Hydrogen Plant Module (HPM)
And Vehicle Fueled by Same

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Hydrogen Plant Module (HPM) and Vehicle Fueled by Same

FINAL REPORT

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Prepared for

US DEPARTMENT OF TRANSPORTATION

and

ALLOY SURFACES COMPANY, INC.

By

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16. Abstract

The goal / objective of the project was to design and fabricate hydrogen plant module (HPM) that is capable of producing hydrogen fuel onboard a vehicle and that obviates one or more of the present issues related to compressed hydrogen fuel storage onboard a vehicle, such as high pressure, weight, volume, cost, and conformability. To achieve this goal / objective, the project began with constructive simulations of HPM and vehicle, modeled entirely in software. Constructive simulation results guided construction of a standalone hardware model HPM as well as the hydrogen fueled vehicle. Once constructed, the standalone hardware model HPM was tested using hardware-in-the-loop simulation methodology, whereby simulated hydrogen demand data was uploaded dynamically to a hydrogen mass flow controller. Hardware-in-the-loop simulation results demonstrated ability of HPM to meet expected hydrogen demand of vehicle. The vehicle was also driven, with hydrogen supplied by a temporary compressed gas tank source, to confirm that actual hydrogen demand of vehicle was reasonably close to expectation. Finally, the standalone hardware model HPM was modified to be integrally retrofit to the vehicle. The HPM and vehicle fueled by the same were then tested in idle mode of operation, and then again in drive mode of operation, at a driving speed of 15.31 mph (i.e., equal to 30kW power requirement set forth by project advisor). Goal / objective of the project was achieved, having designed and fabricated HPM, having demonstrated its capability to produce hydrogen fuel onboard a vehicle, and having clearly demonstrated obviation of at least one of the present issues related to compressed hydrogen fuel storage onboard a vehicle – that issue being high pressure. Note, HPM pressure was nominal 125 psig at all times during operation, whereas the total amount of hydrogen producible by the HPM, if stored onboard as compressed gas, would have required storage at 2000 psig. Now that HPM has been designed and fabricated, future efforts can be directed to further obviation of present issues related to compressed hydrogen fuel storage onboard a vehicle.

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Executive Summary

Goal / objective of the project was to design and fabricate hydrogen plant module (HPM) that is capable of producing hydrogen fuel onboard a vehicle and that obviates one or more of the present issues related to compressed hydrogen fuel storage onboard a vehicle, such as high pressure, weight, volume, cost, and conformability. To achieve this goal / objective, the project began with constructive simulations of HPM and vehicle, modeled entirely in software. Constructive simulation results guided construction of a standalone hardware model HPM as well as the hydrogen fueled vehicle. Once constructed, the standalone hardware model HPM was tested using hardware-in-the-loop simulation methodology, whereby simulated hydrogen demand data was uploaded dynamically to a hydrogen mass flow controller. Hardware-in-the-loop simulation results demonstrated ability of HPM to meet expected hydrogen demand of vehicle. The vehicle was also driven, with hydrogen supplied by a temporary compressed gas tank source, to confirm that actual hydrogen demand of vehicle was reasonably close to expectation. Finally, the standalone hardware model HPM was modified to be integrally retrofit to the vehicle. The HPM and vehicle fueled by the same were then tested in idle mode of operation, and then again in drive mode of operation, at a driving speed of 15.31 mph (i.e., equal to 30 kW power requirement set forth by project advisor). Goal / objective of the project was achieved, having designed and fabricated HPM, having demonstrated its capability to produce hydrogen fuel onboard a vehicle, and having clearly demonstrated obviation of at least one of the present issues related to compressed hydrogen fuel storage onboard a vehicle – that issue being high pressure. Note, HPM pressure was nominal 125 psig at all times during operation, whereas the total amount of hydrogen producible by the HPM, if stored onboard as compressed gas, would have required storage at 2000 psig. Now that HPM has been designed and fabricated, future efforts can be directed to further obviation of present issues related to compressed hydrogen fuel storage onboard a vehicle.

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Narrative Description

Goal / Objective

Goal / objective of the project was to design and fabricate hydrogen plant module (HPM) that is capable of producing hydrogen fuel onboard a vehicle and that obviates one or more of the present issues related to compressed hydrogen fuel storage onboard a vehicle, such as high pressure, weight, volume, cost, and conformability.

Execution, planned vs. actual

Constructive simulations were executed according to plan, with only a few exceptions to plan. Limitations of *Aspen Plus and Dynamics* prevented traditional process modeling of HPM, but some workarounds were possible in *Aspen Plus* with some assistance from AspenTech's technical support staff. Application of workarounds allowed identification of best size and rating of HPM components. Unfortunately, there were no workarounds possible in *Aspen Dynamics*.

Hardware-in-the-loop simulations were not executed according to plan. Because of the limitations of *Aspen Dynamics*, individual powertrain system components were not studied (i.e., they could not be integrated with the software model HPM). Instead, the entire vehicle was studied following its modification to accept hydrogen fuel. Also, the hardware model HPM was studied following its construction. Both of these studies were distributed hardware-in-the-loop simulations, because the vehicle and hardware model HPM were not integrated or connected in any way. In the interest of schedule, parallel hardware-in-the-loop simulations were not executed. Parallel hardware-in-the-loop simulations would have involved connecting the hardware model HPM to the vehicle as a standalone unit, located beside (not inside) the vehicle. Dynamometer would have been used to drive the vehicle.

Closed loop simulations were also not executed according to plan. According to plan, closed loop simulations were to also be performed on dynamometer, similar to how parallel hardware-in-the-loop simulations were to be performed. In the interest of schedule, dynamometer was not used. Rather, closed loop simulations were performed on test track. Note, closed loop simulations were of the standalone hardware model HPM, which was modified and integrally retrofit to (inside) the vehicle.

Live test was / will be executed according to plan. In this case, it was / will be simply a repeat of closed loop simulations, witnessed by project advisor.

Successes, and reasons for them

Overall, the project was a success. Milestone achievements contributed to the overall success of the project. The first milestone achievement was modification of a vehicle to accept hydrogen fuel. Without a hydrogen fueled vehicle to serve as a test platform for the HPM, the project could not have been a success. The second milestone achievement was completion of tests of the standalone hardware model HPM using hardware-in-the-loop simulation methodology, whereby simulated hydrogen demand data was uploaded dynamically to a hydrogen mass flow controller. This was quite possibly the greatest success of the project, because this proved that HPM was capable of producing hydrogen in continuous and controlled manner. This also proved that HPM was capable of responding to dynamic fluctuations in demanded rate. The third and final milestone achievement was completion of tests in idle mode of operation, followed by tests in drive mode of operation, at a driving speed of 15.31 mph (i.e., equal to 30 kW power requirement set forth by project advisor). These proved that integration was successful, and also proved that HPM was able to produce hydrogen at designed rate.

Problems, and how they were addressed

As expected with any project of this magnitude, problems were encountered during its performance. The vast majority of these problems were related to acquisition lead time delays, contract employee resignations, and other common project management issues. Through the application of project management principles, these problems (although unavoidable) were easily addressable. There were a few problems unrelated to project management issues, but these problems were also addressable. One such problem, already mentioned in a previous section of this report, was related to the limitations of *Aspen Plus and Dynamics*. To address this problem, assistance from AspenTech's technical support staff was sought. Another such problem was related to a critical design flaw in the standalone model HPM. This critical design flaw was the root cause of a catastrophic failure due to an overpressurization. To address this problem, the critical design flaw was corrected and safety practices were reviewed. The end result was a heightened awareness of best practices for hydrogen and for systems using hydrogen.

Contribution to the greater problem

The project clearly demonstrated obviation of at least one of the present issues related to compressed hydrogen fuel storage onboard a vehicle – that issue being high pressure.

Unaddressed problems, and how they will be addressed

The goal / objective of future projects will be to obviate additional present issues related to compressed hydrogen fuel storage onboard a vehicle, such as weight, volume, cost, and conformability. To address weight and volume, water recovery will be important, since water can be recycled onboard if recovered from engine (or fuel cell) exhaust. This would facilitate storage of less water onboard. Better thermal management would also facilitate storage of less water onboard, since water is also used to cool the process. Other ways to address weight and volume include better electric power management, better process control, better chemical reaction kinetics, and lighter / smaller equipment items. To address cost, alumina and magnesia regeneration (i.e., to aluminum and magnesium) will be important, since these metals represent the majority of the fuel cost. Conformability will be addressed on a case-by-case basis.

Dissemination of results

Interim results of the project have already been disseminated through several podium and poster presentations at industry conferences and workshops. Final results of the project will be disseminated through similar channels. Success of the project was / will be made public through a press release. Media outlets will be made aware of the success of the project. Industry (i.e., stakeholders and interested parties) will also be made aware of the success of the project. Events will be held, to which media outlets and industry will be invited. The purpose of these events will be to demonstrate the final project deliverable to those in attendance, to further publicize the success of the project and to also generate interest in future projects.

Lessons learned, and how to apply them

In view of the overall success of the project, there is not much that could have been done differently. If anything at all, the one thing that could have been done differently is stricter adherence to regulatory safety codes related to hydrogen. The catastrophic failure that occurred about midway through the project might not have resulted in such a long delay if regulatory safety codes related to hydrogen were strictly adhered to from project start. Thereafter, regulatory safety codes related to hydrogen were strictly adhered to, and similar catastrophic events (and resulting delays) were avoided.

Summary of Results

Alloy Surfaces Company, Inc. designed and fabricated hydrogen plant module (HPM) capable of producing hydrogen fuel onboard a vehicle. HPM produces low pressure hydrogen fuel on-demand, thereby eliminating the need for high pressure hydrogen fuel storage onboard the vehicle.

Summary of Performance Outcome Data

Energy and fuel generation

HPM and vehicle fueled by the same is non-deployable (i.e., for demonstration purposes only). Project application included performance outcome data based on assumptions of a long-term deployment scenario. The following is normalized performance outcome data, based per each mile that HPM and vehicle fueled by the same is driven at a driving speed of 15.31 mph (i.e., equal to 30 kW power requirement set forth by project advisor).

Given (i.e., determined empirically): hydrogen demand at 15.31 mph = 0.000211 kg / sec

1 / 15.31 mph * 60 min / hr * 60 sec / min = 0.0653 sec / mi

0.000211 kg / sec * 0.0653 sec / mi = 0.0497 kg / mi hydrogen generated

Energy and fuel savings

Given (i.e., constant value): gasoline energy content = 47.842 MJ / kg
Given (i.e., constant value): hydrogen energy content = 141.774 MJ / kg

0.0497 kg / mi * 141.774 MJ / kg / 47.842 MJ / kg = 0.147 kg / mi gasoline saved

Energy and fuel generating / saving units manufactured, sold, or deployed

Again, HPM and vehicle fueled by the same is non-deployable. Further, it is not for sale. Only one unit was manufactured.

Cost savings and economic benefit

Again, project application included performance outcome data based on assumptions of a long-term deployment scenario. The following performance data is accurate in the near-term, and is based on current given information rather than assumptions.

Given (i.e., obtained from www.eia.gov): price of gasoline = $3.67 / gal
Given (i.e., constant value): gasoline specific gravity = 2.755 kg / gal
Given (i.e., constant value): HPM feedstock Al mass / kg hydrogen = 6.774 kg
Given (i.e., obtained from Valimet): price of HPM feedstock Al = $15.98 / kg
Given (i.e., constant value): HPM feedstock Mg mass / kg hydrogen = 2.903 kg
Given (i.e., obtained from Reade): price of HPM feedstock Mg = $31.97 / kg
Given (i.e., obtained from Air Liquide): price of hydrogen = $101.84 / kg

Value of hydrogen generated = $101.84 / kg * 0.0497 kg / mi = $5.06 / mi

Value of gasoline saved = $3.67 / gal / 2.755 kg / gal * 0.147 kg / mi = $0.20 / mi

Cost of HPM feedstock Al and Mg used for hydrogen generation =
(6.774 kg * $15.98 / kg + 2.903 kg * $31.97 / kg) / kg * 0.0497 kg / mi = $9.99 / mi

Cost savings = $5.06 / mi + $0.20 / mi - $9.99 / mi = -$4.73 / mi

NOTE: In the near-term, there is no cost savings. There is an incurred cost, because the current price of HPM feedstock Al and Mg is much higher than the price of gasoline. Cost savings are possible based on assumptions of a long-term deployment scenario. In such a scenario, it is assumed that the price of gasoline will continue to increase, while the price of electricity (from grid) will remain relatively stable. Because electricity price will be a determinant of the cost to regenerate alumina and magnesia, the price of HPM feedstock Al and Mg will be affected primarily by the other determinant. The other determinant of cost to regenerate alumina and magnesia is the amount of energy required for the regeneration process. Theoretical minimum energy amounts, considered along with current electricity price, would lower the HPM feedstock Al and Mg price point to cost-competitive level. However, regeneration processes are currently inefficient, so much more than theoretical minimum energy amounts are required. That being said, it is assumed that regeneration processes will eventually be made more efficient, given demand increase. Cost savings are possible based on these assumptions.

Value of energy and fuel generating / saving units manufactured, sold, or deployed is not relevant, because there is no intent to sell. Further, there is no intent to generate revenue from use of HPM and vehicle fueled by the same. HPM and vehicle fueled by the same will be used for demonstration purposes only, to generate interest in future projects. The intent is to generate revenue through future projects (and to also secure funding for future projects).

Number of new jobs created by the project

Two new jobs were created by the project. These jobs were temporary full-time positions held by contract employees until the end of the project performance period.

Number of jobs retained resulting from the project

Two jobs will be retained as a result of the project's overall success. These jobs will be filled by the same two contract employees that held temporary full-time positions during the project performance period. They will now serve as consultants on a part-time basis, providing assistance with demonstrations of HPM and vehicle fueled by the same.

Other economic development benefits

None to report.

Photographs, Charts, Figures, etc.

Poster presentation, 2nd HHVRL Industry Workshop, April 16-17, 2009

Hydrogen Plant Module (HPM) and vehicle fueled by the same

Alloy Surfaces
Part of the Chemring Group

Project Collaborators:
Alloy Surfaces Company, Inc. (ASC)
The Pennsylvania State University (PSU)

PENNSTATE
1855

Project Objective:

Design and fabricate HPM that is capable of producing hydrogen fuel onboard a vehicle and that obviates one or more of the present issues related to compressed hydrogen fuel storage onboard a vehicle, such as high pressure, weight, volume, cost, and conformability.

Project Background:

ASC has developed a novel composition and process for the production of hydrogen. The ASC composition is a mixture of finely divided sodium chloride, finely divided magnesium, and finely divided aluminum. The ASC process involves addition of the ASC composition to water, wherein chemical reaction occurs with hydrogen as product. ASC is financially committed to transitioning this technology to the transportation sector.

PSU is considered to be a national leader in research and development of hydrogen-fueled vehicle systems. PSU has extensive knowledge and experience related to hydrogen-fueled vehicles and vehicle systems design and fabrication. PSU also has state-of-the-art resources and facilities necessary to model, simulate, test, and evaluate hydrogen-fueled vehicles and vehicle systems.

Project Deliverables:

- Software model of HPM, using *Aspen Plus®* and *Aspen Plus Dynamics®*
- Software models of powertrain system components of vehicle, using *Powertrain System Analysis Toolkit*
- In-vitro hardware model of HPM (i.e., external to vehicle)
- Powertrain system components of vehicle (and vehicle itself), fueled by in-vitro hardware model of HPM
- In-situ hardware model of HPM (i.e., internal to vehicle)
- Vehicle fueled by in-situ hardware model of HPM

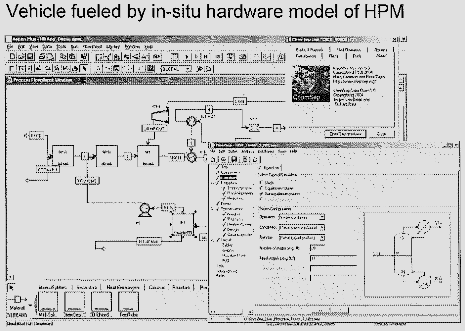

Fig. 1: *Aspen Plus®* and *Aspen Plus Dynamics®* screenshot

Aspen Plus® is a process modeling software for conceptual design, optimization, and performance monitoring of chemical processes. It allows the user to predict the steady-state behavior of a chemical process using fundamental engineering relationships such as reaction kinetics, mass and energy balances, and phase and chemical equilibrium. Given reliable thermodynamic data, realistic operating conditions, and the rigorous *Aspen Plus®* equipment models, the user is able to simulate actual plant behavior.

Aspen Plus Dynamics® extends *Aspen Plus®* steady-state modeling capability, allowing the user to simulate dynamic behavior within a chemical process. With *Aspen Plus Dynamics®*, the user is able to design and verify process control schemes, perform process safety studies and failure mode analysis, and develop startup, shutdown, rate-change, and grade transition policy. *Aspen Plus Dynamics®* supports concurrent process and control design, which helps reduce capital costs, lower operating costs, improve plant safety and prevent control problems.

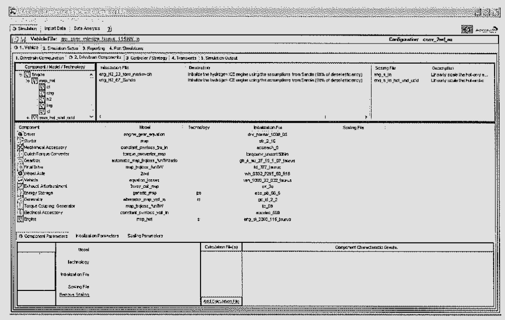

Fig. 2: *Powertrain System Analysis Toolkit* (*PSAT*) screenshot

PSAT is a forward-looking model, developed in *MATLAB®*, based on *Simulink®* and *Stateflow®*. It was developed by researchers at Argonne National Laboratory, sponsored by U.S. DOE, under the direction of (and with contributions from) DaimlerChrysler, Ford, and GM. *PSAT* allows the user to simulate fuel economy and vehicle performance in a realistic manner, taking into account transient behavior and control system characteristics. It provides an extensive library for the simulation of a number of predefined powertrain system configurations (e.g., conventional, electric, fuel cell, series hybrid, parallel hybrid, and power split hybrid).

Because of its accurate dynamic component models, *PSAT* can be implemented directly and tested at the bench scale or in a vehicle. Using the software model as a starting point, the user is provided with the capability for stepwise replacement of software model (i.e., virtual) representations with corresponding actual (i.e., real) hardware systems and components. This capability facilitates smooth transition from the virtual environment of a constructive simulation to the emulated environment of Hardware-in-the-Loop and closed-loop simulations, and then to the real environment of a live test.

Project Major Tasks:

- Constructive simulations
- Distributed Hardware-in-the-Loop (HIL) simulations
- Parallel HIL simulations
- Closed-loop simulations
- Live test

Project Status:

ASC currently is creating software models of HPM, while PSU is creating software models of various powertrain systems that use hydrogen as fuel.

Somewhat concurrently with software modeling activities, ASC is identifying possible components for in-vitro hardware model of HPM, while PSU is identifying possible vehicles and components for hardware model of powertrain system.

Project Funding:

Commonwealth of Pennsylvania,
Department of Environmental Protection,
Alternative Fuels Incentive Grant Program

Contact Information:

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Hybrid and Hydrogen Vehicle Research Laboratory
The Pennsylvania State University (PSU)
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Poster presentation, Reception with Mark Reuss, President of GM North America, September 14, 2010

Hydrogen Plant Module (HPM) and vehicle fueled by the same

Alloy Surfaces

Part of the Chemring Group

Project Collaborators:

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Project Objective:

Design and fabricate HPM that is capable of producing hydrogen fuel onboard a vehicle and that obviates one or more of the present issues related to compressed hydrogen fuel storage onboard a vehicle, such as high pressure, weight, volume, cost, and conformability.

Project Background:

ASC has developed a novel composition and process for the production of hydrogen. The ASC composition is a mixture of finely divided sodium chloride, finely divided magnesium, and finely divided aluminum. The ASC process involves addition of the ASC composition to water, wherein chemical reaction occurs with hydrogen as product. ASC is financially committed to transitioning this technology to the transportation sector.

PSU is considered to be a national leader in research and development of hydrogen-fueled vehicle systems. PSU has extensive knowledge and experience related to hydrogen-fueled vehicles and vehicle systems design and fabrication. PSU also has state-of-the-art resources and facilities necessary to model, simulate, test, and evaluate hydrogen-fueled vehicles and vehicle systems.

Project Deliverables:

- **HPM**
- **Vehicle fueled by HPM**
- **Interface between vehicle and operator**
- **Interface between vehicle and HPM**

Project Status:

ASC has completed development of the HPM and has now begun testing of the HPM for simulated hydrogen fuel demands based on expected fuel consumption by selected vehicle (i.e., Ford F-150) during the FTP-75, HWFET, and US06 driving cycles. PSU provided ASC with simulation data obtained using a model it developed using *Powertrain System Analysis Toolkit*.

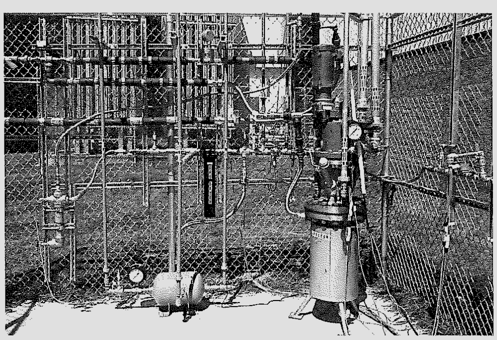

Fig. 1: Photograph of the HPM test apparatus (water feed pump and supply tank not shown)

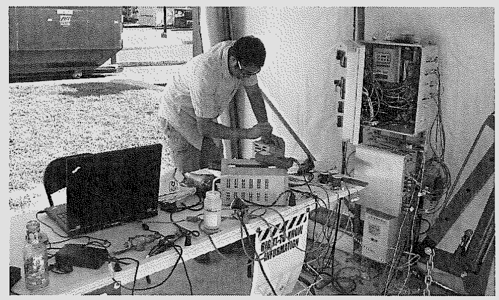

Fig. 2: Photograph of ASC project engineer working on the HPM test apparatus' process control system

ASC hired a contractor to modify selected vehicle (i.e., Ford F-150) such that it runs on hydrogen fuel. Modification is completed, and the HPM will be installed in the cargo box of vehicle once the ongoing testing of the HPM is completed.

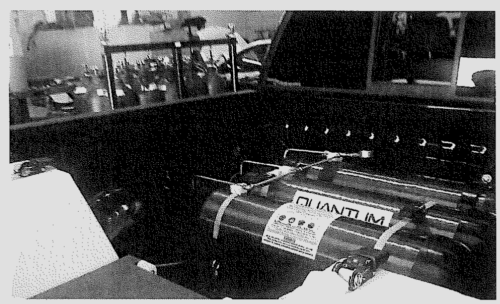

Fig. 3: Photograph of a Ford F-150 modified to run on hydrogen fuel (cargo box of vehicle shown)

PSU is developing interfaces between vehicle and operator and between vehicle and HPM. PSU is also developing a "virtual dashboard" that will allow the operator to monitor (in real-time) certain data acquired from the vehicle and HPM.

Project Funding:

Commonwealth of Pennsylvania,
Department of Environmental Protection,
Alternative Fuels Incentive Grant Program

Contact Information:

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ABSTRACTS

Demand-driven Hydrogen Fuel Production System for Onboard Vehicle Use

John J. Parker, Alloy Surfaces Company, Inc., Joel R. Anstrom, The Pennsylvania State University, Bryan J. Markovich, The Pennsylvania State University and Richard I. Roser, Alloy Surfaces Company, Inc.

Alloy Surfaces Company (ASC) has developed a novel composition and process for the production of hydrogen. The ASC composition is a mixture of finely divided sodium chloride, finely divided magnesium, and finely divided aluminum. The ASC process involves addition of the ASC composition to water, wherein chemical reaction occurs with hydrogen as product.

ASC is financially committed to transitioning this technology to the transportation sector, among other industry sectors. In an effort to fulfill this commitment, ASC has partnered with the Hybrid and Hydrogen Vehicle Research Laboratory at The Pennsylvania State University (PSU). PSU is considered to be a national leader in research and development of hydrogen-fueled vehicle systems. PSU has extensive knowledge and experience related to hydrogen-fueled vehicles and vehicle systems design and fabrication. PSU also has state-of-the-art resources and facilities necessary to model, simulate, test, and evaluate hydrogen-fueled vehicles and vehicle systems.

ABSTRACTS
Listed by author's last name

ASC and its collaborative partner PSU have undertaken a project to design and fabricate a system that is capable of producing hydrogen fuel onboard a vehicle and that obviates one or more of the present issues related to compressed hydrogen fuel storage onboard a vehicle, such as high pressure, weight, volume, cost, and conformability. The project, now close to completion, was funded by an Alternative Fuels Incentive Grant awarded to ASC in early 2009 by the Commonwealth of Pennsylvania. The system, once fabricated, will be installed in a light-duty truck, and it will generate and deliver (as needed) fuel to the truck's internal combustion engine.

This presentation will focus on the project undertaking and will provide the audience with an overview of the project schedule, inclusive of major tasks and deliverables. The progress to date and current status of system development will be reported. Critical developmental and operational issues, such as thermal management and exhaust water recovery, will also be reported.

Photographs of HPM and vehicle fueled by the same