybrid Bus*

Source: UD Fuel Cell Bus Program

Figure 2-4 *Hydrogen refueling station at Air Liquide's R&D Innovation Campus in Newark, DE*

Several research projects pertaining to polymer electrolyte membrane (PEM) fuel cells were also initiated during Phase 1. These included (1) the analysis and measurement of gas flow in canonical flow fields; (2) experimental characterization of catalyst layers and gas diffusion layers; (3) development of innovative metallic gas diffusion layers; and (4) experimental investigation of water transport. They resulted in the publication of the following journal papers:

1. Zhang F.Y., Spernjak D., Prasad A.K., and Advani S.G. 2007. In-situ characterization of the catalyst layer in a polymer electrolyte membrane fuel cell. *Journal of the Electrochemical Society*, 154(11):B1152-B1157.
2. Feser J.P., Prasad A.K., and Advani S.G. 2007. Particle image velocimetry measurements in a model PEMFC. *ASME Journal of Fuel Cell Science and Technology*, 4:328-335.
3. Spernjak D., Prasad A.K., and Advani S.G. 2007. Experimental investigation of liquid water formation and transport in a transparent single-serpentine PEM fuel cell. *Journal of Power Sources*, 170:334-344.
4. Arisetty S., Prasad A.K., and Advani S.G. 2007. Metal foams as flow field and gas diffusion layer in direct methanol fuel cells. *Journal of Power Sources*, 165:49-57.

5. Feser J.P., Prasad A.K., and Advani S.G. 2006. Experimental characterization of in-plane permeability of gas diffusion layers. *Journal of Power Sources*, 162: 1226-1231.
6. Zhang F.Y., Prasad A.K., and Advani S.G. 2006. Investigation of copper etching technique to fabricate metallic gas diffusion media. *Journal of Micromechanics and Microengineering*, 16: N23-N27.
7. Feser J.P., Prasad A.K., and Advani S.G. 2006. On the relative influence of convection in serpentine flow fields of PEM fuel cells. *Journal of Power Sources*, 161: 404-412.

Phase 2

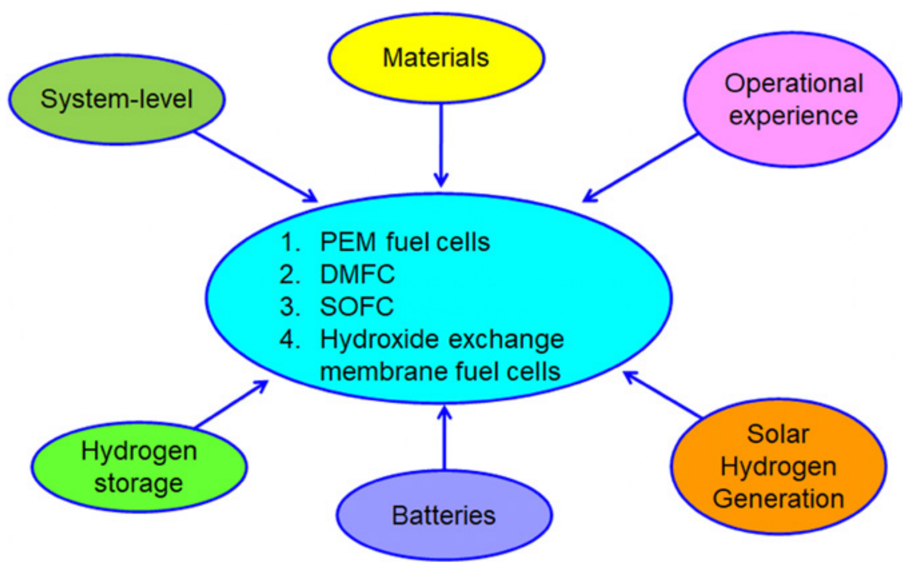
The primary accomplishment of Phase 2 was the design, delivery, and deployment of the UD Phase 2 Fuel Cell/Battery Hybrid Bus. The Phase 2 Bus was the workhorse of the fleet and stayed in service from October 2009 until the COVID-19 pandemic disrupted operations in March 2020. The Phase 2 Bus featured two 20-kW fuel cell stacks for 40-kW total, 60 kWh of Ni-Cd batteries, and 12.8 kg of compressed hydrogen storage. Figure 2-5 shows an image of the Phase 2 Bus.

Source: UD Fuel Cell Bus Program

Figure 2-5 *UD's Phase 2 Fuel Cell/Battery Hybrid Bus*

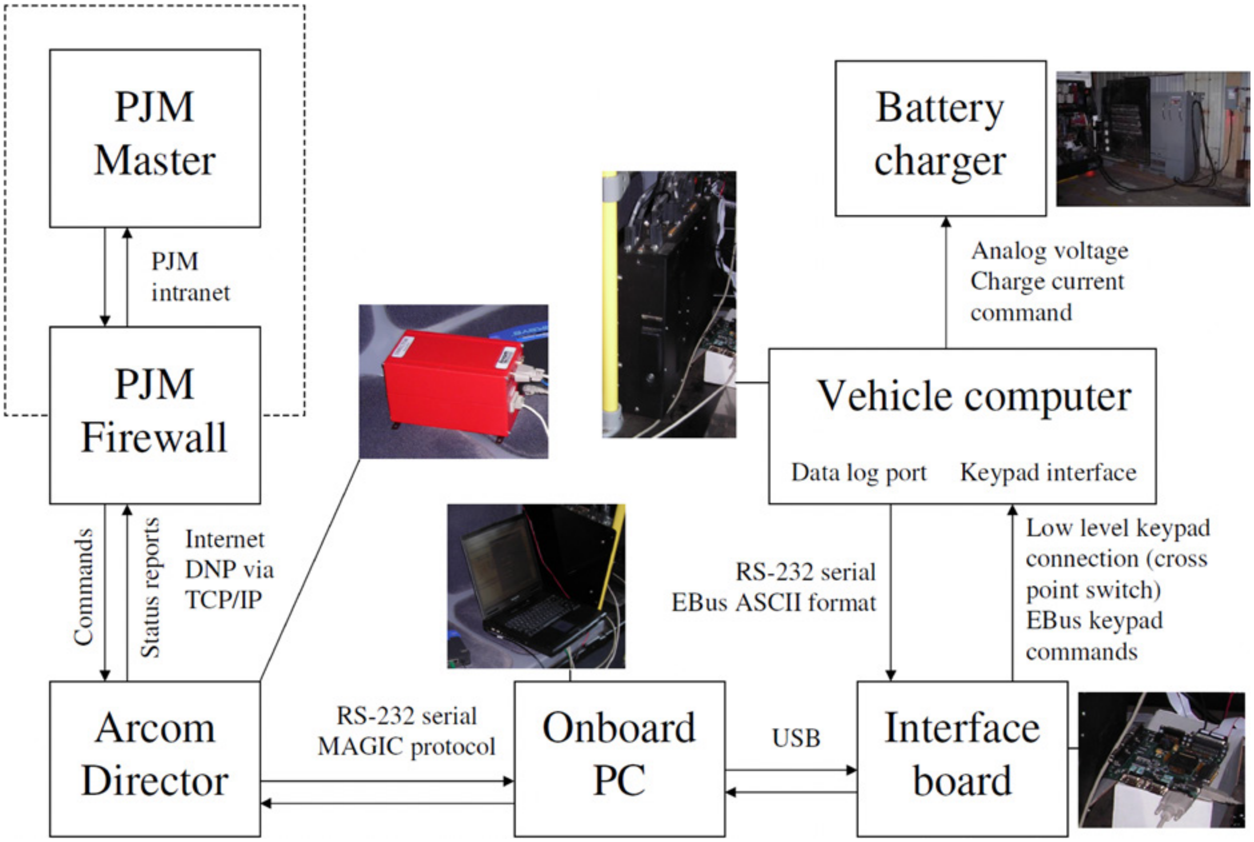
The UD Center for Fuel Cell Research (CFCR) was launched during Phase 2 in 2009. Much of the impetus to create the center came from the UD Fuel Cell Bus Program. CFCR's mission was to promote basic and applied research to improve fundamental understanding of fuel cells; provide students with the opportunity to participate in fuel cell research and demonstration projects; support companies in the region that are engaged in the development of fuel cells, as well as firms engaged in hydrogen production, storage, and distribution; and create an opportunity for national and international recognition and a platform for economic growth. The main activities of CFCR are shown in Figure 2-6. The Center for Fuel Cell Research was renamed the Center for Fuel Cells and Batteries in 2017.

Also during Phase 2, the Program conducted the first-ever demonstration of vehicle-to-grid (V2G) technology in the world. The idea behind V2G is that vehicles equipped with on-board electrical storage systems (such as electric vehicles and fuel cell vehicles) can be plugged into the electric grid while parked, and thereby participate in the two-way flow of electrons, i.e. via battery charging or discharging. The electric utility benefits by not having to fully depend on conventional power sources across four power markets: baseload, peak, spinning reserves, and regulation services. The vehicle owner benefits by charging a fee for allowing their vehicle to participate in these four markets. For this demonstration, the Phase 1 Bus was successfully tested for a full charge cycle in "V2G charge mode"; that is, it was charged at a rate varying according to the real-time power needs of the regional electric grid operator, PJM Interconnection. Figure 2-7 shows the schematic for the V2G protocol.



Source: UD Fuel Cell Bus Program

Figure 2-6 *UD's Center for Fuel Cell Research*



Source: UD Fuel Cell Bus Program

Figure 2-7 *Schematic of the V2G Protocol Deployed on the Phase 1 Bus*

Several research projects were also initiated or continued during Phase 2. These included (1) performance assessment of the novel metallic gas diffusion layer developed in Phase 1; (2) development and assessment of catalysts for direct methanol fuel cells, as well as catalysts for hydrogen generation from sodium borohydride solution; (3) development and validation of a drive-train simulator for a fuel cell hybrid bus; and (4) simultaneous neutron and optical imaging of water transport in PEM fuel cells. They resulted in the publication of the following journal papers:

8. Zhang F.Y., et al. 2009. Quantitative characterization of catalyst layer degradation in PEM fuel cells by x-ray photoelectron spectroscopy. *Electrochimica Acta*, 54:4025-4030.
9. Arisetty S., Jacob C., Prasad A.K., and Advani S.G. 2009. Regulating methanol feed concentration in direct methanol fuel cells using feedback from voltage measurements. *Journal of Power Sources*, 187:415-421.

10. Spernjak D., Advani S.G., and Prasad A.K. 2009. Simultaneous neutron and optical imaging in PEM fuel cells. *Journal of the Electrochemical Society*, 156(1):B109-B117.
11. Palanichamy K., Advani S.G., and Prasad A.K. 2009. Thin-film Co-B catalyst templates for the hydrolysis of NaBH4 solution for hydrogen generation. *Applied Catalysis B: Environmental*, 86:137–144.
12. Palanichamy K., Advani S.G., and Prasad A.K. 2008. Cobalt oxides as Co2B catalyst precursors for the hydrolysis of sodium borohydride solutions to generate hydrogen for PEM fuel cells. *International Journal of Hydrogen Energy*, 33(23):7095-7102.
13. Weigert E.C., Arisetty S., Advani S.G., Prasad A,K., and Chen J.G. 2008. Electrochemical evaluation of Tungsten monocarbide (WC) and platinum-modified WC as alternative DMFC electrocatalysts. *Journal of New Materials for Electrochemical Systems*, 11:243-251.
14. Palanichamy K., Yang T.H., Advani S.G., and Prasad A.K. 2008. Rotating ring-disc electrode (RRDE) investigation of borohydride electro-oxidation. *Journal of Power Sources*, 182(1):106-111.
15. Brown D., Alexander M., Brunner D., Advani S.G., and Prasad A.K. 2008. Drive-Train Simulator for a Fuel Cell Hybrid Vehicle. *Journal of Power Sources*, 183:275-281.
16. Arisetty S., Advani S.G., and Prasad A.K. 2008. Methanol diffusion rates through the anode diffusion layer in direct methanol fuel cells from limiting current measurements. *Heat and Mass Transfer*, 44(10):1199-1206.
17. Zhang F.Y., Advani S.G., and Prasad A.K. 2008. Performance of a metallic gas diffusion layer for PEM fuel cells. *Journal of Power Sources*, 176:293-298.

Phase 3

Phase 3 was initiated in September 2007 and ended in March 2012 after two no-cost extensions. The Phase 3 Bus was actually delivered in December 2015, and was used primarily as a test vehicle until March 2020 when all operations ceased due to the COVID-19 pandemic. The Phase 3 Bus was based on a 40-foot Gillig low-floor bus and featured three 20-kW fuel cell stacks for 60-kW total, 29.5 kWh of Li-Ti batteries, and 19.8 kg of compressed hydrogen storage. An image of the Phase 3 Bus is shown in Figure 2-8.

Source: UD Fuel Cell Bus Program

Figure 2-8 *UD's Phase 3 Fuel Cell/Battery Hybrid Bus*

The primary focus during this period was to conduct research on (1) water dynamics in operational PEM fuel cells; (2) modeling and simulations of fuel cell hybrid vehicles; (3) development of a robust cell voltage monitoring system for analysis and diagnosis of fuel cell stacks; (4) thermal analysis and management of lithium-titanate batteries; (5) freeze/thaw durability of multi-walled carbon nanotube-reinforced Nafion membranes; (6) design and characterization of a variable flow rate ejector for fuel cell applications (which led to the filing of two patents and the formation of a start-up company, Sonijector LLC); (7) design and evaluation of a hydrogen storage system based on hydride materials; and (8) the design and development of a novel beam-down, gravity-fed, solar thermochemical receiver/reactor for renewable hydrogen generation. The following journal publications, book chapters, and patent resulted from this work.

18. Park J., Wang L., Advani S.G., and Prasad A.K. 2012. Durability analysis of Nafion/PTFE membranes for PEMFCs. *Journal of the Electrochemical Society*, 159(12):F864-F870.
19. Koepf E., Advani S.G., Steinfeld A., and Prasad A.K. 2012. A novel beam-down, gravity-fed, solar thermochemical receiver/reactor for direct solid particle decomposition: design, modeling, and experimentation. *International Journal of Hydrogen Energy*, 37:16871-16887.
20. Wang H., Prasad A.K., and Advani S.G. 2012. Hydrogen storage system based on hydride materials incorporating a helical-coil heat exchanger. *International Journal of Hydrogen Energy*, 37:14292-14299.
21. Wang L., Prasad A.K., and Advani S.G. 2012. Novel composite membrane based on SiO2-MWCNTs and Nafion for PEMFCs. *Journal of the Electrochemical Society*, 159(8):F490-F493.
22. Baker A.M., Wang L., Advani S.G., and Prasad A.K. 2012. Nafion membranes reinforced with magnetically-controlled Fe3O4/MWCNTs for PEMFCs. *Journal of Materials Chemistry*, 22:14008-14012.
23. Giuliano M.R., Prasad A,K,, and Advani S.G. 2012. Experimental study of an air-cooled thermal management system for high capacity lithium-titanate batteries. *Journal of Power Sources*, 216:345-352.
24. Palanichamy K., Advani S.G., and Prasad A.K. 2012. Magneli phase TinO2n-1 as corrosion resistant PEM fuel cell catalyst support. *Journal of Solid State Electrochemistry*, 16(7):2515-2521.
25. Wang L., Advani S.G., and Prasad A.K. 2012. Novel ionic liquid-based composite membrane for PEMFCs operating under low relative humidity conditions. E*lectrochemical and Solid-State Letters*, 15(4):B44-B47.
26. Brunner D.A., Marcks S., Bajpai M., Prasad A.K., and Advani S.G. 2012. Design and characterization of an electronically controlled variable flow rate ejector for fuel cell applications. *International Journal of Hydrogen Energy*, 37(5):4457-4466.
27. Wang H., Prasad A.K., and Advani S.G. 2012. Hydrogen storage systems based on hydride materials with enhanced thermal conductivity. *International Journal of Hydrogen Energy*, 37:290-298.
28. Palanichamy K., Advani S.G., and Prasad A.K. 2012. A functional monomer to synthesize sulfonated poly (ether ether ketone) with sulfonic acid group in the pendant side chain. *Journal of Applied Polymer Science*, 123(6):3331–3336.
29. Bubna P., Advani S.G., and Prasad A.K. 2012. Integration of batteries with ultracapacitors for a fuel cell hybrid transit bus. *Journal of Power Sources*, 199:360-366.
30. Wang L., Prasad A.K., and Advani S.G. 2011. Freeze/thaw durability study of MWCNT-reinforced Nafion membranes. *Journal of the Electrochemical Society*, 158(12):B1499-B1503.

31. Shen W., Prasad A.K., and Hertz J.L. 2011. A non-flooding hybrid polymer electrolyte fuel cell. *Electrochemical and Solid-State Letters*, 14(11):B121-B123.
32. Catlin G., Advani S.G., and Prasad A.K. 2011. Optimization of PEMFC flow channels using a genetic algorithm. *Journal of Power Sources*, 196:9407-9418.
33. Palanichamy K., Advani S.G., and Prasad A.K. 2011. Synthesis and evaluation of polythiocyanogen (SCN)x as a rechargeable lithium-ion battery electrode material. *Journal of Power Sources*, 196:7755-7759.
34. Giuliano M.R., Advani S.G., and Prasad A.K. 2011. Thermal analysis and management of lithium-titanate batteries. *Journal of Power Sources*, 196:6517–6524.
35. Arisetty S., Krewer U., Advani S.G., and Prasad A.K. 2010. Coupling of kinetic and mass transfer processes in direct methanol fuel cells. *Journal of the Electrochemical Society*, 157(10):B1443-B1455.
36. Brunner D., Advani S.G., Prasad A.K., and Peticolas B.W. 2010. A robust cell voltage monitoring system for analysis and diagnosis of fuel cell or battery systems. *Journal of Power Sources*, 195:8006-8012.
37. Bubna P., Brunner D., Advani S.G., and Prasad A.K. 2010. Prediction-based optimal power management in a fuel cell/battery plug-in hybrid vehicle. *Journal of Power Sources*, 195:6699–6708.
38. Bubna P., Brunner D., Gangloff J.J., Advani S.G., and Prasad A.K. 2010. Analysis, operation and maintenance of a fuel cell/battery series-hybrid bus for urban transit applications. *Journal of Power Sources*, 195:3939–3949.
39. Spernjak D., Prasad A.K., and Advani S.G. 2010. In situ comparison of water content and dynamics in parallel, single-serpentine, and interdigitated flow fields of PEM fuel cells. *Journal of Power Sources*, 195:3553–3568.

In addition, the following two book chapters were published during Phase 3:

40. Prasad A.K. 2013. Hydrogen Fuel Cells: Current Status and Potential for Future Deployment. *Secure and Green Energy Economies*, Eds. Byrne J., and Wang Y.D. New Brunswick, NJ: Transaction Publishers.
41. Zhang F.Y., Advani S.G., and Prasad A.K. 2012. Degradation Mechanisms in PEM Fuel Cells. *Polymer Electrolyte Fuel Cell Degradation*, Eds. Mench M., Kumbur E.C., and Veziroglu T.N. Elsevier Inc., pp. 365-421.

The following patent was filed and awarded as well:

42. Zhang F.Y., Prasad A.K., and Advani S.G. August 31, 2010. Nano-based novel gas diffusion media. *U.S. Patent No. 7,785,748*.

Phase 4

Phase 4 was initiated in September 2008 and ended in September 2019 after two no-cost extensions. Due to significant delays in the delivery of the Phase 3 Bus, it was decided to cancel and reallocate the capital costs of the Phase 4 Bus to deploy and demonstrate the Phase 3 Bus and to conduct the remaining research and development tasks.

A major accomplishment during Phase 4 was the formation of a start-up company, Sonijector LLC, which provides fuel cell balance-of-plant solutions to companies worldwide. Sonijector was founded based on the patents developed during the UD Fuel Cell Bus Program. Sonijector's patented variable area ejector replaces the power-hungry, corrosion-prone, conventional pumps used to recirculate hydrogen in fuel cell systems. It has virtually no moving parts and consumes only a few watts of power. Sonijector offers a range of standard designs for fuel cell systems ranging from 15kW to 100kW. It also creates custom designs for other applications and specialized customer requirements. Sonijector's customers included Nissan, Toyota, VW, General Motors, Intelligent Energy, Plug Power, Schaeffler, SAIC Motors, Tata Motors, and many more.

Several research projects were continued or initiated during Phase 4. These included (1) several innovations to improve the performance and durability of PEM fuel cell membrane electrode assemblies; (2) modeling and simulations of a fuel cell/battery hybrid forklift truck; (3) development of an agglomerate model for the PEM fuel cell catalyst layer; (4) the development of new membrane materials for high-temperature fuel cell operation; (5) the use of inorganic radical-scavenging additives to mitigate the chemical degradation of fuel cell membranes; (6) the application of heat pipes to accelerate hydrogen absorption in a metal-hydride bed; and (7) the successful demonstration of the solar thermochemical receiver/reactor developed in Phase 3 for renewable hydrogen generation. The following journal papers, book chapter, and patent were published during Phase 4.

43. Koepf E.E., Advani S.G., Prasad A.K., and Steinfeld A. 2015. Experimental investigation of the carbothermal reduction of ZnO using a beam-down, gravity-fed solar reactor. *Industrial and Engineering Chemistry Research*, 54:8319-8332.
44. Cetinbas F.C., Advani S.G., and Prasad A.K. 2015. Optimization of a polymer electrolyte membrane fuel cell catalyst layer with bidirectionally-graded composition. *Electrochimica Acta*, 174:787–798.
45. Wang Y., Wang L., Advani S.G., and Prasad A.K. 2015. Double-layer gas diffusion media for improved water management in polymer electrolyte membrane fuel cells. *Journal of Power Sources*, 292:39-48.

46. Lindemer M.D., Advani S.G., and Prasad A.K.. 2015. Graetz-Brinkman problem in laminar core-annular flow of two immiscible liquids. *International Journal of Thermal Sciences*, 89:362-371.
47. Wang L., Kang J., Nam J.D., Suhr J., Prasad A.K., and Advani S.G. 2015. Composite membrane based on graphene oxide sheets and Nafion for polymer electrolyte membrane fuel cells. *ECS Electrochemistry Letters*, 4(1):F1-F4.
48. Baker A.M., Wang L., Johnson W.B., Prasad A.K., and Advani S.G. 2014. Nafion membranes reinforced with ceria-coated MWCNTs for improved mechanical and chemical durability in PEMFCs. J*ournal of Physical Chemistry, Part C*, 118(46):26796-26802.
49. Cetinbas F.C., Advani S.G., and Prasad A.K. 2014. Investigation of a polymer electrolyte membrane fuel cell catalyst layer with bidirectionally-graded composition. *Journal of Power Sources*, 270:594-602.
50. Wang H., Prasad A.K., and Advani S.G. 2014. Accelerating hydrogen absorption in a metal hydride storage tank by physical mixing. *International Journal of Hydrogen Energy*, 39:11035-11046.
51. Liu Y., Wang H., Prasad A.K., and Advani S.G. 2014. Role of heat pipes in improving the hydrogen charging rate in a metal hydride storage tank. *International Journal of Hydrogen Energy*, 39:10552-10563.
52. Cetinbas F.C., Advani S.G., and Prasad A.K. 2014. An improved agglomerate model for the PEM catalyst layer with accurate effective surface area calculation based on the sphere-packing approach. *Journal of the Electrochemical Society*, 161(6): F803-F813.
53. Koepf E.E., Advani S.G., and Prasad A.K. 2014. Experimental investigation of ZnO powder flow and feeding characterization for a solar thermochemical reactor. *Powder Technology*, 261:219-231.
54. Wang L., Advani S.G., and Prasad A.K. 2014. Self-hydrating Pt/CeO2-Nafion composite membrane for improved performance and durability. *ECS Electrochemistry Letters*, 3(5):F30-F32.
55. Prasad A.K. 2014. Alternative energy technologies for transportation. *Villanova Environmental Law Journal*, 25(1):107-119.
56. Park J., Wang L., Advani S.G., and Prasad A.K. 2014. Mechanical stability of H3PO4-doped PBI/hydrophilic-pretreated PTFE Membranes for high temperature PEMFCs. *Electrochimica Acta*, 120:30-38.
57. Cetinbas F.C., Advani S.G., and Prasad A.K. 2014. 3D PEM fuel cell cathode model using a modified agglomerate approach based on discrete catalyst particles. *Journal of Power Sources*, 250:110-119.
58. Wang L., Advani S.G., and Prasad A.K. 2013. Degradation reduction of polymer electrolyte membranes using CeO2 as a free-radical scavenger in catalyst layer. *Electrochimica Acta*, 109:775-780.

59. Koepf E.E., Lindemer M.D., Advani S.G., and Prasad A.K. 2013. Experimental investigation of vortex flow in a two-chamber solar thermochemical receiver/reactor. *ASME Journal of Fluids Engineering*, 135:111103 (12 pages).
60. Wang L., Advani S.G., and Prasad A.K. 2013. PBI/Nafion/SiO2 hybrid membrane for high-temperature low-humidity fuel cell applications. *Electrochimica Acta*, 105:530–534.
61. Cetinbas F.C., Advani S.G., and Prasad A.K. 2013. A modified agglomerate model with discrete catalyst particles for the PEM fuel cell catalyst layer. *Journal of the Electrochemical Society*, 160(8):F750-F756.
62. Hosseinzadeh E., Advani S.G., Prasad A.K. and Rokni M. 2013. Performance simulation and analysis of a fuel cell/battery hybrid forklift truck. *International Journal of Hydrogen Energy*, 38:4241-4249.
63. Wang L., Advani S., and Prasad A.K. 2013. Membrane electrode assembly with enhanced membrane/electrode interface for proton exchange membrane fuel cells. *Journal of Physical Chemistry C*, 117:945−948.

Also, the following book chapter was published during this period:

64. Wang L., Advani S.G., and Prasad A.K. 2015. CNT/Nafion-Based Composite Fuel Cell Membranes for Improved Durability. *Nanoparticles for Catalysis, Energy and Drug Delivery*, Eds. Chaughule R.S., and Kapdi A.R.. American Scientific Publishers, USA.

The following patent was filed and awarded as well:

65. Krishnan P., Advani S.G., and Prasad A.K. May 27, 2014. Lithium batteries having anodes based on polythiocyanogen. *U.S. Patent No. 8,734,988*.

Phase 5

Phase 5 was initiated in September 2010 and ended in November 2022. Due to delays in Phases 3 and 4, Phase 5 tasks were also delayed. The revised project milestones for Phase 5 were to continue and complete several research tasks pertaining to:

- performance enhancement of PEM fuel cells by the use of inline blockages in parallel flowfield channels;
- hydrogen production via the heterogeneous hydrolysis of Zn vapor in a tube furnace under a temperature gradient;
- experiments to assess the migration of radical-scavenging inorganic additives out of the PEM fuel cell membrane;
- development and testing of the world's first self-healing membrane for PEM fuel cells;
- development of a tungsten carbide-based composite PEM fuel cell membrane;
- development of a highly durable SPEEK-ceria nanocomposite membrane for PEM fuel cells;
- development of an intelligent power management strategy for fuel cell/battery hybrid buses;
- impact of connectivity on energy consumption and battery life for electric vehicles;
- an innovative solvent-free lithium-ion electrode formed under high pressure and heat; and
- the use of organic ligands to mitigate cerium migration in PEM fuel cell membranes.

The following journal papers and patents were published during Phase 5:

66. Agarwal T., et al. 2023. Mitigating cerium migration for perfluorosulfonic acid membranes using organic ligands. *Journal of Power Sources*, 554:232320.
67. Connor W., Arisetty S., Yao K.P., Fu K., Advani S.G., and Prasad A.K. 2022. Analysis of solvent-free lithium-ion electrodes formed under high pressure and heat. *Journal of Power Sources*, 546:231972.
68. Heidary H., Kermani M.J., Prasad A.K., and Advani S.G. 2021, Experimental and numerical studies of enhanced interdigitated flow-field for PEM fuel cells. *Journal of Energy Engineering*, 147(4): 04021026.
69. Connor W.D., Wang Y., Malikopoulos A.A., Advani S.G., and Prasad A.K. 2021. Impact of connectivity on energy consumption and battery life for electric vehicles. *IEEE Transactions on Intelligent Vehicles*, 6(1):14-23.

70. Wang Y., Advani S.G., Prasad A.K. 2020. A comparison of rule-based and model predictive controller-based power management strategies for fuel cell/battery hybrid vehicles considering degradation. *International Journal of Hydrogen Energy*, 45(58):33948-33956.
71. Wang Y., Moura S.J., Advani S.G., Prasad A.K. 2019. Optimization of powerplant component size on board a fuel cell/battery hybrid bus for fuel economy and system durability. *International Journal of Hydrogen Energy*, 44:18283-18292.
72. Wang Y., Moura S.J., Advani S.G., Prasad A.K.. 2019. Power management system for a fuel cell/battery hybrid vehicle incorporating fuel cell and battery degradation. *International Journal of Hydrogen Energy*, 44:8479-8492.
73. Lindemer M.D., Advani S.G., and Prasad A.K. 2018. Lattice Boltzmann simulation of a reactive gas-to-solid reaction and precipitation process in a circular tube. *Computer Modeling in Engineering and Sciences*, 117(3):527-553.
74. Parnian M.J., Rowshanzamir S., Prasad A.K., and Advani S.G. 2018. Effect of ceria loading on performance and durability of sulfonated poly (ether ether ketone) nanocomposite membranes for proton exchange membrane fuel cell applications. *Journal of Membrane Science*, 565:342–357.
75. Parnian M.J., Rowshanzamir S., Prasad A.K., and Advani S.G. 2018. High durability sulfonated poly (ether ether ketone)-ceria nanocomposite membranes for proton exchange membrane fuel cell applications. *Journal of Membrane Science*, 556:12-22.
76. Baker A.M., et al. 2017. Cerium ion mobility and diffusivity in perfluorosulfonic acid membranes measured via hydrogen pump operation. *Journal of the Electrochemical Society*, 164(12):F1272-F1278.
77. Zheng W., et al. 2017. Durable, self-hydrating, tungsten carbide-based composite polymer electrolyte membrane fuel cells. *Nature Communications*, 8:418 (8 pages).
78. Baker A.M., et al. 2017. Zr-doped ceria additives for enhanced PEM fuel cell durability and radical scavenger stability. *Journal of Materials Chemistry A*, 5:15073-15079.
79. Lindemer M.D., Advani S.G., and Prasad A.K. 2017. Experimental investigation of heterogeneous hydrolysis with Zn vapor under a temperature gradient. *International Journal of Hydrogen Energy*, 42(12):7847-7856.
80. Heidary H., Kermani M.J., Prasad A.K., Advani S.G., and Dabir B. 2017. Numerical modelling of in-line and staggered blockages in parallel flowfield channels of PEM fuel cells. *International Journal of Hydrogen Energy*, 42(4):2265-2277.

81. Wang L., Advani S.G., and Prasad A.K. 2016. Self-healing composite membrane for polymer electrolyte membrane fuel cell applications. *Journal of the Electrochemical Society*, 163(10):F1267-F1271.
82. Baker A.M., et al. 2016. Cerium migration during PEM fuel cell accelerated stress testing. *Journal of the Electrochemical Society*, 163(9):F1023-F1031.
83. Lindemer M.D., Advani S.G., and Prasad A.K. 2016. Hydrogen production via the heterogeneous hydrolysis of Zn vapor under a temperature gradient: Modeling and efficiency analysis. *International Journal of Hydrogen Energy*, 41:10557-10567.
84. Heidary H., Kermani M.J., Advani S.G., and Prasad A.K. et al. Experimental investigation of in-line and staggered blockages in parallel flowfield channels of PEM fuel cells. *International Journal of Hydrogen Energy*, 41:6885-6893.

Also, the following patents were awarded during this period:

85. Brunner D., et al. July 14, 2020. Devices, systems, and methods for variable flow rate fuel ejection. *U.S. Patent No. 10,711,805*.
86. Brunner D., et al. August 1, 2017. Devices, systems, and methods for variable flow rate fuel ejection," *U.S. Patent No. 9,719,529*.

Section 3 Conclusions

The UD Fuel Cell Bus Program succeeded in the establishment and demonstration of a zero-emission, hydrogen-powered fleet of transit vehicles on the UD campus, and served as a model that could be replicated across our nation. Over its 17-year duration, the Program's impact can be summarized as follows:

1. The Program undertook the research, development, and deployment of three fuel cell/battery hybrid buses on the UD campus. Each bus incorporated technological advances over its predecessor, such that there was a continuing progression towards reliability, efficiency, and commercial viability.
2. The Program demonstrated a hydrogen refueling station on Air Liquide's R&D Innovation Campus in Newark, DE.
3. The Program facilitated the training of over 50 undergraduate and graduate students, as well as post-docs, many of whom are now employed in the fuel cell, electric vehicle, and electrolyzer industries. This is a significant contribution to workforce development as our nation transitions away from fossil fuels toward renewable and clean fuels.
4. The Program enabled fundamental research on all components within the fuel cell including membranes, catalysts, catalyst supports, gas diffusion layers, and bipolar plates; modeling and simulation of gas flow in fuel cells; modeling and simulation of fuel cell powered buses and fork lifts; renewable production of hydrogen from sunlight by thermochemical cycles; hydrogen storage in metal hydrides; thermal management of lithium-ion batteries; novel dry-electrodes for lithium-ion batteries; and most recently the impact of connectivity on electric vehicles. The publication of over 80 book chapters, patents, and papers in top journals is a significant contribution to the archival literature.
5. The patents filed under the Program led to the creation of a start-up company, Sonijector LLC, which is providing fuel cell balance-of-plant solutions to automotive companies worldwide.
6. Finally, the Program provided the impetus to create the University of Delaware Center for Fuel Cells and Batteries which now represents the base for all fuel cell and hydrogen-infrastructure related activities on our campus.

Acronyms and Abbreviations

CFCR	Center for Fuel Cell Research
FTA	Federal Transit Administration
mpgge	miles per gasoline gallon equivalent
PEM	Polymer Electrolyte Membrane
psi	Pounds per Square Inch
SPEEK	Sulfonated Poly Ether Ether Ketone
V2G	Vehicle-to-Grid
UD	University of Delaware

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