Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Final Technical Report

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1 Executive Summary

This report summarizes the work conducted under U.S. Department of Energy (US DOE) contract DE-FC36-04GO14286 by Chevron Technology Ventures (CTV, a division of Chevron U.S.A., Inc.), Hyundai Motor Company (HMC), and UTC Power (UTCP, a United Technologies company) to validate hydrogen (H2) infrastructure technology and fuel cell hybrid vehicles.

Chevron established hydrogen filling stations at fleet operator sites using multiple technologies for on-site hydrogen generation, storage, and dispensing. CTV constructed five demonstration stations to support a vehicle fleet of 33 fuel cell passenger vehicles, eight internal combustion engine (ICE) vehicles, three fuel cell transit busses, and eight internal combustion engine shuttle busses. Stations were operated between 2005 and 2010.

HMC introduced 33 fuel cell hybrid electric vehicles (FCHEV) in the course of the project. Generation I included 17 vehicles that used UTCP fuel cell power plants and operated at 350 bar. Generation II included 16 vehicles that had upgraded UTC fuel cell power plants and demonstrated options such as the use of super-capacitors and operation at 700 bar. All 33 vehicles used the Hyundai® Tucson sports utility vehicle (SUV) platform. Fleet operators demonstrated commercial operation of the vehicles in three climate zones (hot, moderate, and cold) and for various driving patterns.

Fleet operators were Southern California Edison (SCE), AC Transit (of Oakland, California), Hyundai America Technical Center Inc. (HATCI), and the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC, in a site agreement with Selfridge Army National Guard Base in Selfridge, Michigan).

Accomplishments

Through the design, construction, operation, and decommissioning of the hydrogen stations between 2004 and 2009, the following accomplishments stand out as important achievements of the program:

- **Safe operations** – The Operations team achieved its goal of incident-free operations (no lost time accidents).
- **Technical capability** – The hydrogen program has demonstrated the technical capability to support a U.S. car penetration portfolio that contains up to 10% hydrogen fuel cell vehicles (FCV).
- **Cold startup capability** – Vehicles were demonstrated to start after extended periods in subfreezing temperatures.
- **Hot weather operation** – Vehicles were demonstrated in hot weather climate with positive water balance.

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2 Chevron Infrastructure

Background

In 2003, US DOE solicited industry collaboration on hydrogen station demonstrations. This effort represented a high priority by the Bush administration and Congress to test alternative fuels. Subsequently, CTV collaborated with industry partners and government to evaluate the viability of hydrogen for use as a transportation fuel.

Five unique collaborative teams with a total of over 16 partners were formed in response to the US DOE solicitation. The teams were comprised of representatives from the energy industry, automotive industry, fuel cell manufacturers, technology companies, and local, state, and federal government.

Each of the five teams focused on specific tasks and goals and explored challenges and opportunities unique to the deployment geography and technologies selected. CTV constructed five demonstration stations with funding from US DOE, State of Florida, and Chevron to support a fleet of 33 fuel cell passenger vehicles, eight internal combustion engine passenger vehicles, three fuel cell transit busses, and eight internal combustion engine shuttle busses.

Site Objectives

A high-level overview of the site-by-site objectives is described here.

- **Chino, California:** Conduct hot weather testing of Hyundai-Kia's fuel cell passenger vehicles. Served as the first deployment site for the passenger vehicles.
  - **Key partners:** US DOE, Hyundai-Kia Motors, and UTCP
- **Oakland, California:** Test hydrogen fuel cell transit busses used in day-to-day routes throughout Alameda and Contra Costa counties.
  - **Key partners:** AC Transit, Van Hool, US DOE, Hyundai-Kia Motors, and UTCP
- **Rosemead, California:** Test the efficiency, reliability, cost, and durability of electrolyzer technology.
  - **Key partners:** US DOE, Hyundai-Kia Motors, UTCP, and SCE
- **Selfridge, Michigan:** Conduct cold weather testing of fuel cell passenger vehicles and fueling technology.
  - **Key partners:** US DOE, TARDEC, Ford, Quantum Fuel Systems, Hyundai-Kia Motors, UTCP, and SCE
- **Orlando, Florida:** Test supply and demand optimization and provide an opportunity to fuel internal combustion engine busses.
  - **Key partners:** US DOE, State of Florida, Ford, Progress Energy, SeaWorld, Greater Orlando Aviation Authority, and the Orange County Convention Center

The collaboration between CTV and its partners resulted in significant advancements toward the commercial readiness of fuel cell vehicles and a hydrogen infrastructure.

2.1 Hydrogen Stations

This section describes the five Chevron demonstration stations and provides some of their technical characteristics. See Figure 1 for a map of their locations.

Figure 1: Hydrogen demonstration station locations.

Chevron's goal was to demonstrate state-of-the-art hydrogen technologies for the program. Table 1 provides the key characteristics of each station and highlights the stations' differences.

The stations ranged in size from 10 kg/day to 150 kg/day production capacity. They had a range of minimum turndown capability from 25% to 50%. Turndown is important as it allows an option for reduced consumption periods vs. increasing storage requirements or shutting off the hydrogen generator. The hydrogen compressors were designed to operate with a spill back system to ensure a feed supply if the generator was turned down. Operating at 50% turndown of the generator results in a doubling of the energy used in compression per kilogram. The compression energy consumption ranged between 2 kWh/kg and 4 kWh/kg. Different production methods were used at each station with two trains at Oakland for a total of six production technologies. The stations were designed to operate under a wide range of ambient temperature with the Selfridge station having the lowest range of –23°C (–9°F). The stations were designed with a range of storage capacity to production ratios from 1.7 to 11.7, depending on the maturity of the generation technology used.

Table 1: Comparison of hydrogen stations.

Location (USA)	Rosemead, California	Selfridge, Michigan	Oakland, California		Chino, California	Orlando, Florida
Inception Date	6 Mar 2007	4 Apr 2007	1 Dec 2005		1 Nov 2005	31 Jan 2007
Production Method	electrolysis	steam methane reforming	steam methane reforming		autothermal reforming	steam methane reforming
Survivability (temperature)	–3°C to 50°C (27°F to 122°F)	–23°C to 35°C (9°F to 95°F)	–3°C to 50°C (27°F to 122°F)		0°C to 40°C (32°F to 104°F)	0°C to 40°C (32°F to 104°F)
Product Grade	fuel cell					not fuel cell
Type of Vehicles Fueled	fuel cell SUVs	fuel cell & H2 ICE SUVs	fuel cell busses & SUVs		fuel cell SUVs	H2 ICE busses
Purified Hydrogen Generator						
Technology Provider	Hydrogenics	CTV/Modine	Harvest/ Hydrogenics		CTV	H2Gen
Model Name	HySTAT/IGEN	Advanced SMR	APHG1	APHG2	Halias	HGM-2000
Turndown Ratio	50%	25%	40%		50%	50%
Capacity (kg/day)	35	80 (40 × 2 trains)	75	75	10	114
DI Water (L/kg)	9	14	7.0		10	14–27
Natural Gas (scf/kg)	N/A	169	155		208	188
Operating Temp (Max.) (°C)	70 (158°F)	850 (316°F)	980 (1,796°F)		600 (1,112°F)	950 (1,742°F)
Operating Pressure (psig)	180	120	15	135	14	200
Compression, Storage, & Dispensing						
Technology Provider	Hydrogenics	Air Products	Hydrogenics		Hydrogenics	Air Products
Compressor Type	PDC-3 diaphragm	PDC-4 diaphragm	PDC-3 diaphragm		PDC-3 diaphragm	PDC-4 diaphragm
Compressor Capacity (nominal)	45 kg/day @ 100 psig inlet	2x 76kg/day @ 150 psig inlet	2x 87 kg/day @ 100 psig inlet		16.3 kg/day @ 100 psig inlet	2x 76kg/day @ 150 psig inlet
No. of Stages	2					
Min/Max Suction Pressure (psig)	80/210	70/150	60/130		80/200	70/150
Discharge Pressure (psig)	6,250 to storage tank					
Storage						
Capacity (kg)	60	300	366		117	300
Capacity/Production Ratio	1.7	7.5	2.4		11.7	2.6
No. of Cascaded Banks	3	3	6		3	3
No. of Cylinders	5	18	27		7	18
No. of Dispensers	1	1	2		2	1

2.2 Component Issues and State of Readiness

The following section discusses the key technology components used in hydrogen stations, their commercial readiness, and their issues.

On-Site Hydrogen Production

Hydrogen production technologies used in Chevron hydrogen stations included various types of reformers (developed internally and obtained from suppliers) and electrolyzers. The reformers deployed in the field were first-of-their-kind applications. The Halias®, Harvest high-pressure, and advanced steam methane reformer (ASMR) technologies were deployed for on-site hydrogen production for the first time out of the laboratory in this program. The state of readiness for deploying this young technology in the field was low and resulted in uncertain operations at the sites.

Harvest High-Pressure Reformer

The Harvest high-pressure steam methane reformer (SMR) was developed for the program. The design concept was to compress the natural gas prior to entering the SMR reactor and mix it with high-pressure steam. The result of this design is a greatly reduced operating energy requirement.

Harvest Low-Pressure Reformer

Prior to the US DOE program, the Harvest low-pressure SMR system was being field tested at Chevron's Montebello facility. This hydrogen generator was repackaged for installation at Oakland by Hydrogenics.

H2Gen Reformer

The H2Gen unit is a commercial 114 kg/day hydrogen generator that operates at 200 psig. The unit was the eighth in the production of the H2Gen 1000 line. This was the first application of H2Gen technology to a hydrogen fueling station.

Halias Reformer

The Halias is a natural gas autothermal (partial oxidation) reformer-based hydrogen generator developed by Chevron. The Halias was constructed for the first time out of the laboratory specifically for this program.

ASMR Reformer

The ASMR purified hydrogen generator (PHG) is a Chevron-developed, first prototype ASMR reactor. The ASMR reactor is novel in that the fins on its heat exchanger are coated with reforming catalyst. This approach serves to minimize heat loss and maximize heat recovery.

Hydrogenics Electrolyzer

The Hydrogenics unit uses an alkaline potassium electrolyte (i.e., conduction solution). The electrolyte carries the electric current but is not consumed in the reaction. Water is added continuously as production proceeds.

Compressors

The project used "triple diaphragm" compressors for the compression of purified hydrogen from 100 psig to 6,250 psig. These units maintain a separation of the oil used in compression and the purified gas, and they do not need subsequent cleanup steps prior to dispensing as would be needed with non-diaphragm (e.g., reciprocating) units. Compressors in this project were designed to be used with priority fill of a cascade storage system. While the cascade fill system requires a larger footprint for storage of the hydrogen than a booster compressor, the reliability of nonmoving steel tanks was considered greater than that of mechanical rotating equipment. The booster compressor offers the potential of lower capital cost and smaller footprint at the expense of reliability and operating cost compared to stationary storage tanks.

Storage

Currently, the prevailing form for hydrogen storage in a refueling station is high-pressure compressed gas stored in steel ASME-rated cylinders. The typical storage pressure for hydrogen can range from 5,000 psi to 7,000 psi for a typical station that requires dispensing hydrogen at 5,000 psi. The ASME steel high-pressure vessels are commercial with considerable history of use. This is the dominant technology for high-pressure gas storage. There are well-established processes for design, manufacturing, and service of these storage vessels. In addition, most local government authorities and permitting organizations in the United States require ASME-certified storage vessels for on-site storage of high-pressure flammable gases such as hydrogen.

There are other hydrogen storage technologies being developed but they are at a less mature state of readiness. The carbon fiber wrapped tanks are the main storage technology used in vehicles but can require a permit exemption to be used as stationary storage.

Dispensers

The project involved three dispenser suppliers: FTI, Hydrogenics, and Air Products. The dispensers' human machine interface (HMI) touch screens and programming allowed access by personal identification number for operation. The interface also allowed data entry of vehicle identification numbers and odometer readings to facilitate data recording. The metering of the hydrogen was done using Coriolis mass flowmeters.

The nozzle used at all stations was a WEH TK16. This model is an upgrade to the TK15 initially used at Chino and Oakland and offered superior ease of use. The California stations used WEH breakaways. The breakaway is designed to separate in the event a vehicle drives away while still attached to the nozzle. In an incident in Oakland, a bus drove away while connected and the receptacle on the bus failed prior to the breakaway separating. The check valves on the hose and on the vehicle retained integrity, limiting the gas release to the volume in the hose. No one was hurt in the incident. The Air Products stations used an OPW breakaway.

Hydrogen fueling uses a nozzle connection, like gasoline fueling does, but the connection is gas-tight to contain the hydrogen gas. Hydrogen fueling also uses a communications cable to provide the dispenser with signals for the temperature, pressure, and volume of the fueling tank. The connection and disconnection (sealing and unsealing) of the Deutsch connection is a wear point. The connectors had a 750 lifetime connection limit at Oakland prior to providing erratic signals. At Chino, the connectors had a lifetime of 900 fuelings. The connector used at Orlando provided over 1,500 fuelings prior to requiring replacement. The additional lifetime fuelings at Chino and Orlando may have been due to a smaller pool of fueling operators.

Balance of Plant

The hydrogen station balance of plant (BOP) refers to the additional components required for station operation. These components are of secondary importance because they are considered mature technologies and can be acquired off the shelf.

Instrument Air Compressor System

The air compression requirements of an on-site generation station are much larger than current gasoline stations, which support tire filling and air-operated equipment. Packaged Ingersoll Rand air compressor units are readily available from suppliers and were used at all sites. In addition, the Orlando site employed a compressed hydrogen system to operate air-operated valves, rated for hydrogen service, on the compression, storage and dispensing (CSD) system.

Natural Gas Compressor System

On-site reformation requires a natural gas compressor, which can be purchased off the shelf. Compression is required to boost the local utility supplied pressure, which ranges from approximately 1 psig to 20 psig to the generator inlet pressure of approximately 15 psig to 220 psig, depending on the design.

Feed Water System

Hydrogen generation requires the use of water for both reformation and electrolysis. The specification for the feed water is 5 microsiemens. Municipal water contains total dissolved solids (TDS) that require cleanup prior to use. Either deionization (DI) or reverse osmosis (RO) can be used, depending on the local water quality. The RO system requires rejection of approximately 50% of the feed water. While potentially lower in cost, an RO system consumes twice as much water as a DI system.

Natural Gas Desulfurization

Production of high-purity hydrogen requires removing sulfur compounds used as odorants in the natural gas feedstock. Odorants include mercaptans, DMS (dimethyl sulfide), MES (methyl ethyl sulfide), and THT (tetrahydrothiophene), depending on the odorant package used. Natural gas can also contain some hydrogen sulfide (H_2S). Removal can be conducted either prior to reformation or as part of the pressure swing adsorption (PSA) purification step of the reformate. Sulfur compounds are a known poison to reformation and water gas shift catalyst.

2.3 Data Collection and Station Performance

Automated station control was achieved using several programmable logic controllers (PLC) on individual pieces of equipment. The individual PLCs were connected by a supervisory control and data acquisition (SCADA) system. Real-time process data from the station, as well as historical information such as trends and alarms, were viewed by the operator on the graphical user interface (GUI). Operators and engineers also remotely viewed the process and historical data at all stations using a remote GUI terminal server with access available via the Internet.

Additionally, there was a remote alarm notification capability, where the SCADA system generated automated phone calls to operators and station managers based on a predefined call-out list.

Collected Data

The US DOE infrastructure report calls for efficiency evaluation for the purified hydrogen generator and compression, as well as for the overall station, in terms of specific energy (per kilogram of hydrogen produced). To calculate the specific energy of conversion and compression, the following data are required:

- Natural Gas Feed (kg)
- Natural Gas Fuel (kg)
- Power Consumption of PHG (MJ)
- Power Consumption of H2 Compressors (MJ)
- Energy Consumption (MJ)
- Hydrogen Produced (kg)
- Hydrogen Compressed (kg)

These variables are used in the following equations:

The Specific Energy of Conversion =

[(Lower Heating Value of NG Feed, MJ/kg) × (NG Fuel, kg) + (PHG Energy Consumption, MJ)] / (H_2 Produced, kg)

The Specific Energy of Compression =

(Compressor Energy Consumption, MJ) / (H_2 Compressed, kg)

The infrastructure report also included daily logs of dispensed hydrogen. This was compared against daily production for station mass balance. Mass balance was used to identify leaks and verify flow.

US DOE Infrastructure Reports

The aforementioned data were compiled in the standard US DOE infrastructure report format and submitted to National Renewable Energy Laboratory (NREL) after the end of every quarter. The report is in an electronic spreadsheet and contains the following sections as tabs:

- Non-Technical
  - Site summary
  - Site manager’s log
  - Maintenance log
  - Safety log
  - H2 purity log

The nontechnical sections of the report are routinely updated by station personnel. The station manager's log records general station activities such as personnel training, fire and safety drill, and public tours. The maintenance log documents any routine or nonroutine maintenance performed on station equipment. The safety log records any safety incidents/near-misses that have occurred at the station. The hydrogen purity log details the results of each quarterly hydrogen product sampling.

- Technical
  - Refueling log: Includes vehicle refueling data such as vehicle ID, temperature, pressure, average refueling rate, percent full fill, and amount of hydrogen dispensed.
  - On-site efficiency log: Lists monthly average specific energy of conversion, compression, and dispensing; calculates the overall on-site efficiency using the specific energies.
  - Reformer/electrolyzer logs: List daily and monthly production and energy consumption data; calculate monthly specific energy of conversion and conversion efficiency.
  - Compression log: Lists daily compressor operation and storage inventory data; calculates monthly specific energy of compression.
  - Storage and dispensing log: Lists daily and monthly production and dispensing data; calculates daily mass balance around the storage unit. Energy consumed in dispenser operation is considered negligible; therefore, specific energy for dispensing is not reported.

NREL consolidated the data submitted by the participants of the Controlled Fleet and Infrastructure Demonstration and Validation Project and published it as composite data products (CDP), which are disclosed to the public at *http://www.nrel.gov/hydrogen/cdp_topic.html*.

2.4 Economic Analysis

An economic model was developed to calculate the dispensed cost of hydrogen on a $/kg basis for CTV's demonstration hydrogen stations and potential future one-off 200, 600, and 1500 kg/day stations at 5,000 psi. Actual cost data from the demonstration stations and 2009 equipment vendor quotes were used to forecast capital and operating costs required for potential future one-off stations. Hydrogen costs at future one-off hydrogen stations do not include the benefits of mass commercialization and long-term technology advancements. The costs developed in the model were compared to the published costs in the US DOE H2A model.

Projected Costs of Future Stations

Costs for future one-off 5,000 psi hydrogen stations were calculated. The 1500 kg/day station is assumed to be as follows:

- Located in Southern California
- Greenfield site
- On-site hydrogen production from natural gas
- Hydrogen fuel only
- Nonfuel offerings not available (convenience store, maintenance bay, car wash, etc.)

Chevron provided cost analysis results to NREL as part of this program. NREL used the US DOE H2A model and reported a hydrogen production cost for US DOE as part of the technology validation program in January 2010. The reported cost for a 1500 kg/day station was reported as CDP #15, as shown in Figure 2, and is in the range of $8/kg to $10/kg.

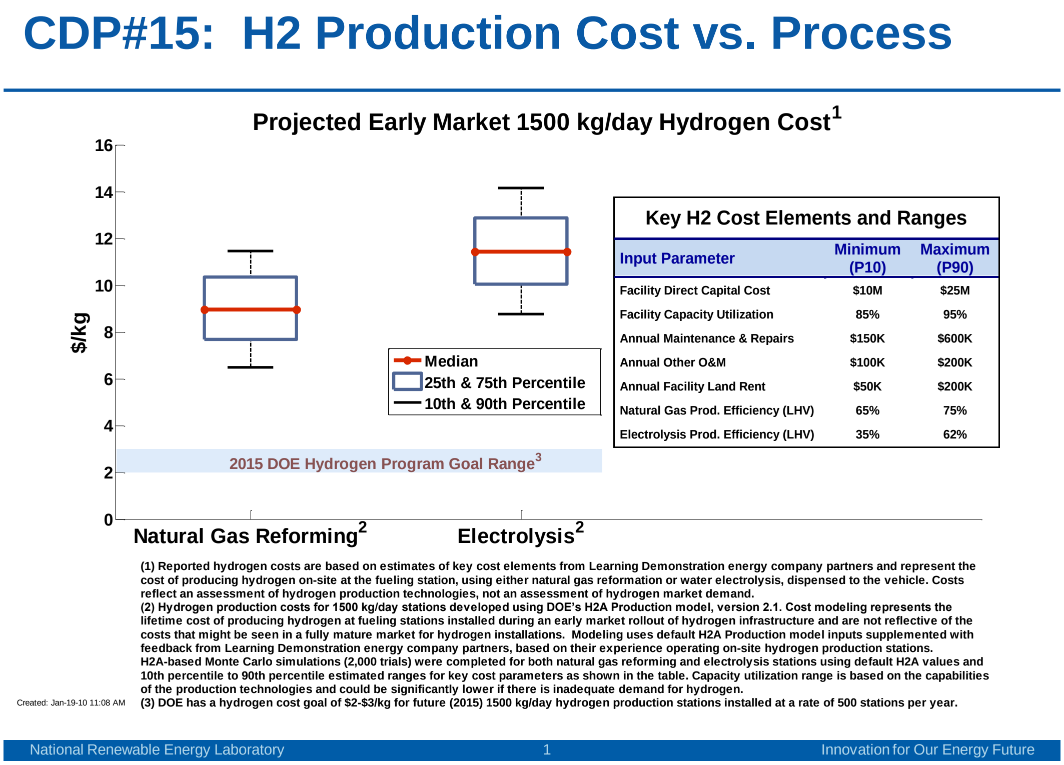


Figure 2: Reported hydrogen production cost aggregated from US DOE hydrogen demonstration program participants. (Source: NREL)

2.5 Program Management

Under the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, CTV, HMC, and UTCP validated both hydrogen infrastructure technology and fuel cell hybrid vehicles. CTV established hydrogen energy stations using multiple technologies for on-site hydrogen generation, storage, and vehicle fueling. HMC tested two generations of fuel cell cars powered by UTCP for commercial operation under three climatic conditions (moderate, hot, and cold) and for various driving patterns.

In addition to key project partners CTV, HMC, and UTCP, four fleet operators operated the hydrogen energy stations and drove the hydrogen vehicles. Each fleet operator had a hydrogen energy station and assigned vehicles. The four fleet operators were HATCI, SCE, AC Transit and TARDEC (who used Selfridge Army National Guard Base as the project's cold weather site).

The partners in the program are shown in Figure 3.

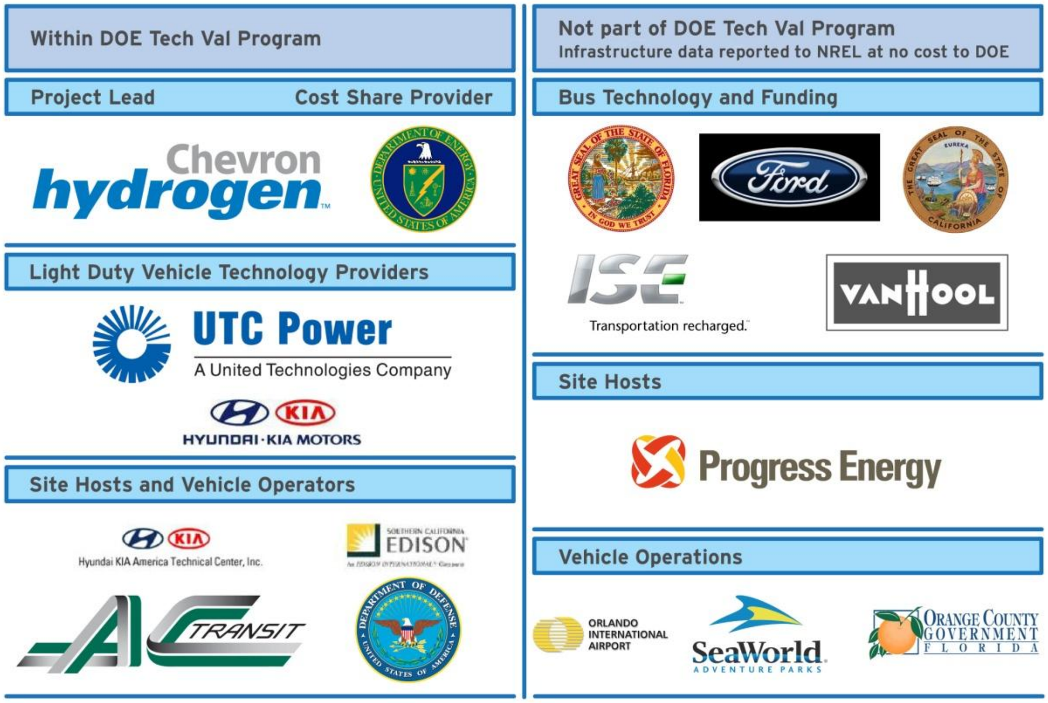


Figure 3: Partners in program management.

For management and reporting purposes, this project was divided into two main groups – infrastructure-related activities and vehicle-related activities.

Infrastructure activities included design, construction, and operation of five hydrogen energy stations that used a range of feedstock, technologies, and locations. Three of these stations were funded by US DOE program cost share, and two were funded by CTV and other parties. Chevron, at no additional cost to US DOE, volunteered to provide data on two other non-DOE program stations – AC Transit's Oakland station and Florida Department of Environmental Protection's (DEP) Orlando station. AC Transit's Oakland station serviced three 40-foot (12-m) fuel cell hybrid busses and up to 10 Hyundai fuel cell cars covered under this US DOE program. Florida DEP's station serviced eight hydrogen internal combustion engine busses. Chevron partnered with the State of Florida, Ford, and Progress Energy to demonstrate the hydrogen internal combustion engine busses in Orlando. The vehicle operators in that project were the Greater Orlando Aviation Authority, SeaWorld, and the Orange County Convention Center. While this work was not funded by US DOE, all of the infrastructure data were shared with NREL by Chevron at no cost to US DOE.

Hyundai, Kia, and UTCP, together, demonstrated vehicle improvements such as increased on-board gas storage to improve vehicle driving range and improved manufacturing processes for the production of fuel cell components in order to lower the overall cost of fuel cell vehicles. Both of these activities were necessary in order to evaluate the commercial viability of meeting the two fuel cell performance targets.

2.6 Permitting and Emergency Responders

Permitting

The purpose, scope, and objective of the CTV permitting process ensured compliance with all local, state, and federal permit requirements at all five CTV hydrogen stations. The time required for permits varied for the five stations from 1 month to 10 months. The shortest duration was at the Selfridge Air National Guard Base, and the longest was working with county government in Los Angeles. Table 2 shows the permitting time for each site. A key point was the early engagement for education and outreach efforts to expedite the permitting process. The success of the demonstrations in the communities in which they operated was due in part to the effective use of the training and outreach plans.

Table 2: Permitting authorities and duration for each hydrogen station.

Location (USA)	Permitting Authority	Duration (months)
Chino, California	City of Chino	6
Oakland, California	City of Oakland	7
Rosemead, California	Los Angeles County, California	10
Orlando, Florida	City of Orlando	7
Selfridge, Michigan	Selfridge Air National Guard Base, Michigan	1

There were inconsistencies in the requirements of local jurisdictions. Fire suppression systems were not required at Chino, Orlando, and Oakland but were required at Los Angeles County and Selfridge. The fire alarm control panel (FACP) was required at all sites, but the design varied by locale. Design of the flame and gas detection system was included in the FACP in some sites but a separate system at other sites. Permitting was a challenging part of station construction because the permitting agencies had never seen hydrogen stations before, and thus standards were open for interpretation.

First Responder Training

The purpose, scope, and objective of the first-responder training program ensured the local emergency responders (ER) were familiar with the hydrogen stations, the safety features, the hydrogen generation process, and the operating personnel. As an example, the Chino station experienced a false alarm that called out the fire department. The street was closed while the incident was investigated. This led to the institution of ER retraining on an annual basis in an effort to foster an ongoing relationship between Chevron and the local emergency response professionals. When training first responders in the future, training sessions may need to be planned far in advance due to scheduling difficulties with ER staff.

Emergency Management

An emergency management plan was developed to address the unique challenges of the hydrogen stations. A site-specific emergency management plan was developed for each station that identified and addressed with specific instructions all emergency situations. All operators, staff, and management were trained on this emergency action plan (EAP), and it was shared with site owners. Each station had an FACP and central station monitoring that would contact both local fire departments and hydrogen staff. The Chevron Corporate Emergency Response line was employed to provide an 800 number for reporting emergencies. Hypothetical emergency response drills were conducted with local first responders. Part of the community outreach program included site-specific training with local fire departments and first responders.

2.7 Conclusions

The hydrogen program has demonstrated the technical capability to support a car penetration portfolio in the United States that contains up to 10% hydrogen fuel cell vehicles. The program was able to demonstrate the safe refueling of vehicles and on-site production of hydrogen for over four years.

The use of hydrogen as a transportation fuel is not currently economically competitive with conventional fuels. Additional technology breakthroughs in the following areas are needed to improve hydrogen fuel station economics:

- Reformer scalability and cycling
- Storage footprint at the forecourt
- Clean/green hydrogen

Government investments in these areas can be instrumental in making hydrogen a viable future transportation.

3 Hyundai-Kia Fuel Cell Vehicles

3.1 Introduction

The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, also known as the Fuel Cell Vehicle and Infrastructure Learning Demonstration, was a five-year US DOE project that started in 2004 and ended in 2009. The project's purpose was to conduct an integrated field validation that simultaneously examined the performance of fuel cell vehicles and the supporting hydrogen infrastructure. Hyundai-Kia Motor Company deployed and operated 33 vehicles during the five-year project period with UTCP's cooperation under Chevron's management. The fuel cells and fuel cell systems were provided by UTCP in Connecticut. Vehicles were built in Korea and shipped to each U.S. fleet location. Hyundai conducted many tests and participated in several activities during this period. Hyundai-Kia promoted environmentally friendly policies in the United States and contributed to the development of positive public perception of hydrogen and fuel cells through vehicle environmental testing and multiple outreach activities. Hyundai-Kia is accelerating FCV development and hydrogen infrastructure in the United States as well as in Korea.

Hyundai-Kia is introducing improved FCV performance and solving key technical barriers, such as reducing cost and improving fuel cell durability. These barriers are well-known for FCV commercialization. Hyundai-Kia will continue to operate fuel cell vehicles in the United States as well as Korea. Hyundai-Kia expects more vigorous fuel cell activity in the United States.

3.2 Objective

Hyundai-Kia Motor Company manufactured and deployed 33 vehicles, one more vehicle than the original plan. Its fuel cell technology was provided by UTCP. These vehicles demonstrated the current state of technology, and Hyundai worked toward improvements such as increasing on-board gas storage to improve vehicle driving range and improving manufacturing processes for faster production times and more reliable fuel cell components. Both of these activities are necessary in order to lower the overall cost of fuel cell vehicles and to evaluate the commercial viability of meeting US DOE vehicle range and fuel cell stack durability performance targets.

This project's objective was to conduct parallel learning demonstrations of hydrogen infrastructure and fuel cell vehicles to allow government and industry to assess progress toward technology readiness. Table 3 contains the initial US DOE vehicle and infrastructure targets. A second generation fuel cell and system was introduced to address the durability target and a 700 bar tank system to address the range target. Both targets are key to consumer acceptance of new vehicle technologies.

Table 3: US DOE key targets.

Performance Measure	~2009	~2015
Fuel Cell Stack Durability	**2,000 hours**	5,000 hours
Vehicle Range	**250+ miles (400+ km)**	300+ miles (480+ km)
Hydrogen Cost at Station	**$3/GGE[1]**	$2~3/GGE

[1] gasoline gallon equivalent

Role of Hyundai-Kia

Hyundai-Kia was selected by CTV to participate in this project because of its extensive experience with the technologies related to the distributed production of hydrogen and design and manufacture of fuel cells and hydrogen fuel cell powered vehicles. The team members worked together to assure effective management of the project.

Table 4. Participants' main roles.

Organization	Main Role
Chevron Technology Ventures LLC	Team lead & fuel provider
Hyundai-Kia Motor Company	Fuel cell integrator & vehicle provider
UTC Power	Fuel cell developer & provider
Hyundai-Kia America Tech Center, Inc	Maintenance, fleet, & coordination
AC Transit	Fleet operator
Southern California Edison	
TARDEC-Selfridge	

As a major project partner, Hyundai-Kia worked with UTCP to produce 33 fuel cell vehicles that were distributed throughout the U.S. fleet locations. Hyundai-Kia coordinated with UTCP to ensure that vehicle manufacturing and commissioning proceeded on schedule. The first vehicles began operation in 2005.

HMC trained its U.S. affiliate, HATCI, in the maintenance and repair of the fuel cell vehicles and coordinated any necessary fuel cell replacements through UTCP. HATCI supervised the local training of the various infrastructure site hosts, who also acted as fleet operators. HATCI and UTCP trained the operators in the safe operation of hydrogen fuel cell vehicles and instructed the operators to drive the vehicles to reach the appropriate mileage target. These accumulated miles provided the necessary vehicle and fuel cell operating data in a manner that allows HMC, HATCI, and UTCP to submit all US DOE-required vehicle and fuel cell data under CTV's prime contract with US DOE.

As necessary, HMC and HATCI worked with CTV and UTCP to make recommendations on appropriate codes and standards for hydrogen vehicles and fueling stations.

3.3 Program Overview

Under the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, CTV, HMC, and UTCP validated both hydrogen infrastructure technology and fuel cell hybrid vehicles. CTV established hydrogen energy stations using multiple technologies for on-site hydrogen generation, storage, and vehicle fueling. HMC tested two generations of fuel cell vehicles powered by UTCP for commercial operation under three climatic conditions (moderate, hot, and cold) and for various driving patterns.

In addition to key project partners CTV, HMC, and UTCP, four fleet operators operated the hydrogen energy stations and drove the hydrogen vehicles. Each fleet operator had a hydrogen energy station and assigned vehicles. The four fleet operators were HATCI, SCE, AC Transit, and TARDEC (who used Selfridge Army National Guard Base as the project's cold weather site).

Generation I vehicles (17 each) used 350 bar fuel tanks and had limited freeze capabilities. Generation II vehicles (16 each) had reduced manufacturing costs and improved fuel cell stack freeze capabilities. Other applicable technology improvements were implemented when they became available.

Hyundai provided supplemental data regarding ambient operating temperatures, fuel consumption, vehicle performance, and safety. The data were reported to US DOE in the specified format.

Fleet Overview

Hyundai-Kia deployed 16 Hyundai Tucson fuel cell vehicles and 17 Kia Sportage® fuel cell vehicles during the project (see Figure 4). The vehicles were operated in hot-, mild- and cold-weather climates in the United States (see Figure 5). TARDEC used five vehicles for cold startup testing and cold-weather operation each winter in Michigan. SCE vehicles were used for hot-weather operations each summer in the Palm Desert area. Oakland and Sacramento were selected to accumulate mild-weather mileage.

Figure 4: A fuel cell Hyundai Tucson and Kia Sportage.

Figure 5: Operating locations by climate.

FCV use varied depending on location. Some operators used vehicles as security vehicles, equipping them with horns, sirens, and lights. Another operator used vehicles in scouting bus routes, responding to bus accidents, and transporting internal mail among various buildings. Others used the vehicles for stakeholder outreach, commuting, and general vehicle testing.

FCV Safety Features

Hyundai-Kia fleet vehicles are equipped with several safety devices. Figure 6 shows the type and location of these devices. Redundant mechanisms ensure hydrogen safety. An active ventilation system ensures exhaust hydrogen concentration under 25% of the lower flammable limit of hydrogen. Crash sensors are installed to detect impacts at the front and rear of the vehicle. A hydrogen shut-off valve is activated by signal relay from these sensors. Safety design is used for the hydrogen sensors under the hood, in the fuel cell power plant, and around the fuel storage system.

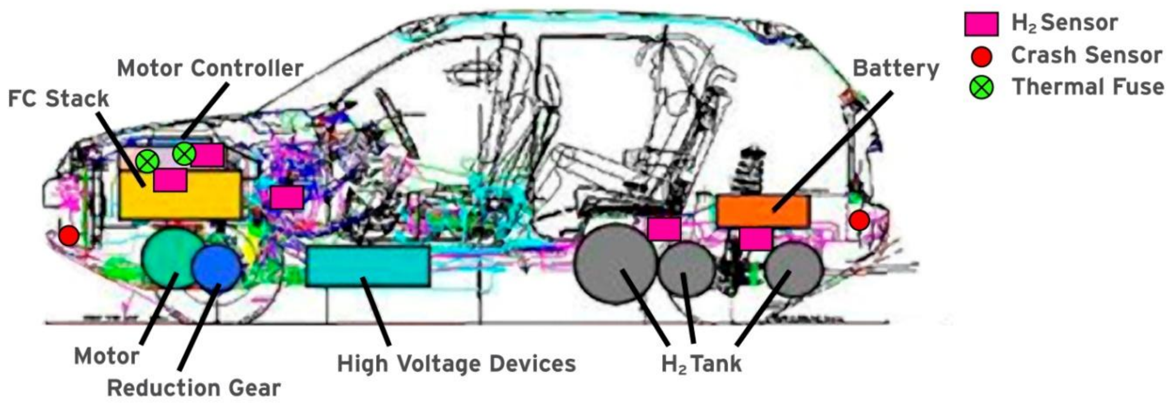


Figure 6: Hyundai-Kia fleet vehicle safety devices.

During an emergency, such as a collision or high-voltage short circuit, the high-voltage relay opens to stop electricity flow automatically and the high-voltage fuse provides short-circuit protection. The high-voltage line can be manually separated by a service plug located in the cargo area. A ground fault detector monitors the high-voltage leakage current during driving. If fault is detected, the vehicle controller starts to shut down the process. The fleet vehicle safety system is illustrated in Figure 7.

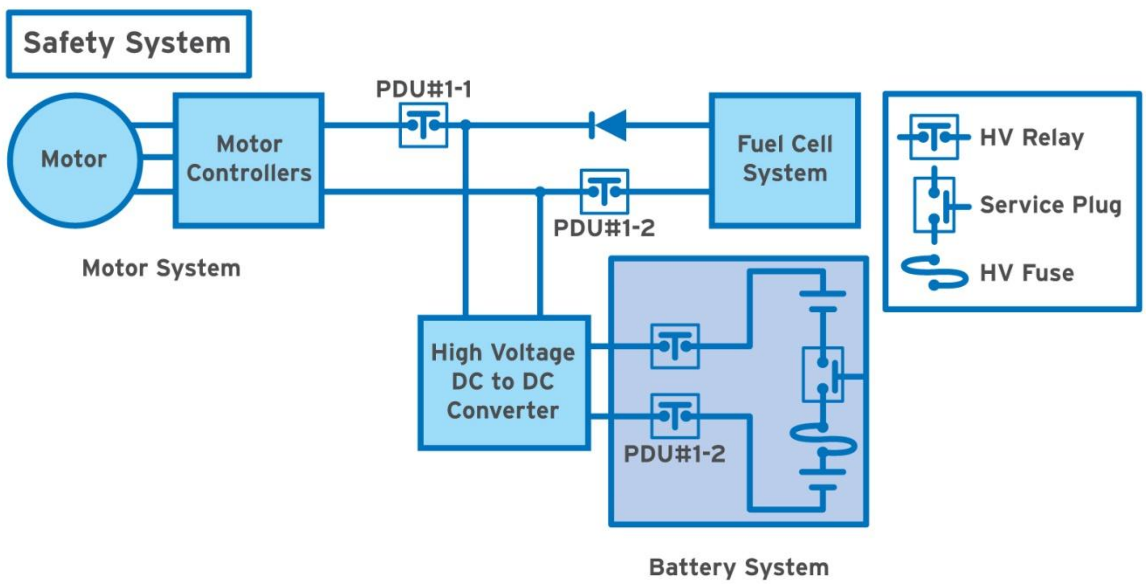
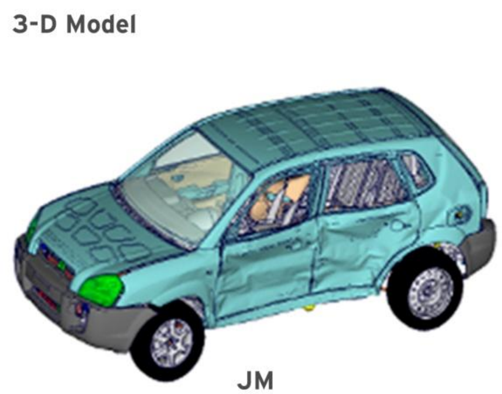


Figure 7: Hyundai-Kia fleet vehicle emergency activation systems.

Vehicles were reviewed and analyzed by following U.S. Federal Motor Vehicle Safety Standards (FMVSS) compliance for fleet purposes, and vehicles were computer-simulated for front, side, and rear impact conditions by FMVSS codes (see figures 8, 9, and 10). No major issues were identified in FMVSS compliance testing.



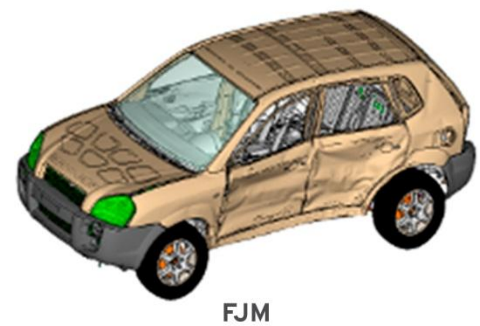


Figure 8: FMVSS208 Frontal impact.

Figure 9: FMVSS214 Side impact.

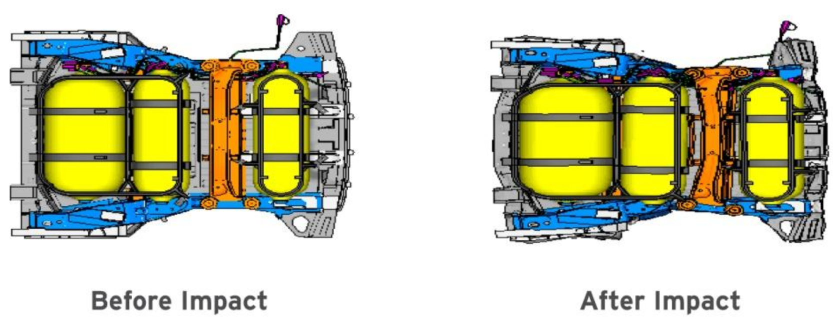


Figure 10: FMVSS301 Rear impact.

3.4 Results

FCV Performance

Hyundai-Kia selected Hyundai Tucson and Kia Sportage SUV fuel cell vehicles for fleet operation. The vehicles' specifications are nearly identical since the same fuel cell and fuel cell systems are used in each. Performance differences, if any, are due to different vehicle weights and features. Table 5 shows Generation I vehicle specifications.

Table 5: Generation I vehicle specifications.

FC Stack Power	**80 kW**	**Fuel Efficiency**	**57 mpg (24 km/l)**
Vehicle Weight	3,920 lb (1800 g)	Max. Speed	94 mph (151 km/h)
Motor	80 kW	Range	191 miles (307 km)
Battery	Li-PB (144V, 6Ah)	Emission	Water vapor only
Fuel Tank	152 liters (3.5kg H2)		

Besides the characteristics that appear in Table 5, tests have proven that operating temperature ranges from –20°C to 40°C (–4°F to 104°F), life cycle extends beyond 1500 hours, and driving altitude reaches up to 4300 m (14,000 ft). Additional characteristics of note are that the fuel cell version of the vehicle is much quieter, more reliable and easier to operate than the ICE version.

Generation I and Generation II Features

During the course of the project, Hyundai introduced a second generation fuel cell vehicle. Gen I and Gen II tank system features are compared in Table 6. The Gen II 700-bar hydrogen tank system (Figure 11) expanded vehicle range by more than 25%.

Table 6: Gen I and Gen II tank system comparison.

Item	Gen I, 350 bar	Gen II, 700 bar
Volume	152 L	120 L
Range	300 km (186 miles)	400 km (249 miles)

Figure 11: Gen II 700 bar hydrogen tank system.

In addition to the tank system change, a super-capacitor system was installed to replace the high-voltage battery system. The super-capacitor (Figure 12) increased vehicle performance and improved cold startup capability.

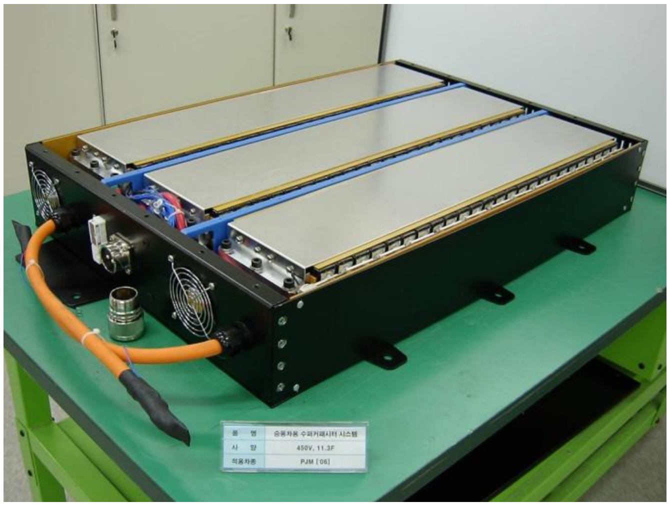


Figure 12: Super-capacitor.

Gen II vehicles also had improved vehicle software logic and controller, an improved BOP component and a new fuel cell stack with second generation function for the 2007 model year. More information on the Gen II stack can be found in Chap. 4, "UTC Power Corporation."

Data Collection System

The data required under the US DOE cooperative agreement included certain performance analysis of vehicles, fuel cell power plants, and infrastructure using state-of-the-art data acquisition technology combined with continuous monitoring and validation. The data were collected quarterly and provided for compilation, analysis, and benchmarking against project objectives as well as for US DOE template reporting.

The data acquisition system for the project (Figure 13) was composed of following parts:

1. Hardware – Data logger: Storage capacity (1 GB, 250 hours), SD card, Bluetooth® Standard 2.0.
2. Software – Data transfer program (vehicle to local server): 20 vehicles per local server.
3. Entire system – Data transfer (Korea ↔ Chino ↔ Fleet), WOL setting at local server.

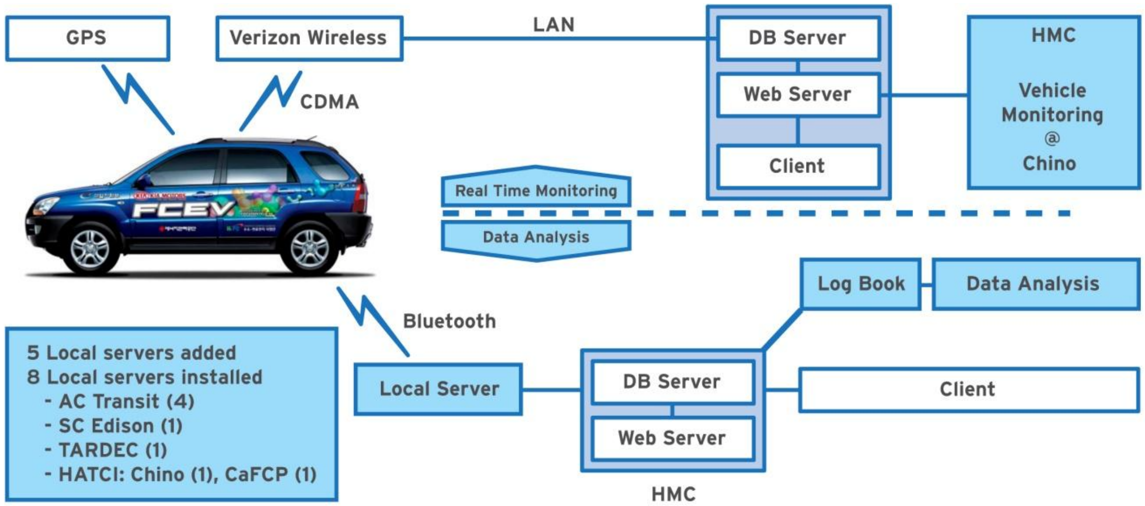


Figure 13: Fleet Vehicle monitoring system.

HMC also maintained site-specific logs, each set including a site manager's log, a scheduled and unscheduled maintenance log, and a hydrogen refueling system log. Data were summarized and reported periodically, either by event or as averages.

Facilities

During the US DOE project, HMC provided facilities such as monitoring rooms and FCV dynamometer cell and maintenance work bays designed to safely test and maintain vehicles.

Monitoring Rooms

Two monitoring rooms, one at HATCI (Figure 14) and one at HMC facilities (Figure 15), were used during the project for real-time vehicle operation status monitoring of speed, range, temperature, fault code, etc. Close monitoring helped ensure operator and vehicle safety.

Figure 14: Monitoring room at HATCI.

Figure 15: Monitoring room at HMC.

H2 Safe Dynamometer Cell & Work Bays

One dynamometer cell and four hydrogen safe work bays were set up across the United States. Fuel economy tests were conducted at this dynamometer cell in Chino, California, by using an H2 weight measuring device and on-board vehicle sensors that measure H2 flow rate, current, pressure, and temperature. H2 safe maintenance work bays (Figure 16) were located near fleet operators in order to address preventive and repair/replacement maintenance needs.

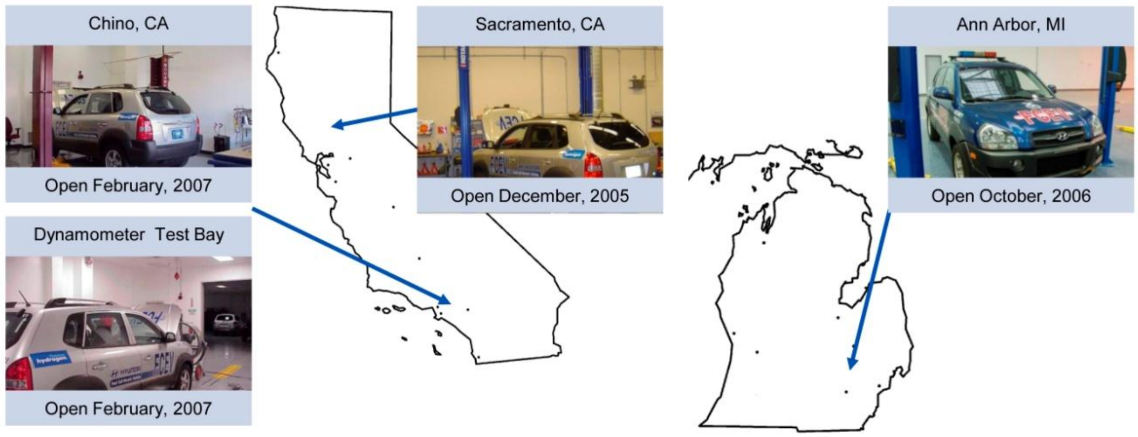


Figure 16: H2 safe maintenance work bays by location.

Vehicle Deployment

In 2005, the first four fuel cell vehicles were deployed, and by 2008, all 33 fuel cell vehicles were successfully deployed to fleet locations. In total, the fleet included 16 Hyundai vehicles and 17 Kia vehicles. Fleets were based at five sites that were in hot, moderate, and cold climates. Gen I vehicles were deployed at the beginning of the project, and then Gen II vehicles were introduced step by step.

Beyond the close of the project, HATCI employees continue to operate several of the vehicles for their daily commute.

Training and Outreach Activity

HMC conducted several training sessions on H2 fueling (Figure 17) and vehicle operation (Figure 18) for fleet operators at various project locations. HMC has also provided an emergency response diagram and operating manual at first responder training and a safety presentation on the Tucson and Sportage fuel cell vehicles to the National Highway Traffic Safety Administration (NHTSA).

Figure 17: H2 fueling training at various project locations.

Figure 18: Fleet operator training and first responder training at various project locations.

Fuel Economy Test

At the Chino H2 safe dynamometer cell, all the data related to fuel economy were gathered using fuel economy test equipment that can measure H2 weight (Figure 19) and provided to NREL based on SAE J2572. Pressure and flow method results were also measured with off-board and on-board vehicle sensors. Pressure method was used to measure fuel economy of on-road vehicles with maintenance operating data of on-board vehicle sensors.

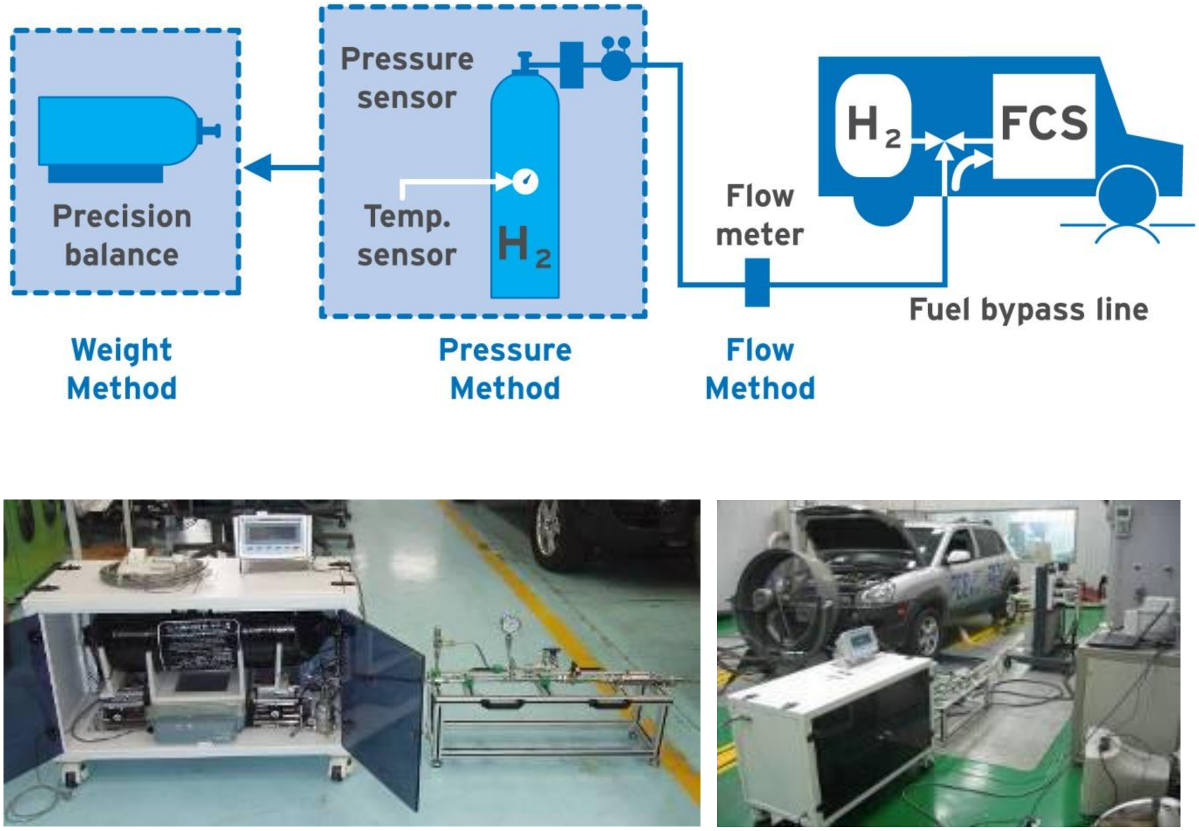


Figure 19: Weight measurement equipment for fuel economy test.

Hot Test

During hot testing (Figure 20) of vehicle cooling modules and other systems in California's Death Valley and Mojave Desert areas, temperatures exceeded 45°C (113°F). HMC improved cooling module performance and verified that power did not degrade. The vehicles had a positive water balance during testing.

To verify performance of a variable speed driver (VSD) module that included controllers for BOP parts, another hot weather test was performed in the Palm Desert, California, area. In this region, a vehicle was tested at various duty cycles without VSD module problems.

Figure 20: Hot weather test at hot locations.

Cold Test

Cold startup tests with UTCP were performed at Selfridge Air National Guard Base in Selfridge, Michigan (Figure 21), and UTCP in Connecticut (Figure 22). More than 20 deep freezing tests with more than 60 hours cold soaking were performed below –10°C (14°F). HMC and UTCP successfully developed cold startup and shutdown processes, and these operating processes were applied to all the fleet vehicles.

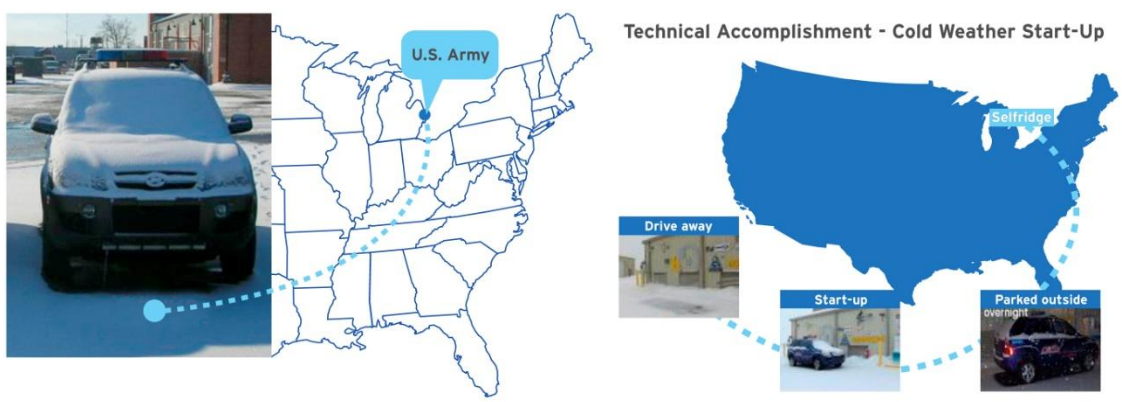


Figure 21: Cold weather test and operation in Selfridge, Michigan.

Figure 22: Cold performance test at UTCP in Connecticut.

Other Tests

Further testing was performed to demonstrate that the fuel cell vehicles would be reliable in various real-world situations. To improve wind resistance, i.e., better drag coefficient, wind tunnel tests were performed (Figure 23) that led to upgrades that improved fuel economy. In addition, EMS (electromagnetic spectrum) tests were performed at Hyundai-Kia Technical Research Center in Korea, and a high-altitude test (at approximately 4300 m, or 14,000 ft) was performed in Colorado for confirming altitude effect on the fuel cell system (Figure 24).

Figure 23: Wind tunnel test at HMC.

Figure 24: EMS test at HMC and high-altitude test in Colorado.

Crashworthiness

HMC performed impact tests through simulations and vehicle tests according to U.S. FMVSS at the Hyundai-Kia research and development center in Korea. In each simulation and vehicle test, no leak of the hydrogen system was detected, which meets FMVSS requirements. Test results (Figure 25) confirm that the fuel cell versions of these models can be as safe as or safer than the mass production ICE versions.

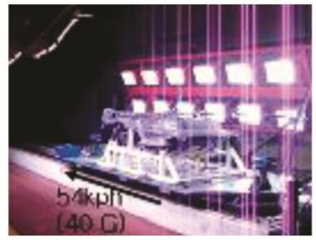
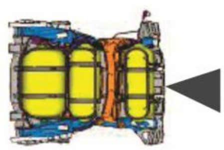
Test Item	Simulation	Vehicle Test	
Sled Impact Test			Before: He gas, 30bar No leak Check the deformation of H_2 storage and delivery system.
Sled Impact Test (FMVSS 305)	 33.5 MPH		Before: He gas, 30bar No leak Check the deformation of H_2 storage and delivery system. Check the H_2 tank burst pressure.
Rear Crash Test (FMVSS 301)	 30 MPH		Before: He gas, 30bar After: He gas, 30bar No leak in the H_2 storage and delivery system.

Figure 25: FCV crashworthiness evaluation in Korea.

Fire tests were performed comparing a fuel cell vehicle and hydrogen storage system (350 bar) with a gasoline vehicle and compressed natural gas (CNG) tank (150 bar). When fire was initiated from the vehicle's ashtray, the pressure relief device (PRD) in the FCV activated after 22 minutes whereas the fuel tank on the gasoline vehicle exploded after 40 minutes. The FCV's PRD activation resulted in a controlled release of hydrogen gas. In fuel tank tests, maximum height of hydrogen flames was shorter than flames from the CNG system under the same PRD activation test conditions. Test results (Figure 26) show that the FCV system can be safer than a conventional system when safety devices work as designed.

	Gasoline Vehicle	FCEV with Type 3 Tank
Test Condition	Fire initiated from the ashtray	
Result	Fuel tank exploded after 40 minutes	PRD activated after 22 minutes
Vehicle		

	CNG Tank (150bar)	Hydrogen Tank (350bar)
Test Condition	Fire source: LPG gas	
Result	PRD activated: CNG vent Max, flame height 11m	PRD activated: H_2 vent Max, flame height 8m
Vehicle		

Figure 26: Fire test.

Learning From an FCV Accident

Over the five-year period of the project, only one fleet vehicle was in an accident. The accident occurred in downtown Oakland, California. An FCV was hit by a gasoline vehicle on the driver's side of the front bumper (Figure 27). The collision activated all safety devices as designed. Specifically, the crash sensor activated the air bag, the emergency shutdown device caused the high-voltage supply to shut off, and the hydrogen supply to shut off. Even though the FCV was totaled, the resulting inspection of the safety devices showed everything successfully functioned.

This accident was the first FCV accident in the world. It demonstrated that the FCV safety system functioned as designed in a real-world accident. Hyundai-Kia provides this example to other hydrogen communities as a case study.

LH front side impact   Air Bag activated   Accident location

Figure 27: Side impact, activated air bag and location of sole FCV accident.

Customer Feedback

Through formal surveys during the demonstration period, fleet operators provided a tremendous amount of feedback regarding the vehicles and the overall program. Current and former drivers as well as fuelers were questioned about fuel cell vehicle and hydrogen station performance. The goal of the survey was to apply the collective feedback to future work.

Survey results revealed a very positive overall experience by the operators, as shown in Figure 28. The survey employed a 1-to-10 scale for which 10 represented the most positive experience.

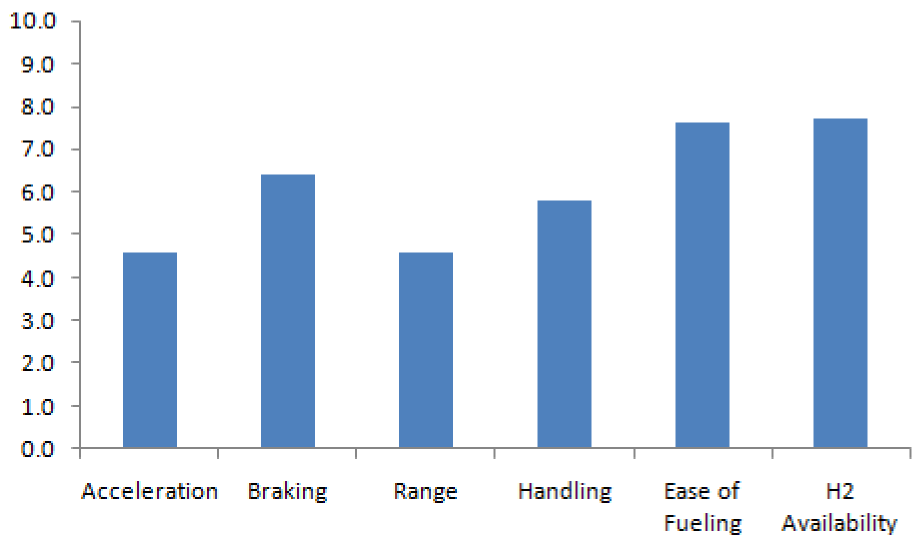


Figure 28: Vehicle and station performance survey results.

All of the drivers surveyed stated they would participate in another fuel cell program. Comments typical of respondent feedback include:

Demonstrations are necessary to get this technology off the ground.

The programs give the OEM opportunity to learn what customers want…I expect driver input will have a positive effect on the next generation FCVs.

I have had many positive experiences with hydrogen cars and stations…

3.5 Hyundai Recommendations

US DOE's first FCV fleet and infrastructure demonstration was well-organized and achieved many of the technical targets and performance improvements it set forth. However, many issues still must be addressed, particularly regarding infrastructure, which is critical to the successful introduction of fuel cell vehicles for real-world operation. Government plays a significant role in this early stage and must invest more to drive the development of a world built for fuel cell vehicles. If the U.S. government initiates a second phase FCV demonstration program, Hyundai-Kia is eager to be involved. If a U.S.-based program does not come to fruition, Hyundai-Kia will continue to operate fuel cell vehicles in California in limited numbers and focus on areas where vehicles can be fueled.

Specifically, Hyundai-Kia recommends that the U.S. government focus on market readiness in the next phase of FCV exploration. Since original equipment manufacturers (OEM), the federal government, and the State of California have agreed that the general Los Angeles area is the first location for fuel cell vehicle introduction, a targeted incentive program for fuel cell vehicle lease or purchase in the next five years is needed. In the early years, a higher buyer incentive/OEM cost share is needed. As market penetration improves, less government involvement is acceptable.

In addition to the market aspects of fuel cell vehicle introductions, funding should continue for hydrogen storage and fuel cell BOP research. Research needs to continue to further reduce cost and weight while improving reliability.

3.6 Conclusions

It is a great honor to be a part of such an important federal government program and to collaborate with two key partners, UTCP and CTV. As part of the team, Hyundai-Kia deployed 33 vehicles to various areas in the United States, which provided real-world lessons for our team and the overall program. Total mileage at end of December 2010 was over 800 000 km (500,000 miles), and some vehicles are still operating. The on-road data were provided on a monthly and quarterly basis. All vehicle data and information were supplied to NREL and US DOE.

Deploying two vehicle generations demonstrated advancement within a short amount of time and showed the speed at which technology is accelerating. Hyundai-Kia developed vehicle technology that exceeds the 2010 targets set forth by Generation II vehicles.

Hyundai put a considerable amount of time and resources into building vehicles that were fun to drive and that provided adequate range and safety. The operator survey proved that, although the vehicles were not perfect, they did provide the operators with a quality experience. All of the operators who completed the survey stated that they would participate in another program. Unfortunately, one of our operators was in an accident, but circumstances demonstrated that the FCV functioned comparably to a conventional vehicle in an accident and the testing performed demonstrated that the redundant safety features provide more than adequate safety – safety that more than equals that of conventional vehicles.

Hyundai-Kia placed considerable resources behind its efforts within the demonstration team. In fact, it built all 33 vehicles and vehicle spare parts without any US DOE cost share. The vehicles provided our operators many hours and miles of usage within each of their operations. Some of the vehicles displaced or idled existing vehicles, thus lowering operating costs.

Overall, Hyundai-Kia's experience in the program was very positive, and we look forward to participating in future U.S. government programs focusing on fuel cell vehicles and related technologies.

4 UTC Power Corporation

4.1 Program Background and Overview

An agreement between Chevron Technology Ventures, Hyundai Motor Company, and UTCP was created to validate hydrogen infrastructure technology and fuel cell hybrid vehicles. UTCP's fuel cells were integrated into Kia and Hyundai vehicle platforms. Two generations of UTCP fuel cell technology were used in the program. The program spanned the time period of April 1, 2004, to June 30, 2009. The operation of the vehicles was extended to December 2009 at the request of US DOE. It should be noted that this report is available to the public under the terms of the contract. Consequently, UTCP is under no obligation to disclose data, results, observations, conclusions, or any other information in this report that is deemed proprietary by UTC Power Corporation.

Figure 29 shows the project's organizational structure.

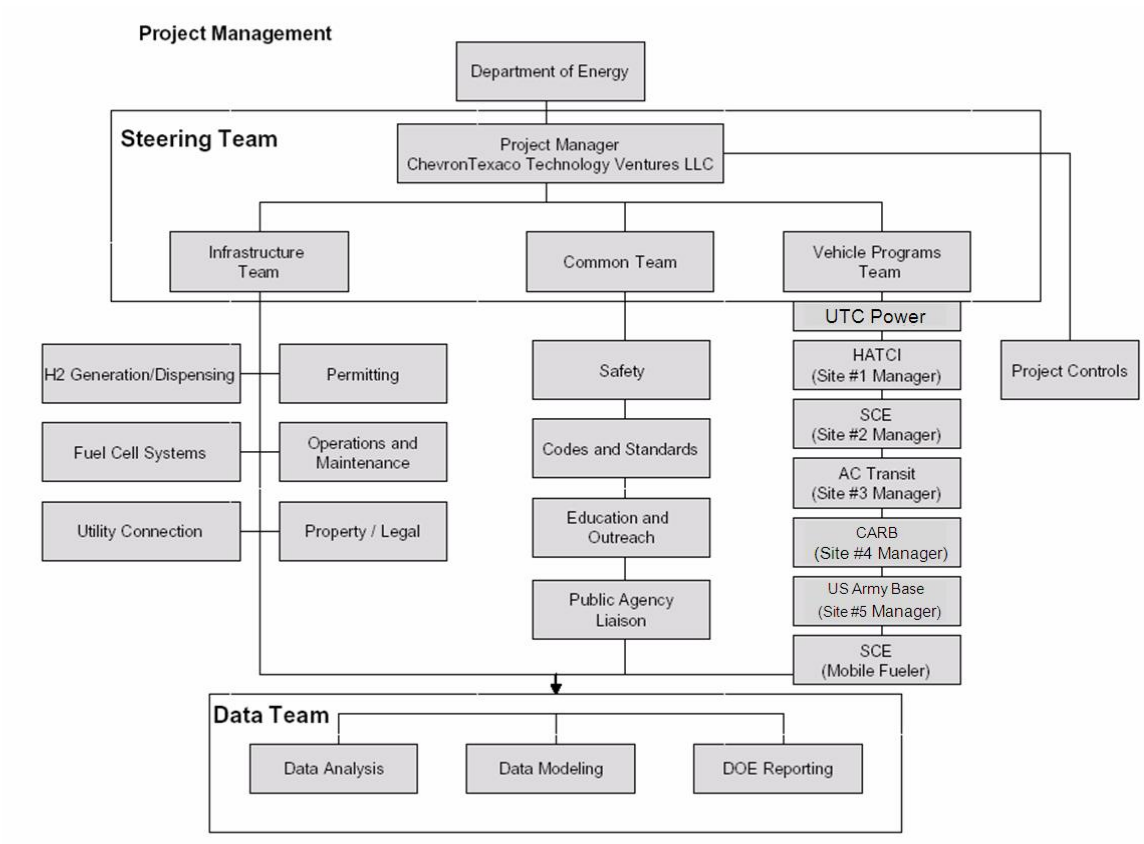


Figure 29: Project organization.

4.2 Fleet Overview

UTCP developed fuel cell power plants for the Hyundai-Kia SUV vehicle platforms. The fleet of 32 FCHEVs was divided into two generations of fuel cell technologies. Seventeen of the vehicles used Generation I technology, and the remaining 15 vehicles used Generation II technology. The difference between Gen I and Gen II fuel cells was primarily that Gen II fuel cells were freeze-capable and used cost reduced components. Southern California Edison (Rosemead, California), AC Transit (Oakland, California), Hyundai America Technical Center (Chino, California), UTCP (South Windsor, Connecticut), and Selfridge Air National Guard Base (Selfridge, Michigan) were the fleet operators. Fleet operators demonstrated commercial operation of the vehicles in three climate zones – hot, moderate, and cold – using various driving patterns and drive cycles.

One additional vehicle remained at UTCP to support technology development and freeze testing as well as troubleshooting issues in the field. The remaining vehicles were owned by HMC and operated by the fleet operators. The vehicle at UTCP was not included in the data analysis because it was not operated on a regular basis as a fleet vehicle. Most of the testing of UTCP's vehicle was done indoors while connected to a loadbank.

Only vehicles with Gen II fuel cells underwent cold-weather testing. UTCP and Selfridge were able to perform freeze testing on five vehicles. UTCP introduced freeze-capable power section systems (PSS) mid-2006 that were first used on FJM #12 and FJM #13 at Selfridge.

UTCP worked closely with HMC and the fleet operators to provide technical support and spare components in the event of failures or necessary upgrades. The PSS and FPS were assembled and tested by UTCP in Connecticut and then sent to Korea for integration into the vehicles. The first 10 vehicles employed a UTCP thermal management system (TMS) using components selected or developed by UTCP. The remaining vehicles used TMS components designed or selected by HMC engineers, but they were based on the UTCP design requirements. UTCP supplied other components such as specialized pumps and fuel cell power plant controllers, but the remaining components were supplied by HMC.

As part of the contract, each partner in the program was required to analyze and provide summary data from the fleet. Vehicle data that included encrypted data from the fuel cell system were sent wirelessly from each car to a local computer at an operator site. The data were downloaded from the site server to an FTP server. From there, HMC would parse the data for content control. UTCP accessed the FTP site to download, decrypt, and store the data on a structured query language (SQL) server. Fuel cell summary data were sent by UTCP to HMC and then to CTV, who forwarded it NREL for further analysis and compilation into detailed and composite data products.

4.3 Fuel Cell Technology and Goals

Primary traction power for all the vehicles was provided by fuel cells that employ UTCP's patented ambient pressure, porous bipolar plate technology. Ambient pressure, porous bipolar plate technology differs from most other fuel cell technologies because the water that is produced in the fuel cell is carried away from the cell via the porosity of the bipolar plates. This approach to water management allows the use of a low-power blower to provide the process air to the fuel cell instead of a compressor. Use of a low-power blower results in higher overall system efficiency. UTCP and HMC worked together to determine the performance and durability targets for the fleet. The primary targets were 2,000 load-hours and 4,000 start/stop cycles while maintaining performance at or above the predicted level. Rated power for the fuel cell power plants is 86 kW (gross) at BOL and 69 kW (gross) at EOL. Maximum open circuit voltage is 450 VDC, and minimum operating voltage is 240 VDC.

4.4 Results

Generation I Fuel Cells

The Gen I fuel cell power plants were developed to demonstrate the feasibility of using fuel cells as primary traction power for automobiles. The focus of the development was on fuel cell stacks and system design. The Gen I stacks and system were not designed to be freeze-capable. The vehicles in which they were installed were deployed to warm- and hot-weather sites primarily in California. The vehicles were operated in a variety of real-world conditions including different drive cycles, locations, and drivers. The performance and durability of the fuel cell stacks varied as a result. Approximately 40 Gen I stacks were manufactured. Variations in the stack component and system component manufacturing and stack assembly were also observed. The low manufacturing quantities were not sufficient to allow the development of repeatable processes and consistent output. This was also a contributing factor in the variation of performance and durability results.

Generation II Fuel Cells

UTCP and HMC recognized the importance of demonstrating that fuel cell stacks and systems could be freeze-capable. Consequently, UTCP continued to pursue stack and system technology development that would enable freeze capability and introduced the Gen II fuel cells as a result. The vehicles using the Gen II technology were primarily deployed at the Selfridge site. The Gen II fuel cells also included other developments that resulted in lower material and labor costs. On the following page, Table 7 shows the evolution of the project's fuel cell technology.

Freeze-Capability Testing

The Gen II PSS enabled vehicles to be started from a fully frozen state. Fuel cells produce water as a product of the reaction within the fuel cell stack. Cold weather conditions cause this water to freeze within the stacks and the BOP components in the system. Freeze startup problems within the TMS were the most difficult to overcome because water that was not drained properly during fuel cell system shutdown would freeze and cause issues during subsequent startups. Components such as pumps and valves were most susceptible to these issues. Ice buildup in hoses occasionally blocked fuel flow and prevented valves from sealing properly, causing prolonged or failed startups. Despite the issues with frozen BOP components, UTCP was able to demonstrate that the stacks provide power from a fully frozen state. Vehicles used in the freeze-capability testing are pictured in Figure 30.

Figure 30: Vehicles used in freeze tests.

Table 7: Fuel cell evolution

			Fuel Cell Generation					
				Gen II				
Vehicle No.	Vehicle Type	Site Operator	Gen I	Freeze-Capable Stack	Hot-Weather Upgrades	BOP Component Performance & Durability	Modeled FC Parts	Low-Cost Water Transport Plates
V1	FJM #1	Chino	X					
V2	FJM #3	CaFCP	X					
V3	FKM #1	Chino	X					
V4	FJM #5	ACT	X					
V5	FJM #6	ACT	X					
V6	FJM #7	Chino	X					
V7	FJM #8	ACT	X					
V8	FKM #3	ACT	X					
V9	FKM #6	ACT	X					
V10	FKM #5	ACT	X					
V11	FKM #7	Chino	X					
V12	FKM #8	ACT	X				X	
V13	FKM #4	CARB	X					
V14	FJM #9	SCE	X		X		X	
V15	FJM #10	SCE		X	X		X	
V16	FJM #11	SCE	X		X		X	
V17	FJM #12	SANG		X			X	X
V18	FJM #13	SANG		X			X	X
V19	FKM #9	SCE		X	X		X	
V20	FKM #10	SCE		X	X	X	X	
V21	FKM #11	ACT		X		X	X	X
V22	FKM #12	ACT		X		X	X	X
V23	FKM #13	ACT		X		X	X	X
V24	FKM #14	SCE		X	X	X	X	X
V25	FKM #15	SANG		X	X	X	X	X
V26	FKM #16	SANG		X		X	X	X
V27	FKM #17	SANG		X		X	X	X
V28	FJM #14	Chino		X		X	X	X
V29	FJM #15	CARB		X		X	X	X
V30	FJM #16	SCE		X		X	X	X
V31	FJM #17	SCE		X	X	X	X	X
V32	FJM #18	SCE		X	X	X	X	X
TOTAL			**15**	**17**	**9**	**13**	**20**	**14**

System Component Reliability

BOP components designed specifically for fuel cell applications did not exist at the time when the fuel cell power plant systems were being developed. The nonrecurring engineering cost to develop FC-specific BOP components that would be used in low quantities was prohibitive. Therefore, off-the-shelf BOP components were selected for use in the fuel cell systems. Consequently, some of the TMS components needed to be replaced more frequently because they were used in a manner that was inconsistent with their original intended applications. One particular pump, which was originally designed to pump air, was partially exposed to water during startup. Exposure to the water caused premature failure of the pump. Additionally, water accumulated within the pump and resulted in complications during freeze startup. A second pump that circulated coolant through the fuel cell stacks also failed frequently because it was not designed for use in a fuel cell system.

Crashworthiness

FJM #8 was involved in a traffic accident in Oakland, California, on July 13, 2007, while it was being operated by personnel from the AC Transit site. The car was moving at approximately 31 km/h through an intersection and was struck by another vehicle in the left front quarter (Figure 31 and Figure 32). The fuel cell system TMS and accumulator were damaged beyond repair. After checkout and testing by both HMC and UTCP, it was determined that the PSS was not damaged and was suitable for further use. The PSS was transferred into FKM #04 and continued to operate in the new vehicle. While this is only one incident, it provides some evidence that a fuel cell in a vehicle can survive the impact of a traffic accident without loss of hydrogen containment.

Figure 31: View 1, FJM #8 accident damages.

Figure 32: View 2, FJM #8 accident damages.

Vehicle Testing

The vehicle owned and operated by UTCP (Figure 33) underwent test scenarios that were not directly incorporated into the US DOE fleet test plan. However, results from this testing were invaluable for troubleshooting and improving system performance and vehicle operability. High-altitude and cold-weather tests were performed on the UTCP vehicle. High-altitude tests were performed in Denver, Colorado, at 1600 m and 3960 m (5,200 ft and 13,000 ft) and revealed that the vehicle could perform well at high altitudes, but maximum power was slightly reduced.

Figure 33: UTCP vehicle and team at high-altitude point, Pikes Peak, Colorado.

Freeze testing was performed in the winters of 2004 and 2005 at the vehicle level. This testing was mainly done in South Windsor, Connecticut, using a freeze chamber. The focus of the testing was different for each year but with the same goal of independent startup and operation in freezing conditions.

In 2004, the main focus of freeze testing was to demonstrate that the Gen II power plant was capable of starting without external assistance. Initially, the testing started with only short freeze cycles of about five hours to confirm water in the TMS devices prone to freezing did not pose any concerns. After several successful short freeze cycles, the testing was conducted on a completely frozen power plant. Over a one-month period, the vehicle was completely frozen seven times with six instances yielding successful starts. The most substantial test of the season consisted of storing the vehicle in the environmental chamber for 330 hours at –10°C (14°F) and then starting and driving the vehicle without any issues. In 2005, the focus shifted to proving out the new components that were developed for system simplification and the new controls that were implemented based on the high altitude. At the end of winter, the vehicle logged an additional 30 to 40 partial freezes and another 20 complete freezes.

The hot weather testing of the FJM #1 vehicle was conducted in Death Valley, California. The ambient temperature ranged from 30°C to 45°C (86°F to 113°F), and the altitude ranged from 1.5 m to 1511 m (5 ft to 4,956 ft). FJM #1 was used because it was already located in California. The vehicle performed satisfactorily, having only a few problems with the TMS during startup which were subsequently resolved.

The testing under high altitude, hot weather, and cold weather demonstrated that a fuel cell vehicle can operate in extreme real-world conditions.

4.5 Lessons Learned

- Key BOP components that require development specifically for use in freeze-capable fuel cell systems must be identified. Suppliers are unwilling to invest in the development of these components because they may not realize a return on the investment due to low production volumes of fuel cell vehicles.
- Cost reduction initiatives for fuel cell components should be executed as early in the program as possible in order to derive the most benefit.
- There needs to be a better understanding of the causes for differences between the test results of fuel cells in the lab and the results from operating in the field.

4.6 UTCP Recommendations

- US DOE and other government agencies should consider supporting the development of BOP components that could be commonly used among several fuel cell power plant manufacturers. Those involved should look at components used in internal combustion engine vehicles today and ask auto OEMs and fuel cell companies for recommendations on which components should be targeted.
- US DOE and other government agencies should re-examine the established guidelines and standards for hydrogen safety in autos. The current guidelines and standards result in increased cost and reduced reliability because they require systems to be more complex,

have more components, and require more expensive materials than may be necessary to ensure auto fuel cell systems are safe.

- US DOE and other government agencies should consider funding a program that investigates the differences between lab results and field results in fuel cell durability and identifies technologies to close the gaps.

4.7 Conclusions

The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Program has been an invaluable source of data for the development of fuel cells for automotive applications. There had not been a program previously that tested fuel cell vehicles in real-world, on-road conditions. The program has shown that fuel cell vehicles are technically feasible. However, more work needs to be done in the area of fuel cell durability and cost.

5 Acronym List

Acronym	Term
A	
ACT	Alameda Contra Costa Transit
ASME	American Society of Mechanical Engineers
ASMR	advanced steam methane reformer
B	
BOL	beginning of life
BOP	balance of plant
C	
CDP	composite data products
CNG	compressed natural gas
CSD	compression, storage and dispensing
CTV	Chevron Technology Ventures
D	
DEP	Department of Environmental Protection
DI	deionization
DMS	dimethyl sulfide
E	
EAP	emergency action plan
EMS	electromagnetic spectrum
EOL	end of life
ER	emergency responder
F	
FACP	fire alarm control panel
FC	fuel cell
FCHEV	fuel cell hybrid electric vehicle
FCV	Hyundai-Kia's fuel cell hybrid vehicle
FMVSS	(U.S.) Federal Motor Vehicle Safety Standards
G	
GUI	graphical user interface
H	
H2	hydrogen
HATCI	Hyundai America Technical Center Inc.
HMC	Hyundai Motor Company
HMI	human machine Interface
HYUNDAI-KIA	Hyundai Motor Company and Kia Motors

Acronym	Term
I	
ICE	internal combustion engine
M	
MES	methyl ethyl sulfide
N	
NHTSA	(U.S.) National Highway Traffic Safety Administration
NREL	National Renewable Energy Laboratory
O	
OEM	original equipment manufacturer
P	
PHG	purified hydrogen generator
PLC	programmable logic controllers
PRD	pressure relief device
PSA	pressure swing adsorber or pressure swing adsorption
PSS	power section system
R	
RO	reverse osmosis
S	
SAE	Society of Automotive Engineers
SCADA	supervisory control and data acquisition
SCE	Southern California Edison
SMR	steam methane reformer
SQL	structured query language
SUV	sport utility vehicle
T	
TARDEC	(U.S. Army) Tank Automotive Research, Development and Engineering Center
TDS	total dissolved solids
THT	tetrahydrothiophene
TMS	thermal management system
U	
US DOE	U.S. Department of Energy
UTCP	UTC Power Corporation
V	
VDC	volts direct current
VSD	variable speed driver