Ford Motor Company

U.S. Department of Energy

Controlled Hydrogen Fleet and Infrastructure Demonstration Project

Cooperative Agreement No. DE-FC36-04-GO14287

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Ford Motor Company
Final Technical Report

Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project

Cooperative Agreement DE-FC36-04GO14287
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Project Director: Dr. Scott Staley, Ford Motor Co.

Team Members:
- **BP America**
- **SMUD**
- **NextEnergy**
- **Icelandic New Energy**
- **Ballard**
- **Progress Energy**
- **States of California & Florida**
- **Cities of Ann Arbor & Taylor, MI**

This program was undertaken in response to the US Department of Energy Solicitation DE-PS30-03GO93010, resulting in this Cooperative Agreement with the Ford Motor Company and BP to demonstrate and evaluate hydrogen fuel cell vehicles and required fuelling infrastructure. Ford initially placed 18 hydrogen fuel cell vehicles (FCV) in three geographic regions of the US (Sacramento, CA; Orlando, FL; and southeast Michigan). Subsequently, 8 advanced technology vehicles were developed and evaluated by the Ford engineering team in Michigan. BP is Ford's principal partner and co-applicant on this project and provided the hydrogen infrastructure to support the fuel cell vehicles. BP ultimately provided three new fueling stations. The Ford-BP program consists of two overlapping phases.

The deliverables of this project, combined with those of other industry consortia, are to be used to provide critical input to hydrogen economy commercialisation decisions by 2015.

Program Goal

To support industry efforts of the US President's Hydrogen Fuel Initiative in developing a path to a hydrogen economy. This program was designed to seek complete systems solutions to address hydrogen infrastructure and vehicle development, and possible synergies between hydrogen fuel electricity generation and transportation applications.

Principal Program Objectives

Ford Motor Company objectives are:

- Gain vehicle operational data in differing climate conditions, to direct and augment future design efforts
- Provide input to the industry-government efforts to define a future hydrogen economy

BP America objectives are:

- Establish an initial hydrogen infrastructure network to fuel small fleets of fuel cell vehicles across a metropolitan area
- Develop retail compatible hydrogen refueling systems
- Evaluate emerging hydrogen technologies that have the ability to meet DOE cost and performance targets
- Explore cost and commercial feasibility of renewable-based hydrogen generation

Executive Summary

On Jan 29, 2003 President Bush spoke to the promise of hydrogen in his State of the Union Address: “Tonight I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles. A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car, producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy.”

This project, in support of that national goal, was designed to gain real world experience with Hydrogen powered Fuel Cell Vehicles (H2FCV) "on the road" used in everyday activities, and further, to begin the development of the required supporting H2 infrastructure.

Implementation of a new hydrogen vehicle technology is, as expected, complex because of the need for parallel introduction of a viable, available fuel delivery system and sufficient numbers of vehicles to buy fuel to justify expansion of the fueling infrastructure. Viability of the fuel structure means widespread, affordable hydrogen which can return a reasonable profit to the fuel provider, while viability of the vehicle requires an expected level of cost, comfort, safety and operation, especially driving range, that consumers require. This presents a classic "chicken and egg" problem, which Ford believes can be solved with thoughtful implementation plans.

The eighteen Ford Focus FCV vehicles that were operated for this demonstration project provided the desired real world experience. Some things worked better than expected. Most notable was the robustness and life of the fuel cell. This is thought to be the result of the full hybrid configuration of the drive system where the battery helps to overcome the performance reduction associated with time related fuel cell degradation. In addition, customer satisfaction surveys indicated that people like the cars and the concept and operated them with little hesitation. Although the demonstrated range of the cars was near 200 miles, operators felt constrained because of the lack of a number of conveniently located fueling stations. Overcoming this major concern requires overcoming a key roadblock, fuel storage, in a manner that permits sufficient quantity of fuel without sacrificing passenger or cargo capability.

Fueling infrastructure, on the other hand, has been problematic. Only three of a planned seven stations were opened. The difficulty in obtaining public approval and local government support for hydrogen fuel, based largely on the fear of hydrogen that grew from past disasters and atomic weaponry, has inhibited progress and presents a major roadblock to implementation. In addition the cost of hydrogen production, in any of the methodologies used in this program, does not show a rapid reduction to commercially viable rates. On the positive side of this issue was the demonstrated safety of the fueling station, equipment and process. In the Ford program, there were no reported safety incidents.

The important learning from this program includes:

Vehicle Results and Lessons Learned

A key contribution of this program includes the documentation of both successes and failures. The successes show validity of design concepts and strategies taken, and failures build a platform of knowledge to enable acceleration of progress in future work. In this sense both are valuable outputs from this cooperative agreement.

The vehicle physical architecture and accompanying software control architecture were a key success. Most operational issues encountered in the field trials were addressed by software calibration changes. In addition the hybrid powertrain configuration, which was initially driven by freeze-start energy and power requirements, proved to have benefits to vehicle performance, robustness and lifetime.

Vehicle performance over the project period and user acceptance of the vehicle was a success point. Several driver surveys were taken and the results reported out at the yearly DOE program review meetings in Washington DC. Driver's main concerns were with driving range and usable trunk space. These items were related in that both were governed by the storage tank for hydrogen fuel which was sized to provide 200 miles range, but intruded into the trunk space. Hydrogen fuel storage technology and cost were shown to be significant areas of concern in this program. A concept called "designed around hydrogen" was demonstrated in several concept vehicles developed as part of this program and showed a path to packaging over 350 miles range in a Ford Explorer class vehicle, however the issues of cost of the hydrogen fuel system are still open.

This program demonstrated the significant overlap of technologies that can be shared by electrified vehicles in general. The regenerative braking system used on the Ford Focus fuel cell vehicle was taken directly from the Ford production Hybrid Escape. In addition the battery system of the Focus also heavily borrowed from the Hybrid Escape. As hybrid vehicles capture a larger volume of the market the cost of some of these shared components will benefit battery electric and fuel cell electric vehicle designs.

Developing a FMVSS certified production vehicle requires a significant resource investment. In some ways this can slow technology development progress as designs must be "frozen" so the large testing effort required to ready the vehicle for public use can accomplished. On the other hand gaining the experience of taking such advanced technology vehicles all the way to a product implementation provides valuable feedback as this program has shown. Nevertheless, until some of the remaining key questions around cost of the technology and availability of the fueling infrastructure are settled increasing the volumes of demonstration vehicles is not required. The vehicle fleet of this program has produced significant volumes of data that have been analyzed to provide future research direction. Increasing the size of the fleet further would increase costs, while not significantly increasing the knowledge obtainable. Until some of the key technical questions that this work has raised are adequately addressed research and development emphasis is better placed in systems level improvements and concept vehicle demonstration rather than production vehicle development.

Hydrogen Fuel Storage Results and Lessons Learned

Compressed hydrogen storage is a technology that is available today and worked safely and robustly in our field trials. In this program both 350 bar and 700 bar fuel systems have been successfully demonstrated on the road. Packaging of the hydrogen fuel system in existing vehicle architectures is a significant challenge for both space and weight reasons. It is possible to “design around hydrogen” to get the range that customers expect based on their gasoline vehicle experience, but this requires an all-new vehicle physical architecture which is very costly for the low-volume vehicles. In addition the cost of the fuel system is prohibitive with current materials (carbon fiber), and no clear path to affordability has been shown.

Hydrogen Fuel Infrastructure Results and Lessons Learned

The process of installing hydrogen fueling stations is complex, costly and takes a long time. The process is governed by local codes and standards (not a uniform national code) and in each location the process can be different. Standards are evolving and sometimes add new unanticipated costs into the project in mid-stream (e.g., NFPA 52). Even where municipalities are supportive the process is onerous and slow. Installed equipment costs contribute about 35% to the total station cost and have increase by a factor of 3 since 2003. Construction costs contribute another 60% to total station cost. It is difficult to justify building multi-million dollar fueling stations give the current situation of low vehicle volumes. On the other hand, new stations that have been built as part of this project showed the way to diverse hydrogen on-site generation methods that provided valuable data to the DOE which can be used for cost analysis and government strategic planning for hydrogen infrastructure. Finally, this project maintained a perfect safety recorded in the design, installation, commissioning and operation of the hydrogen fueling stations.

Final Comments

This report closes out the project that started in September of 2003 with Ford’s response to the DOE solicitation DE-PS36-03GO93010. Since that time Ford has logged more than 1.3 million miles of fuel cell vehicle operation with its production Ford Focus fuel cell vehicle, participated in the development of the next generation of fuel cell system and demonstrated this system in vehicle operation in a Ford Explorer. We have operated next generation 700 bar hydrogen storage system technology in vehicle (Ford Focus and Explorer) and have delivered over 270 gigabytes of program data to the DOE for analysis and development of composite data products (CDPs) at NREL. Elements of over 1.4 terabytes of data were also shared with NREL for special assessments. Ford was the first OEM to run a fuel-cell-powered land speed racer at the Bonneville Salt Flats. This 400 kW Ford Fusion set the bar at 207 mph for a fuel cell vehicle. This project, in various ways, supported all these accomplishments. Much more was accomplished working together with the DOE than would have been accomplished by Ford working alone. Therefore, we thank you for this opportunity and we would certainly look forward to future collaboration opportunities.

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Glossary of Abbreviations

ACU	Actuation Control Unit (Brakes)
AM	Air Module
APCI	Air Products & Chemical Inc.
APU	Auxiliary Power Unit
ASTM	American Society for Testing & Materials
Bar	Unit of pressure; approx. 14.5 psi
BCM	Battery Control Module
BOC	Linde-BOC, a supplier of hydrogen gas
BOM	Bill of Material
BOP	Balance of Plant
BSCM	Brake System Control Module
CaFCP	California Fuel Cell Partnership
CAN	Controller Area Network
CC	Critical Characteristic
CdA	Coefficient of Drag* Frontal Area
CSC	Climate System Controller
CVJ	Constant Velocity Joint
CVM	Cell Voltage Monitor
DAE	Data Acquisition Equipment
DC/DC	Direct Current Conversion
DFMEA	Design Failure Mode and Effects Analysis
DI	De-ionized (water)
DIWEG	De-ionized Water and Ethylene Glycol mixture
DOE	(US) Department of Energy
DP	Dew Point
DPG	Dearborn Proving Grounds
DTC	Diagnostic Trouble Code
DVP&R	Design Verification Plan and Report
DYNO	Dynamometer
EATC	Pg 145 bullets
EHB	Electro Hydraulic Brake
EHPAS	Electro Hydraulic Power Assisted Steering
EMM	Energy Management Module
EOL	End of Life
EOL	End of Line
EPO	Emergency Power Off
ER	Emergency Responders
EVFA	Electric Vehicle Final

	Assembly
FC	Fuel Cell
FCS	Fuel Cell System
FCU	Fuel Cell Control Unit
FCM/PDU	Fuel Cell Module Power Distribution Unit
FMEA	Failure Mode and Effects Analysis
FMVSS	Federal Motor Vehicle Safety Standards
FUDS	Federal Urban Driving Schedule
GH2	Gaseous hydrogen
H2	Hydrogen
H2FCV	Hydrogen Fuel Cell Vehicle
HAZID	Hazard Identification
HAZOP	Hazard and Operability
HCU	Hydraulic Control Unit
HIC	Hydrogen Interface Controller
HSE	Health, Safety and Environment
HT	High Temperature
HV	High Voltage
HVB	High Voltage Battery
HVEC	High Voltage Energy Converter
HwFET	Highway Fuel Economy Test Schedule
ICE	Internal Combustion Engine
ICM	Instrument Cluster Module
IPT	Integrated Power Train
LT	Low Temperature
LV	Low Voltage
MPG	Michigan Proving Grounds (Ford)
NFPA	National Fire Protection Assoc
NiMH	Nickel Metal Hydride
NREL	National Renewable Energy Laboratory
NVH	Noise Vibration and Harshness
P	Pressure
P/S	Power Steering
PDA	Personal Data Assistant
PDU	Power Distribution Unit

PEM	Proton Exchange Membrane
pHSSEr	Project Health Safety Security & Environment Requirements
PiHB	Plug-in Hybrid Battery
PSI	Pounds per squire inch
RGC	Reactant Gas Conditioner
RH	Relative Humidity
R-Mode	Reconditioning Mode
SAE	Society of Automotive Engineers
SC	Significant Characteristic
SCU	Solenoid Control Unit
SIMU	Systems Interface Module
SLI	Starting, Lighting and Instrumentation
SM	Systems Module
SMTL	Sustainable Mobility Transportation Labs
SOC	State of Charge
SS	Sustained Speed
STM	Stack Module
SUV	Sport Utility Vehicle
T	Temperature
TDV	Technology Demonstration Vehicle
TROS	Technician Repair Order System
TSB	Technical Service Bulletin
TSC	Thermal System Controller
VNG	Vehicle Network Gateway
VSC	Vehicle Systems Controller
VSC	Vehicle Systems Controller
WDS	World-wide Diagnostic System
WEG	Water Ethylene Glycol

Planning & Preparation

High Level Objectives

This project was undertaken as a part of Technology Verification (Section 3.6) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan. Technology validation objectives were to test, demonstrate and validate components and complete systems in real-world environments and provide feedback to the hydrogen and fuel cell R&D programs as appropriate. Learning demonstrations conducted in the Technology Validation program element emphasize integration of hydrogen infrastructure with hydrogen fuel cell-powered vehicles to permit industry and the DOE program to assess progress toward technology readiness.

The following technical barriers identified in section 3.6.4 of the Technology Validation program were addressed in this project:

- Lack of Fuel Cell Vehicle Performance and Durability Data
- Hydrogen Storage
- Lack of Hydrogen Refueling Infrastructure Performance and Availability Data
- Maintenance and Training Facilities
- Codes and Standards

At the outset of the demonstration, the following high-level, vehicle related objectives were defined from the identified barriers:

1. **Fleet Test phase (Phase I):**
    - Deploy eighteen cars in three geographic locations beginning in the first quarter of 2005 (Figure P1)
    - Target 1500 hours of operation per vehicle over a three year drive period
    - Build three hydrogen vehicle maintenance facilities
    - Work with industry groups for the formulation of beneficial codes and standards

2. **Technology Demonstration (Phase II):**
    - Demonstrate improved fuel cell durability, greater operating range and cold start capabilities.

The following high-level infrastructure objectives were defined from the identified barriers:

1. **BP to install a network of seven refueling stations**
    - Sacramento, Southeast Michigan and Orlando to demonstrate various hydrogen infrastructure technologies.
    - Install several hydrogen stations at BP retail sites with additional refueling stations at maintenance facilities and customer locations.
    - To meet the delivery timing of the first vehicles, stations will be implemented in phases with the initial phase incorporating dispenser, compressor and storage either by tube trailers or multi-cylinder packs

2. **Implementation of second phase upgrades** to include hydrogen generation equipment (considered permanent stations).
3. **700 bar (10,000 psi) dispensing for Generation II vehicles**; additional equipment upgrades to be added to the MI stations to accommodate.

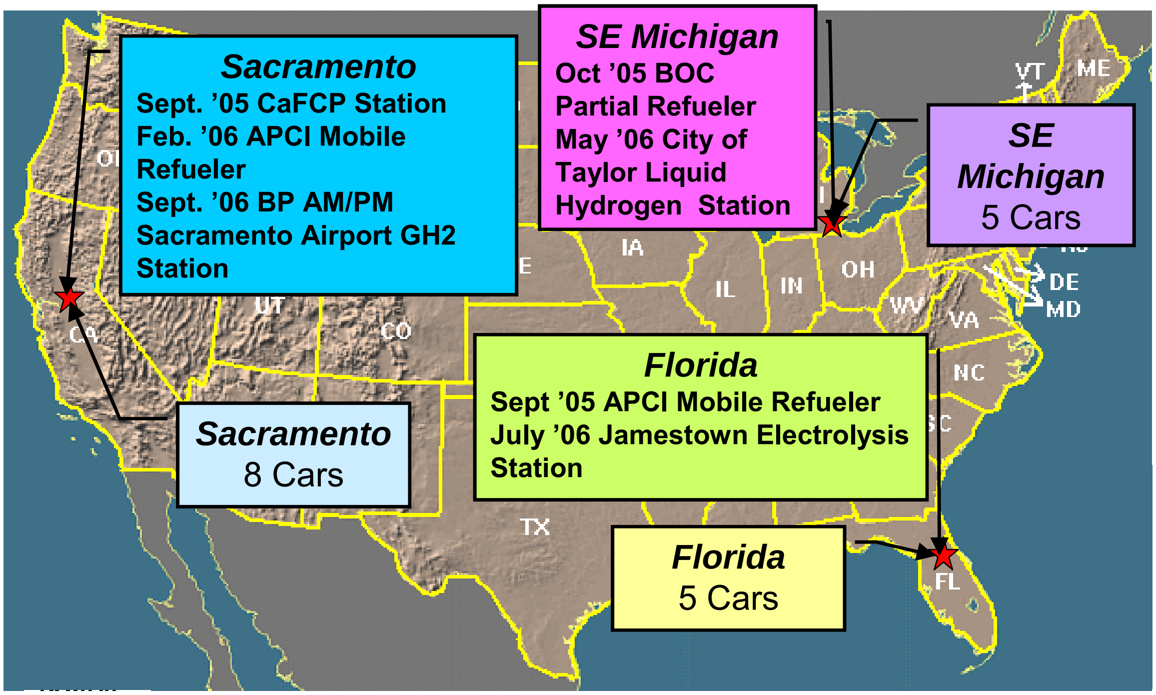


Figure P1 Planned Fleet & Station Deployments

Variances from the Original Plan

The program was completed largely as planned at the outset. However there were some changes that happened as a result of efforts to optimize program outputs and to take advantage of emerging technologies that became known during the demonstration. The following are the key changes:

Vehicle Deployments:

Originally planned for the first quarter of 2005, deliveries were delayed until August 2005 and all 18 cars were in service by mid October. This late start was driven by Ford's demands that all identified systems issues related to customer satisfaction with the cars had been addressed. A principle issue in this regard related to the controls software. Updates were made to enhance the interaction between the fuel cell and the high voltage battery to provide smooth driving characteristics and improved charging in the electrical system.

In late 2007, Ford was asked by Icelandic New Energy Ltd of Reykjavik, Iceland if it would be feasible to deploy a vehicle in Iceland to enhance that country's effort to learn about and move to a hydrogen energy based economy. A study of the DOE fleet vehicle use identified one vehicle that had fallen significantly below the targeted miles and hours for the demonstration, and it was judged that there might be more value to the DOE effort, as well as benefits of international cooperation, if the underutilized FCV could be redeployed to Iceland.

A formal proposal was made to the DOE outlining the expected benefits of a vehicle reassignment that highlighted:

- Continued supply of meaningful data
- Operation in a completely different environment (grades, humidity and temperatures)
- Faster accumulation of miles/hours of operation in a more operationally aggressive placement
- International cooperation in the assessment of hydrogen as an energy source
- Goodwill demonstration for and with the people of Iceland.

With DOE approval, one of the vehicles (P22) was sent to Iceland in March of 2008. The vehicle continues to operate there and operational data is collected and reported as a part of the regular data submissions to the DOE. A copy of the proposal letter outlining the benefits for this relocation has been included in Appendix 1 of this report.

Fuel Station Deployment:

The original plan called for installation of seven fueling stations with upgrades (to 700 bar) at the Southeast Michigan sites. As a result of problems in both cost and extended time for approvals in the early stages of the project (i.e. the “permanent” 350 bar stations), BP scaled this plan back and ultimately built three “permanent” stations to support the Ford project.

The plans for 700 bar fueling that were part of the BP second phase upgrade were not implemented. This was largely due to the extended time and effort that had been required just to open the 350 bar permanent stations that had been planned.

In addition, BP determined not to continue operation of the stations and scheduled all three for decommissioning at the end of the vehicle demonstration.

BP Program Objectives Restated:

In recognition of the challenges above, BP restated their program objectives in 2007 and again in 2008 to the following:

- Establish an initial retail compatible hydrogen infrastructure to fuel a small fleet of fuel cell vehicles
- Evaluate emerging hydrogen technologies that have the ability to meet DOE cost and performance targets
- Explore cost and commercial feasibility of renewable-based hydrogen generation

Vehicle Upgrades to 700 Bar (10,000 psi):

Originally Phase I of the demonstration assumed that customers would use the fleet vehicles for 36 months. At the end of the first 24 months, four of the SE Michigan vehicles were to be updated to utilize 700 bar hydrogen storage systems and returned to the customers for an additional 15 months. Ford subsequently revised the number of vehicles from 4 to 1. Initially the plan was to evaluate two different 700 bar system suppliers and use the learning from this sub-task to apply to later Technology Demonstration Vehicle units. However, the value of upgrading four vehicles was reduced because fueling station upgrades to 700 bar were not complete, and an alternative system supplier was being developed for future TDV use. Sufficient knowledge was obtained from one vehicle with a significant reduction in required spending.

Data Acquisition Equipment (DAE):

DAE was originally planned to be installed in one vehicle within each geographic region. As the program developed, it became clear that the collection of vehicle data could be done effectively using the vehicle network gateway (VNG) with weekly downloads to fleet computers which were networked to a larger data base operated by a Ford sub-contractor. This methodology saved the cost of computers for the vehicles and improved the frequency of data collection.

In an attempt to improve the access of data from the vehicles to the service personnel in Ford's Engineering Center, PDA's were installed in many of the fleet vehicles. In this form, operators could connect the vehicle VNG data system through cellular telephone links, with computers in Dearborn. However, these installations ultimately proved to be inefficient in providing useful diagnostic data. In nearly all cases it was necessary to contact the local service center to obtain more data that was not available from the VNG. Although attempts to improve the collection of data were made, the ability to continue this capability became economically unfeasible when telephone service providers changed their communications protocol. With that change, it was determined that all PDAs would be removed.

Technology Demonstration Vehicles:

At the outset, the DOE desired to have at least two generations of fuel cell systems in vehicles. In the original solicitation, they wrote: "The 5-year Validation project will monitor the operation and performance of hydrogen-powered vehicles spanning two technology development generations. It is anticipated that vehicle improvements and parallel R&D during the 5-year schedule will result in lower costs to produce hydrogen-powered vehicles, increased fuel cell durability, and improved vehicle performance and efficiency." The TDV effort was revised several times to accommodate emerging technology and concepts as originally envisioned by the DOE. The original commitments were to demonstrate vehicle concepts that showed progress in three areas:

- Develop and build Robustness Demonstrator (one)
- Develop and build Design Around Hydrogen Demonstrators (five)

- Develop and build Freeze Start Demonstrator (two)

The number of vehicles in Phase II was changed as several plan alternatives were pursued. The alternatives included a novel Auxiliary Power Unit drive train, a “Critically Efficient Vehicle Design” and additional “designed around hydrogen” vehicles to demonstrate FMVSS compliance for commercial use. Ultimately, the total number of vehicles was reduced to six. Details of the TDV concepts are presented later in this report.

Update Safety sections of the 1997 Study Title Direct Hydrogen Fueled Proton *Exchange Membrane Fuel Cell System for Transportation Applications*.

The safety sections of the referenced report are part of report DOE/CE/50389-502 and are contained in sections 5.0 through 9.0 as follows:

5.0 General Hydrogen System Safety Design Issues
6.0 Vehicle Safety Hazards and Failure Modes
7.0 Failure Mode Risk Assessment
8.0 Hydrogen Failure Mode Countermeasures
9.0 Dispensing Station-Specific Safety Design Issues

The report was an extensive examination of hydrogen issues specific to vehicles, and contained observations, anecdotes and examples in addition to data. There was no effort at that time to provide quantitative measures of severity, frequency of occurrence or detectability in the safety analysis.

It was determined during the evaluation of the report, that the information covered a broad range of hydrogen safety issues, most of which had not changed since the initial report (e.g. inside storage of hydrogen vehicles, consumer fear of hydrogen) and was in a structure that did not permit meaningful updates. It was judged that a thorough FMEA for both the vehicle and the infrastructure would constitute a far more meaningful update of the key concerns identified in the original report. For this reason, this task was eliminated in the 2006 revision of the work plan for this project.

Program Extension

The original plan defined the fleet operational period to be 36 months per car. Based on the value of data that is being collected and the learning from high hour fuel cell stack data, Ford, BP and the DOE agreed, in October 2007, to continue field operations through the end December 2009. This permitted significantly more miles to be accumulated by the fleet, and provided more high-hour performance and maintenance data to help understand the lifetime performance attributes of the fuel cell power plant. In addition, it provided for further TDV development with latest generation components.

Program Management

The Ford Motor Company plan for the Hydrogen Fuel Cell Vehicle & Infrastructure Demonstration Program detailed work and expectations for both building and operating vehicles as well as the initial fueling station implementations by the fueling partner, BP America. The overall effort was detailed in the program Statement of Work and the Statement of Objectives.

The Department of Energy required the preparation of a number of planning documents that were used to guide the safe and effective execution of the demonstration. These plans for the vehicle operation portion of the demonstration, submitted to the DOE on March 7, 2005 are briefly described as follows with more detailed information in later portions of this section of the report:

Project Management Plan: This presented a Gantt chart detailing the planned tasks, task durations and timing for the five major tasks of the project. These tasks were:

1. Planning, Schedule, Build & Delivery of 18 vehicles
2. Data Collection & Analysis
3. Phase I Fleet Operations
4. Phase II Technology Demonstrator Operation
5. Fueling Infrastructure

For reporting purposes, a sixth task was defined as Project Management to identify the details of how the program activities and costs would be monitored and reported. Each of the six tasks was budgeted to develop the overall financial plan for the demonstration.

Vehicle Safety Plan: Actions taken by Ford Motor Co to identify, design and install requisite safety attributes and features were detailed in this plan. The document described in an overview format, the process that Ford has developed to build safe vehicles and to certify compliance with Department of Motor Vehicle Safety requirements. Special attention to the newly applied hydrogen fuel technology was also documented.

Risk Mitigation Plan: Planned and implemented actions to minimize hazards or risks in the execution of the Hydrogen Fuel Cell Vehicle Demonstration project were identified, and risk mitigation actions were detailed that were based on the results of safety strategies that were initiated in the early development of the vehicles, the sub systems, and the program.

Delivery Plan: This document identified the planned customer/users of the vehicles and provided details of the intended preparation of the personnel, buildings and special tools to begin vehicle operation in real world applications.

Facilities Plan: The maintenance and repair of the 18 vehicles required building or modifying facilities in each of the three geographic areas where the cars were to be operated. This plan document described the necessary activities to ensure that each location was properly manned and equipped, and had the necessary hydrogen safety devices in place to support on-going operations.

Training Plan: Preparation of all personnel involved in the fleet operations of the vehicles was detailed in this plan. This included detailed instruction for Fleet Managers, Vehicle Operators, Emergency Responders and Vehicle Technicians. Content of the training plans is presented in subsequent sections of this report.

Data Reporting Plan: The DOE defined specific data reporting objectives. This plan provided detail of how the desired data would be collected within the vehicle architecture and retrieved for reporting and analysis.

Communications Plan: This is a detailed plan document that prescribes the steps to be taken in the event of a safety or potential safety related event. It provided detailed decision and communications steps in flow-chart formats to guide both vehicle operators, fleet managers and Ford personnel in effective communications. It listed all involved program personnel and their contact information to ensure complete communication of any important information related to the operation of the fleet, and transfer of learning between fleet locations. (Note: this plan was submitted on March 31, 2005)

BP prepared similar plans for the infrastructure portion of the demonstration and these were submitted on June 8, 2005.

Program Safety

Ford Motor Company is committed to the safety of all people associated with the operation of any Ford products, and further to the safe conduct of all activities related to the development and evaluation of hydrogen powered vehicles. Several activities, both required by the DOE and others required by Ford, were undertaken with the objective of ensuring that no harm to personnel, property or the environment would happen during the demonstration program. These include FMEAs, Safety Plans, Risk Mitigation Plans and Communications Plans, which are summarized here.

Safety Performance Plan

In this demonstration program, Ford Motor Company utilized its formalized policies that address vehicle safety. It is a long established policy that Ford vehicles must meet or exceed applicable laws and regulations, and advance the state-of-the-art in safety wherever possible.

The Ford policy follows guidelines that are periodically reviewed and updated and include Evolving Alternative Fuel Technologies. This demonstration followed Ford's philosophy of evaluating each proposed production application of an evolving/experimental alternative fuel technology, and developing a program specific set of targets, practicable and appropriate for the hydrogen technology being employed and consistent with providing a high level of safety in Ford products.

The program specific safety targets and activities included:

Planning

1. Establish the initial design strategies

Design

1. Set Vehicle Safety Design Targets
2. Development of Ford Design Failure Modes and Effects Analysis (DFMEA)
3. Vehicle System Design Reviews

Testing & Validation

1. Plan Safety related testing
2. FMVSS Vehicle Safety compliance and documentation (detailed later in this report)

Vehicle Build Processes

1. Identify vehicle Significant (SC) and Critical (CC) characteristics
2. Identification of Critical Characteristics (CC) and Significant Characteristics (SC) on assembly process sheets
3. Perform safety-related End of Line Testing
4. Complete Post-Production Drive Evaluation

Internal Product Development Reviews

1. Document safety incidents
2. Define corrective/improvement action
3. Document lessons learned.

Fleet Operation

1. Fueling/defueling design FMEA
2. Develop and deliver service facility safety guidelines for hydrogen vehicles
3. Reviewing safe storage requirements for hydrogen vehicles
4. Develop driver safety training material
5. Develop technician safety training material
6. Develop emergency responder safety training material
7. Deliver timely training to technicians, operators, and emergency responders
8. Work with SAE Safety committees

After all vehicles had been deployed to customer locations, the FCV Service Department developed a detail ***Operational Safety Plan Document***. This instructional document provided detailed information about safe operations in fourteen sections as follows:

1. Safety Policy Statement
2. Roles and Responsibilities
3. Overall Project Safety Management Procedures
4. Documentation and procedure Change Procedures
5. Training Plans
6. Safe Vehicle Operating Procedures
7. Service Facility Procedures
8. Service Technician Procedures
9. Safe Refueling and Hydrogen Handling Procedures
10. Accident/Immanent Hazard Procedures
11. Emergency Response Procedure Training
12. General Precautions and Safety Rules
13. Accident/ Incident Reporting Procedures
14. Dealing with the Media

The Operational Safety Plan provided a consolidation of all FCV related safety information for use by fleet managers and technicians as a ready reference manual. Each site was also asked to insert specific information into the plan book so that, in a potential emergency, all helpful information would be immediately available.

An element of this plan was a requirement for an annual physical audit of the facility. The audit was designed to ensure that procedures were being followed, equipment continued to be available, and safety devices were functioning properly. The audit form is attached as Appendix 2 of this report.

Ongoing safety awareness and communication was reinforced through bi-monthly Safety Teleconferences. An assigned Service Site Manager hosted the meetings. In these meetings, representatives of all service sites called in to listen to and participate in discussions of audit findings, potential safety concerns or relevant events that might affect their use and understanding of the hydrogen vehicles.

Risk Mitigation Plan

During the vehicle development process actions were developed to reduce or eliminate risks as part of the safety strategy. Beginning with overall vehicle safety based on Federal Motor Vehicle Standards, the overall strategy for the Ford Focus FCV risk mitigation was enhanced include the ability to detect hydrogen leaks and react before flammable limits are reached. Elements of this strategy include hardware design that minimizes risk if leakage occurred and on-board tests for detecting slow leakages. Actions based on this strategy include:

1. Isolate hydrogen sources from the passenger compartment
2. Design and locate points of hydrogen release to minimize possibility of injury
3. Dilute operating hydrogen emissions below flammable concentration
4. Utilize hydrogen sensors in the vehicle and the fuel cell system
5. Utilize pressure checks to assess possible leakage.

Risk mitigation also involved the design of the fueling /defueling processes with cooperation with Fuel station vendors. Finally, Risk Mitigation was defined for the personnel who were involved in the program.

The following addresses the principle ***Vehicle & Program Risk Mitigation*** actions, implemented or employed in this demonstration program:

Safety Strategies

- Safety equivalent to Focus model
  - Analytical & Test confirmation

- Meet FMVSS requirements
  - Completion of FMVSS testing

- Isolate Hydrogen sources from passenger compartment
  - Attention to location of points of release of Hydrogen
  - Dilute operating emissions
  - Underbody Sealing
  - Underbody airflow strategy
  - Develop system & sub-system FMEA

Design

- Hydrogen Storage
  - Locate Hydrogen tank in trunk
  - Fueling shut off valve
  - Fuel door switch
  - Incorporate in-tank shut off valve
  - Fueling prevented if key is in run/star
  - Pressure relief devices employed
  - Inertia/impact shut-off switch
  - Clear identification of on-board hydrogen storage

- Hydrogen Leakage
  - Established safe hydrogen concentration limits to guide design
  - Established time requirements to pressurize/exhaust cabin
  - Forced Air Ventilation
  - Use Hydrogen detectors in vehicle and fuel cell system
  - Interior Hydrogen sensors and control module
  - Use pressure checks to assess possible leaks
  - Hydrogen overpressure release: low pressure side
  - Implement CNG experience

- Systems & Controls
  - No restart permitted when high level fault has been detected

- Software permits safe control to pull over if problem occurs
- Indicator lights provide operator warnings

- High Voltage
  - Inertia/impact shut-off switch
  - Implement High Voltage hybrid experience
  - High Voltage service disconnect switch installed on the High Voltage battery
  - Interlock on High Voltage connectors.
  - Clear identification of High Voltage lines and devices

Vehicle Maintenance/Service
- Implemented leak check in quarterly maintenance procedure
- Defuel procedures require performance outdoors or in an approved ventilated facility
  Purge system with inert gas prior to filling with H2

Program Risk Mitigation
- Develop safety training for operators, technicians, emergency responders, re-fuelers
- Utilize formalized safety incident reporting procedures and formalized safety procedure
- Update procedures, processes and training using lessons learned.

Failure Mode and Effects Analysis (FMEA)

Ford Motor conducts a systems analysis exercise designed to assess each component of a vehicle sub-system for its potential to cause a safety issue or to produce customer dissatisfaction. The Department of Energy requested that this analysis be made available as a part of the program. Ford could not agree to supply this extremely confidential and extensive documentation.

A number of discussions were held with DOE personnel to define the approach and content of this document. Through these discussion, it was agreed that the inclusion of failure modes would be made based on the assignment of numerical ratings, by teams of expert vehicle engineers, for Severity, Occurrence and Detection of a failure mode, and represent, in their opinions, those items that present the most significant safety related issues for this vehicle design. As also agreed, the matrix would not include those rating factors, since they address some of our company's most confidential vehicle development information.

This high level review of the vehicle FMEA was subsequently provided. The high level review consists of a matrix that identifies Key Safety Failure Modes, Effects, Causes and Actions taken to ensure safety. This matrix represents an extraction from Ford Motor Company FMEA reviews of the unique vehicle systems in the Fuel Cell Vehicle. The unique fuel cell vehicle systems covered are:
- Fueling Interface
- Fuel Storage
- Fuel Cell
- Vehicle Hydrogen System Leaks

From 1723 individual failure modes for these systems, our engineers identified 181 high priority issues and have reported on 76 key safety related failure modes.

The FMEA documents associated with this program have been reviewed in light of program performance to date. No safety incidents or near misses have been experienced in the program through December 2009. No deficiencies have been identified in the FMEA. No changes have been or are being made to the plan documents as originally submitted for this program. Therefore the extensive FMEA analysis conducted for the hydrogen vehicle systems, subsystems and components are considered effective. Ford recognizes that the FMEA is a living document and will continue to consider updates for the benefit of future product development programs.

Submission of this information has been made to the controlled data center at NREL as the methodology agreed to by the DOE and Ford Motor Company as the most appropriate method for protecting the level of information provided. A copy of the submission cover letter dated Dec. 7, 2005 is included in Appendix 3 of this report.

As detailed below in BP's infrastructure safety implementation, BP utilized the Hazard Identification (HAZID) and Hazard and Operability (HAZOP) assessment procedures in planning for the safety of each fueling station. All assessment results were shared with the DOE as the program developed.

Communication Plan

Ford prepared and implemented a Health, Safety and Environmental (HSE) Communications Plan as requested by the DOE. This plan was documented and provided in both written and electronic format to the service centers.

As the program progressed and changes, especially to assigned personnel, happened, the document was revised and placed in the Technician Repair Order System (TROS) Service Documents section so that all locations and personnel could have access to the most current information. A manual, e-mail format system was utilized to ensure that all recipients provided written acknowledgements of receipt of the updated plan documents.

The Communications Plan defined actions and assigned responsibilities in five phases (Sections) of reaction to a potentially critical incident. The first two phases define the initiation of communications and immediate response. These are:

Section 1 Concern Reporting
Section 2 Action Program Preparations

Using the procedures explained in these sections, the Service Center Manager (or Lead Technician) has a defined method to respond to any safety related issue in the vehicle, or safety procedure employed in the service of the vehicle, or facility practice in this Fuel Cell Vehicle Demonstration project.

Management response to safety related issues in either the Vehicle or Procedures was defined in the following sections:

Section 3 Program Management Team Review of Field Actions
Section 4 Service Plan for FCV Demonstration Program
Section 5 FCV Service Action Follow Up

Using the procedures explained in these sections, the Program Management Team was prepared to respond to any safety related issue in the vehicle, or safe procedures employed in the service of the vehicle, or facility practices in this Fuel Cell Vehicle Demonstration project. The response included immediate actions to eliminate potential safety hazards throughout the fleet, defining root cause for the initiating event, and implementing service actions and ensuring that all vehicles/locations had corrective actions implemented

Infrastructure Safety Implementation

BP followed developing international procedures such as the European Hydrogen for Transport formulations, which are committed to no accidents, no harm to people, and no damage to the environment. For each new fueling site, BP utilized the following approaches:

Project Management

- Managerial Gate Approvals
- Management of Change
- Pre-Construction Safety Induction for Contractors and Suppliers (Injury and Incident Free training)
- Advanced Safety Audits
- Integrity Management Standard

Adherence to relevant safety codes (examples):

- NFPA 52
- SAE J2600
- SAE J2601(planned)
- ASME B31.3

Collaborative system safety assessments, reviews and plans

- HAZID / QRA
- HAZOP
- pHSSEr approach
- BP-Global Alliance safety training for contractor and supplier
- Emergency Response Plan

H2 Safety Training

- Contractors
- Fleet operators
- Station operators
- Emergency Responders

Vehicle Scheduling & Build

The final plans for Ford's fleet development called for a total build of 30 vehicles. Of these, 18 were assigned to this DOE program. These vehicles were to be "production" level vehicles; certified to be operated on public roads. In preparation, a series of tests, designed to address relevant Federal Motor Vehicle Standards to permit certification were conducted.

The details of the vehicles components and systems are presented in the Fleet Operations section of this report. In the following paragraphs, details of pre-production testing, the production process and post-production assessments are presented.

Applicable FMVSS Compliance

The following is a listing of the Federal Motor Vehicle Safety Standards that were addressed in the preparation of the Ford Focus Fuel Cell Vehicle:

Std No.	FMVSS Title
101	Controls & Displays
102	Transmission Shift & Interlock
103	Windshield Defrosting & Defogging Systems
104	Windshield Wiping & Washing Systems
106	Brake Hoses
108	Lamps, Reflective Devices
109	New Pneumatic Tires
110	Tire Selection & Rims
111	Rearview Mirrors
113	Hood Latch Systems
114	Theft Protection
116	Motor Vehicle Brake Fluids
118	Power-operated Windows
124	Accelerator Control Systems
135	Hydraulic Brake Systems
201	Occupant Protection in Interior Impact
202	Head Restraint
203	Impact Protection for the Driver from the Steering Control System

Std No.	FMVSS Title
204	Steering Control Rearward Displacement
205	Glazing Materials
206	Door Locks & Door Retention Components
207	Seating Systems
208	Occupant Crash Protection
209	Seat Belt Assemblies
210	Seat Belt Assembly Anchorages
212	Windshield Mounting
214	Side Impact Protection
216	Roof Crush Resistance
219	Windshield Zone Intrusion
225	Child Restraint Anchorage System
302	Flammability of Interior Materials
305	EV Electrolyte Spillage & Electric Shock Protection
Part 565	Vehicle Identification Number
Part 567	Certification Level
Part 574	Tire Identification & Record Keeping
Part 575	Consumer Information

Examples of some of the crash testing are shown here. All of the tests indicated that the vehicle integrity met the requirements of the standards. The rear impact tests demonstrated that the fuel tank, located in the normal trunk area, was not damaged during impact. Roof crush testing indicated that the added weight of the batteries and fuel cell was adequately accommodated with the special body structure.

90º 30 MPH Front Fixed Barrier Impact

90º 30 MPH Rear Moving Barrier Impact

Prior to release, Proving Grounds tests of three vehicles were completed to equivalent of 150% of program duration 4.5 years and 65,000 miles (109,000 km) target.

Other significant testing to investigate and prepare the vehicles to meet Ford's internal standards was also conducted. The following are a few of the tests that were conducted in preparation for the customer fleet deployment.

14,000 Ft Altitude Testing

Mud Bath / Salt Water Fording

Sault Ste Marie Brake Testing -18 C

Cobblestone Roads

Hot Weather Thermal / Durability Tests

6700 miles of Development Result: Achieved 50 mpg M-H Target

Vehicle Build

The 30 Focus FCVs were built on a production line, designed for this program. A third party contractor was employed to conduct the assembly operations because of the unique nature of the cars.

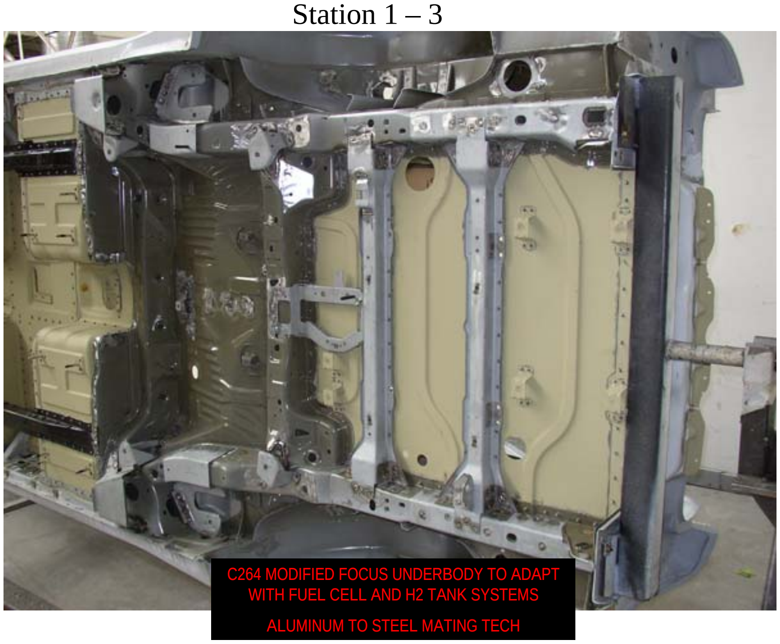
The assembly process consisted of six workstations. Each station had the unique components and specially trained assemblers to complete the phased assembly. Ford engineers and quality personnel provided oversight, assistance and training where needed.

The following were the steps in the assembly process:

Station 1 – 3

Specially designed components were used in the body structure. Although the overall vehicle looked very much like a 2004 Focus, in fact there were many structural differences to accommodate higher mass components and to reduce weight. In the first three assembly stations, special floor pan components were bonded and riveted in place.

Station 1 – 3



The aluminum and steel components were bonded together using specially adapted technologies to ensure durability of the body structure.

Station 4

Distinctive paints and identification were used for these production vehicles.

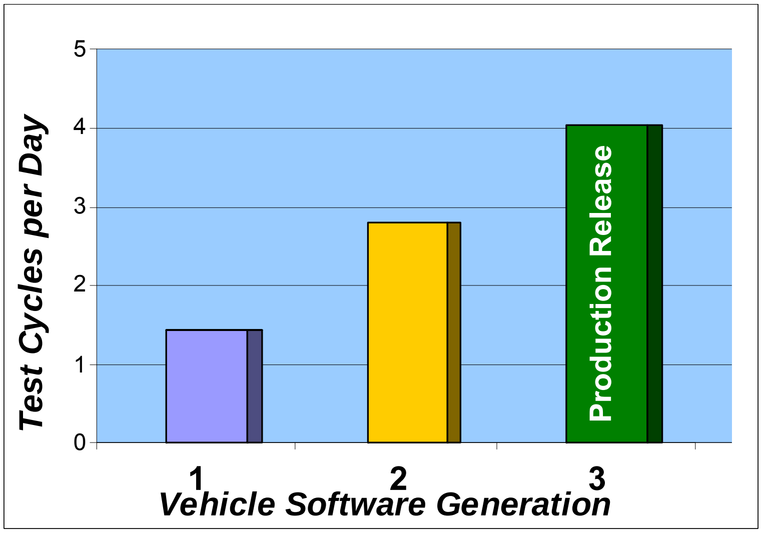
Station 5

Trim operations were completed in the same manner used for commercially offered Focus models. Special components were selected or developed to ensure a "production" look to the car, avoiding an experimental image for the program.

Station 6

Modular assemblies were used in the fuel tank, systems module and stack module designs. Although the resultant vehicles are complex, the serviceability was maintained to the highest levels.

The planned build schedule was interrupted by the identification of system and component issues. In the preparation for production, technical issues were identified and improvement activities initiated. Several improvements to vehicle robustness were implemented, mainly software revisions that addressed operational issues identified during extensive pre-production validation. Numerous revisions and improvements were made and ongoing pre-production testing demonstrated a significant improvement in systems and vehicle-level reliability. This can be seen in the following chart showing increased test cycle uptime with each improved software generation.

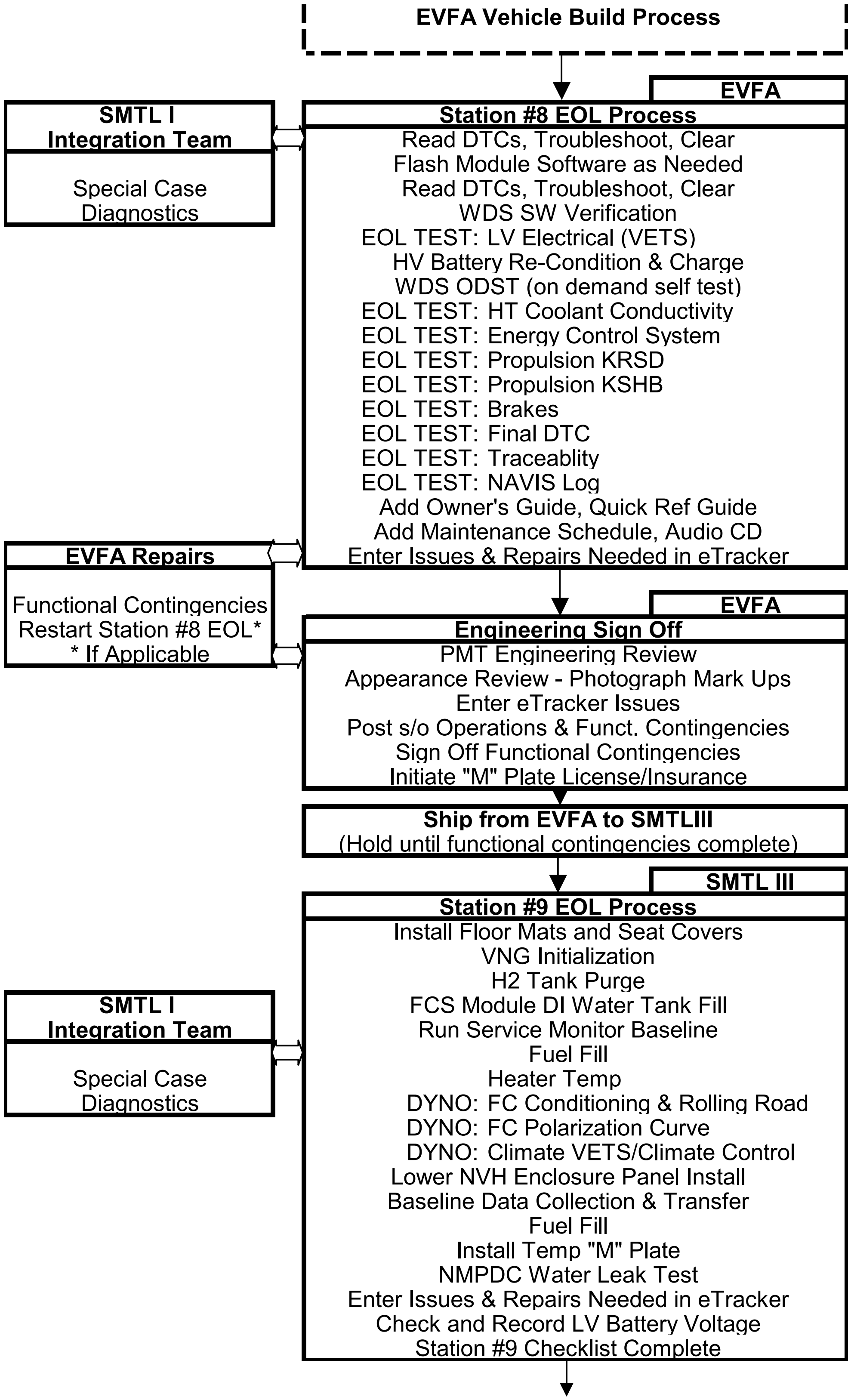


The original plans to complete all vehicle build activity by early in the first quarter of 2005 were modified to accommodate the reliability improvement activities defined above. All vehicles were assembled with the latest design levels of components and software. All efforts were made to minimize or eliminate any post build rework, or field modification. The improvement efforts lead to continuing the assembly operation into the third quarter of 2005.

Production validation testing was completed on each of the finished vehicles. This detailed process provided for the complete assessment of all vehicle operating systems to maximize customer satisfaction and minimize operational problems when the vehicles were placed in customer fleets.

The following table provides the detail of post-production testing. When issues were identified, they were entered into an electronic database file, (the e-Tracker), to be assessed for required corrective actions and possible design modification for this and future fuel cell programs. The acronym “EOL” refers to “End of Line”.

Post Production Vehicle Testing Detail



Post Production Vehicle Testing Detail (continued)

SMTL I /DPG

Station #10 Post Build Drive Evaluation

Receive Vehicle at SMTL III
Install Test-Dedicated Trunk Trim
Diagnostics, VNG data scan w/Service Monitor
Weigh Car - DPG Scale
Drive Evaluation (No Mileage Bogey)
Diagnostics / Read & Clear DTCs
Special Part Inspection: Leaks: P/S, H/T Valve
Download DTC Data
Enter Issues in eTracker
Post Build Drive Issues Review and Sign Off
Send to EVFA for Contingency Repairs
Complete Driver Log and Data Sheets
Remove Test-Dedicated Trunk Trim
Sign Off ALL Remaining Contingencies
Re-Drive & M-10 Sign Off Checklist
Drive to SMTL I. De-fuel as Needed
VNG data scan with Service Monitor
If DOE Car, Drive to SMTL III

A*

A

De-Fuel to 250 PSI
for EVFA repairs

EVFA Repairs

Restart Station #8 EOL*
*(as applicable)

SMTLIII H2 Tank Purge
if any H2 Sys work done

SMTL III

Select DOE Cars ONLY

Station #9b DOE DYNO Baseline Test

H2 Fuel Line Modification
Scan Vehicle with Service Monitor
DOE Baseline Environ. DYNO Test (16 hrs)
Scan Vehicle with Service Monitor
H2 Fuel Line Restore
DOE Data Baseline & Transfer
Drive to SMTL I

A*

SMTL I

Station #11 Customer Preparation

Check LV Battery Health, Replace if Necessary
Perform HV battery reconditioning procedure
Car Wash / Clean Up
Final Fuel Level Adjustment
Remove "M" Plate
Add Roadside Assistance Label
Add Air Bag Hang Tag, Owners Guide (updated)
Add Graphics (Fuel Cells Canada Only)
Compile Final BOM from Original Build Book
Forward Electronic Copy of BOM to ASG
Update and File Build Book
Schedule Vehicle Pick Up & Notify All
Check and Record LV Battery Voltage
Install Production Trunk Trim Kit
Remove Floor Mats and Seat Covers
VNG data scan with Service Monitor
OK2S - Shipping Checklist Sign Off Complete

A*

SMTL I

Station #12 Vehicle Pick Up / Delivery to Appropriate FC Service Center

FC Service Ctr.

Receive Vehicle

Technician Pre-Delivery Process
Confirm Delivery

FC Service Ctr.

Deliver to Final Customer

Customer Hand Off

A*

Process "A" required during any build station for all cars returned to EVFA for repair and for any H2 System repairs.

Vehicle Delivery

With the completion of all build and evaluation activities, eighteen vehicles were placed in customer operations. The following table reflects placements during most of the program. At the outset, a vehicle (P2) was placed in Ann Arbor in Southeast Michigan but when fuel availability was lost at the beginning of 2007, that car was moved to the Florida fleet (Progress Energy). Also, at the beginning of April 2008, one of the Florida cars assigned to the Florida Department of Environmental Protection (P22) was relocated to Reykjavik, Iceland.

Taylor, Michigan

Vehicle #	Start of Service	User	Usage Profile
P12	9/21/2005	City of Taylor Dept. of Public Works	Daily Fire Department use, pool vehicle, employee drive home, local events.
P10	10/1/2005	City of Taylor Dept. of Public Works	Daily Fire Department use, pool vehicle, employee drive home, local events.
P24	10/19/2005	City of Taylor Dept. of Public Works	Daily Fire Department use, pool vehicle, employee drive home, local events.
P25	10/19/2005	City of Taylor Dept. of Public Works	City Manager daily use, employee drive home, local events.

Orlando, Florida

Vehicle #	Start of Service	User	Usage Profile
P20	8/30/2005	Progress Energy	Public Relations, local outreach events, In home energy evaluations for Progress energy customers, employee drive-homes
P19	9/26/2005	Progress Energy	Public Relations, local outreach events, In home energy evaluations for Progress energy customers, employee drive-homes
P21	9/26/2005	FDEP Central District Office	Public Relations, local outreach events, employee drive-homes
P22	9/26/2005	FDEP Central District Office	Public Relations, local outreach events, employee drive-homes
P23	9/26/2005	FDEP Forestry Service	Public Relations, Educating Visiters to Park, local outreach events, park ranger patrol vehicle
P2	10/19/2005	Progress Energy	Public Relations, local outreach events, In home energy evaluations for Progress energy customers, employee drive-homes

Sacramento, California

Vehicle #	Start of Service	User	Usage Profile
P9	9/21/2005	SMUD	Daily use, pool car
P11	9/21/2005	SMUD	Public Relations, local outreach events
P13	9/21/2005	SMUD	Daily use, pool car
P18	9/26/2005	State of CA, Air Resources Board	Daily use, pool car, public relations, local outreach events
P26	10/19/2005	SMUD	Public Relations, local outreach events
P16	10/21/2005	State of CA, Department of General Services	California State Fire Marshall daily use
P17	10/21/2005	State of CA, Energy Comission	Daily use, pool car, public relations, local outreach events
P3	11/2/2005	SMUD	Daily use, pool car

Site Plans

Service centers were in place in Sacramento, CA and Dearborn, MI from the start of the program, and each of these facilities has been reviewed for access to required equipment, tools and information. In Sacramento, the servicing was done in the California Fuel Cell Partnership (CaFCP) building where Ford was a participating member. In Southeast Michigan, servicing was provided in the Ford Motor Company engineering center.

In Florida, the Progress Energy vehicle maintenance group prepared a new, open-air facility to service the 5 vehicles in the Orlando area. All permitting and site approvals were obtained and the center began servicing cars. In addition, a local Ford dealership, Greenway Ford, agreed to provide a service area for those operations that require specialized vehicle service equipment that is not unique to the Fuel Cell Vehicle.

After opening, the Progress Energy open-air facility underwent evaluation for possible modifications to improve usability during inclement weather. Modifications were considered to improve protection and isolation of the vehicles. It was ultimately determined that the cost to make the necessary improvements to the structure was not reasonable within the program. After assessments and discussions, it was determined that Greenway Ford could provide facilities for Ford FCEV technicians to accomplish both maintenance and repair operations. Arrangements were made to provide additional labor as needed so that the Progress Energy fleet cars continued to operate as originally planned. These arrangements worked well and help to demonstrate that the hydrogen vehicles could be serviced in a commercial service center.

In Iceland, hydrogen vehicle facilities were already operating. Ford provided FCV specific training to Icelandic New Energy personnel to permit them to maintain, diagnose and repair the vehicle. Ford ensured that all proper service tools and safety equipment were available.

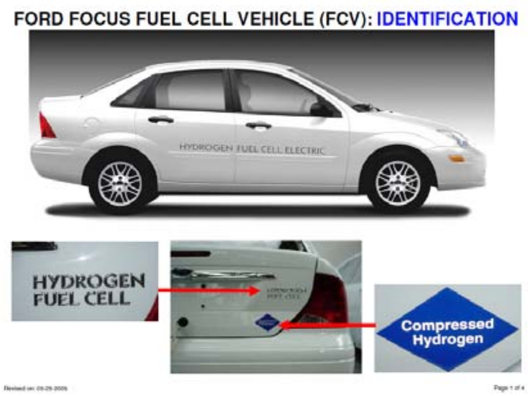
Site Training

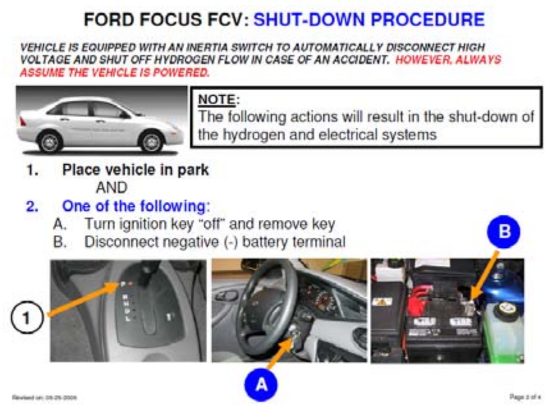
Ford and BP training courses and materials were developed and presented at all locations with the objective of providing all involved personnel with the information necessary to perform their roles in a safe and effective manner.

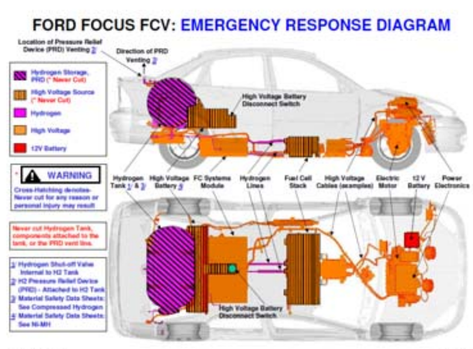
The following is the overview of the subject matter that was prepared and presented by Ford personnel to each of the selected audiences. The details of extensive technician training and more information about Operator Training are presented in the Vehicle Demonstration section of this report.

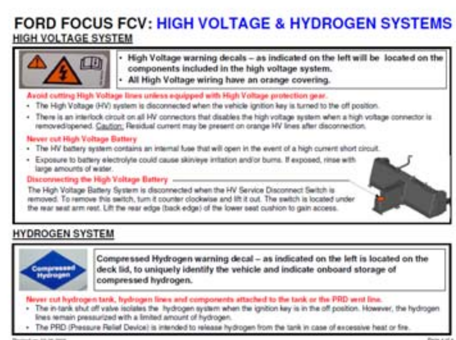
First Responders Training

The following pictures are reductions of the Emergency Responder (ER) class ready reference take-away material. The class itself was delivered with PowerPoint, video and lectures by safety experts. A copy of the training material was provided to the DOE and to NextEnergy for their other program uses.









Fleet Operations (Customer) Training

A complete collection of training materials was prepared for the participants in the operations of the vehicles and the local fleet managers. Every effort was made to define all of the information that a novice operator would need to safely and effectively drive the FCV, as well as participate in the learning and data gathering experience. The following is a summary of the subject matter for each audience:

Fleet Manager Training	Vehicle Operator Training	Local Fuel Station Operator Training
Focus Understand emergency information and emergency response procedures, and fleet management requirements	**Focus** Understand how the vehicle works and the unique requirements for safe operation	**Focus** Understand correct operating and emergency response procedures
Communication Requirements • Emergency Response Information • Incident Reporting Procedures • Procedural Updating	**Safe Operation** • Hydrogen safety training • High voltage safety • Emergency response procedures • Service and maintenance requirements	**Safe Operation** • Concepts and risk of H2 • Proper use of the operational equipment • Safety procedures • Maintenance regimes • Start-up procedures • Operating procedures • Maintenance procedures • Shutdown procedures • Designated authorities identified • Records maintenance and retention • Fuelling and defuelling procedures
Vehicle Maintenance & Data Collection Procedures • Completion of vehicle logs • vehicle inspections • Operation of electronic data reporting devices on the vehicle • Routine service and repairs • Diagnostic and repair responsibilities • 90-day maintenance and reporting procedures • Define service responsibilities between Ford and Ballard (Fuel Cell System Supplier) • High voltage safety • Hydrogen safety • Vehicle overview • Driving features • Pre-delivery inspection • Fuelling and defuelling	**Vehicle Information** • How the FCV works • Meaning of instrumentation and indicator lights • Required and safe operating procedures • Emergency procedures • Local contact personnel • Data collection requirements and procedures • Fuelling and defuelling procedures	

Hydrogen Health and Safety Instructions

Operator training materials were delivered to all program participants. The essential elements of Hydrogen Health and Safety comprised the first portion of this training program. As mentioned above, more detail about this instructional material is presented in the Vehicle Demonstration section of this report.

BP developed instructional material on required and safe fuelling and de-fuelling procedures, and other health related information. In cooperation with its suppliers, BP provided site-specific training for all involved personnel at all locations. The purpose of the training was to ensure safe practices by vehicle operators who would use the stations in much the same way as commercial gasoline stations are used. The unique elements of hydrogen dispensing were covered in detail. The following is a listing of the typical elements of this Hydrogen Training:

- Physical Properties of Hydrogen
  - Uses of Hydrogen
- BP Hydrogen Fueling Station
- Major Equipment
  - Liquid Hydrogen Storage
  - Vaporizer
  - Hydrogen Compressor
  - High Pressure Storage Cylinders
  - Hydrogen Dispenser
- Hazards
  - High Pressure Hazards
  - Hydrogen as an Asphyxiant
  - Spills
  - Air Condensation
  - Cold Contact
  - Expansion Ratio of Hydrogen
  - Eight Causes of Hydrogen Mishaps
- Fueling
  - Weather Conditions
  - Fueling Procedure Safety
  - Fueling Procedure
- What to do in an Emergency
  - Emergency Response Matrix
  - Emergency Response Plan

Vehicle Codes and Standards

This activity was coordinated with other industry participants through NextEnergy, in Detroit, Michigan. NextEnergy will be providing a separate report to the DOE detailing their accomplishments and activities during the demonstration. Here are summary highlights of what NextEnergy has done:

- Conducted the annual Codes and Standards conferences in 2006, 2007, and 2008 and will lead the next annual conference on September 30th, 2009.
- Created the first-responder training module, which is a comprehensive PowerPoint coupled with a video.
- Conducted H2 First Responder Training for first responders at Selfridge Air National Guard Base in 2007 and 2008, as well as at the NREL Permitting Workshop at NextEnergy Center in 2008.
- Created two website-based database tools: The H2 Permitting Officials Database and the H2 Permitting Experiences Database.

- The Officials database identifies the Authorities in several cities throughout the state of Michigan who will have a decision-making ability on hydrogen in their municipality (i.e. fire chiefs, building inspectors). Populated and shared with DOE in 2008. Still not yet transferred to DOE ownership. A web link has been established at http://www.nextenergy.org/nextenergyh2/h2permittingofficials/

- The Experiences Database is a listing of H2 stations and their technical specifications, as well as codes followed during the permitting process. This database is setup with its template, but not yet populated due to relative lack of information available. A web link has been established at http://www.nextenergy.org/nextenergyh2/h2permittingexperiences/

- Next Energy has recommended that DOE take ownership of both databases and use them to their benefit.

- Served as an active Task Group for in the development of the National Fire Protection Agency (NFPA) Hydrogen Technologies Code. Conducted Quality control and templating efforts for the code.

In addition to the NextEnergy cooperation, Ford maintained membership in numerous Standards groups whose work supports the overall objectives of this portion of the DOE project. Table 2 summarizes Ford and BP's involvement in the development of Hydrogen Codes and Standards at the outset of the project:

Standards Organization and Committee	**Ford Representative Committee Responsibilities**
California Fuel Cell Partnership	Founding Member Voting Member
DOE Codes and Standards Coordinating Committee	Voting Member
EIHP International Link Work Group	Member Team Lead
EV Forum	Voting Member
EV Safety Committee	Voting Member
High Voltage Electrical Distribution Systems	Voting Member
ICC Ad Hoc Committee on Hydrogen	Voting Member
International Code Council (ICC) Ad Hoc Committee on Fuel Cells	Non-Voting Member
International Hydrogen Infrastructure Group (IHIG) Steering Committee	Voting Member
International Hydrogen Infrastructure Group (IHIG), Codes and Standards Working Group	Co-Chair
International Standards Organization TC 197-USTAG	Member Voting Member
MIT Consortium – Battery Condition Monitoring Committee (vehicle battery diagnostics)	Non-Voting Member
MIT/Industry Consortium on Advanced Automotive Electrical and Electronic Systems and Components	Non-Voting Member
National Hydrogen Association	Voting Member
NFPA Committee 52	Voting Member
SAE 42V Battery Connector (termination system)	Voting Member
SAE EV Charging Systems Committee (SAE J1772/J1773)	Voting Member
SAE Fuel Cell Standards Committee – Emissions and Fuel Consumption Working Group	Chairperson and Four Voting Members
SAE Fuel Cell Standards Committee – Fuel Cell Standards	Voting Member
SAE Fuel Cell Standards Committee – Interface Working Group	Chairperson Voting Member
SAE Fuel Cell Standards Committee – Recyclability Working Group	Voting Member
SAE Fuel Cell Standards Committee – Safety Working Group	Three Voting Members
Standards Organization and Committee	BP Representative Committee Responsibilities
USCAR 42V Jump Start Connector Standard	Voting Member

Program Management & Reporting

A Project Management Task was defined for the ongoing requirements of reporting and communication with all involved program organizations. The fundamental reporting requirements of the DOE were all met in accordance with the original planning statement.

Quarterly progress reports were issued beginning with the report on activity in the fourth quarter of 2004. This earliest reporting detailed the activities leading up to production and the preparation of the field operations. All required reports were submitted quarterly after the initial report.

A number of discussions were held with NREL personnel to ensure that the data that was collected and submitted to the Secure Data Center at NREL would both meet program informational needs and move easily into the NREL databases. Quarterly data files taken from the vehicle data systems and pre-reviewed for errors and omissions were submitted to NREL on CDs.

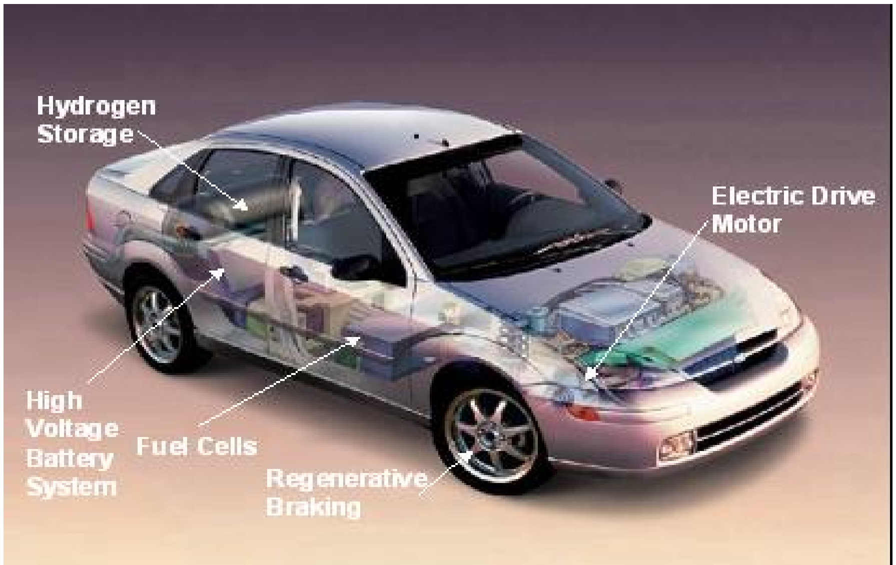
Program management also provided detailed quarterly financial summaries and program invoices in accordance with DOE needs. The project was completed within the approved budgets, and in fact finished significantly under the agreed budget..

Annual Program Review meetings were held with DOE program personnel to discuss progress, problems and opportunities in the ongoing effort. These meetings were held in both Dearborn and at DOE sites to provide effective and timely reviews.

Finally, a Topical Report was prepared to present Ford’s overview on the “Economic and Commercial Viability of Fuel Cell Vehicles at 500,000 Units per Year”. This comprehensive report was submitted in June 2007. A copy of the abstract of this report is contained in Appendix 4 of this report.

Vehicle Demonstration

Vehicle Description & Specifications



The Ford Focus Fuel Cell Hybrid Electric vehicle (FCV) is a 3600-pound (1633 kilograms) vehicle that operates on electricity, which is generated by a hydrogen fuel cell. The electricity powers traction motors that then turn the vehicle's drive wheels. The Powertrain architecture of the vehicle is shown in the following illustration (Fig. D1).

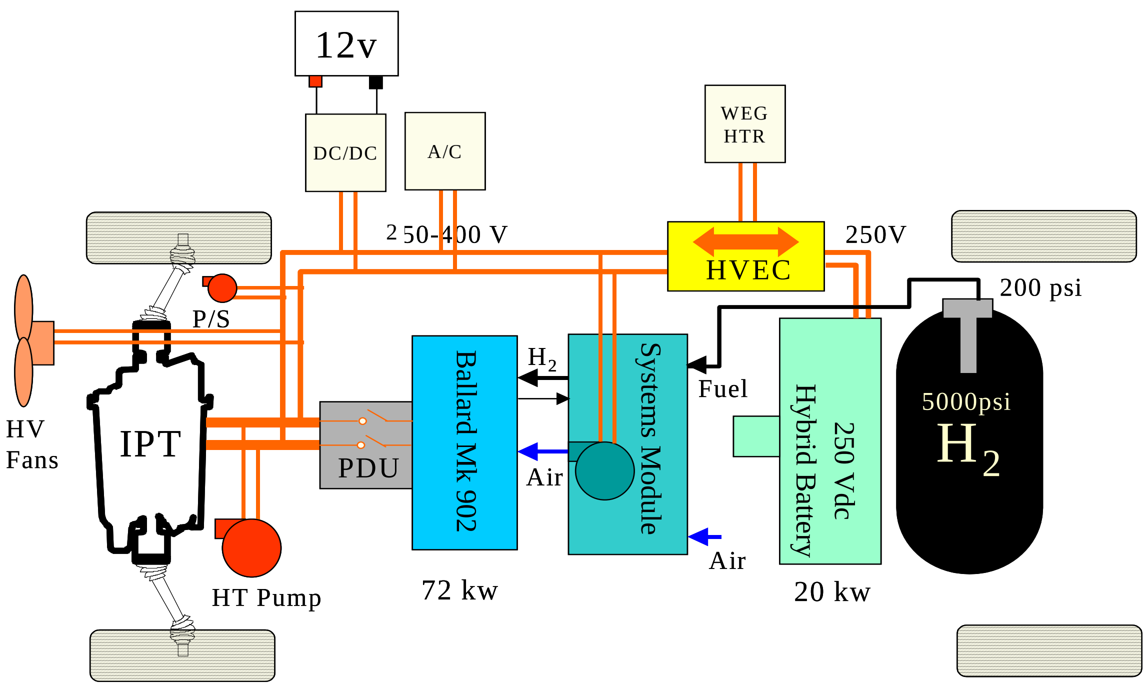


Figure D1: Ford Focus Fuel Cell Powertrain Architecture

This system uses a hybrid powertrain architecture, meaning the High Voltage battery pack aids vehicle performance. The battery cannot drive the vehicle by itself during normal operation or for extended periods of time due t its low energy content.

There are eight subsystems in the vehicle that work together:

1. Fuel Cell Stack
2. Fuel Cell Systems Module (sometimes referred to as the Balance of Plant)
3. High Voltage Battery System
4. Electronic Control System
5. Hydrogen Storage System
6. Electric Drive Motor System (referred to as the Integrated Power Train or IPT)
7. Regenerative Braking System
8. Low Voltage Electrical system

These systems will be explained in more detail later.

How it Works

The vehicle starts using a 12-volt Starter/Light/Ignition battery to supply electrical power to the vehicle control modules and the HV battery to supply HV electrical power to the necessary components. Hydrogen and compressed air begin to flow to the stack from the systems module. When the stack begins to produce electricity at drive-away level, the fuel cell becomes the source of power to the hybrid drivetrain. This power is controlled by the amount of hydrogen and air flowing through the stack module and is responsive to the drivers demand. The power is fed to the electric drive that propels the car.

For the driver, the vehicle operates much like a conventional internal combustion engine car after the fuel cell systems unique start-up procedure. The instrument panel provides an indicator to the driver to show the status of the fuel cell system, and identifies when the car is ready to drive.

This indicator is the only operational gage that distinguishes the FCV from a conventional ICE vehicle. There are several other indicator lights that alert the driver to specific operational problems or conditions. When an operator begins the start-up cycle, the indicator is in the “OFF” position. A short key-on and hold rotation of the ignition key moves the indicator to the “START UP” position.

During Start Up, batteries power the car’s systems. An electronic monitoring system makes checks on seven H2 sensors in the hydrogen system (Fig. D2) for the presence of hydrogen gas. A computer makes a comparison of H2 storage pressure at shut down with pressure at start-up. If these checks do not indicate a possible H2 gas problem, the start cycle begins.

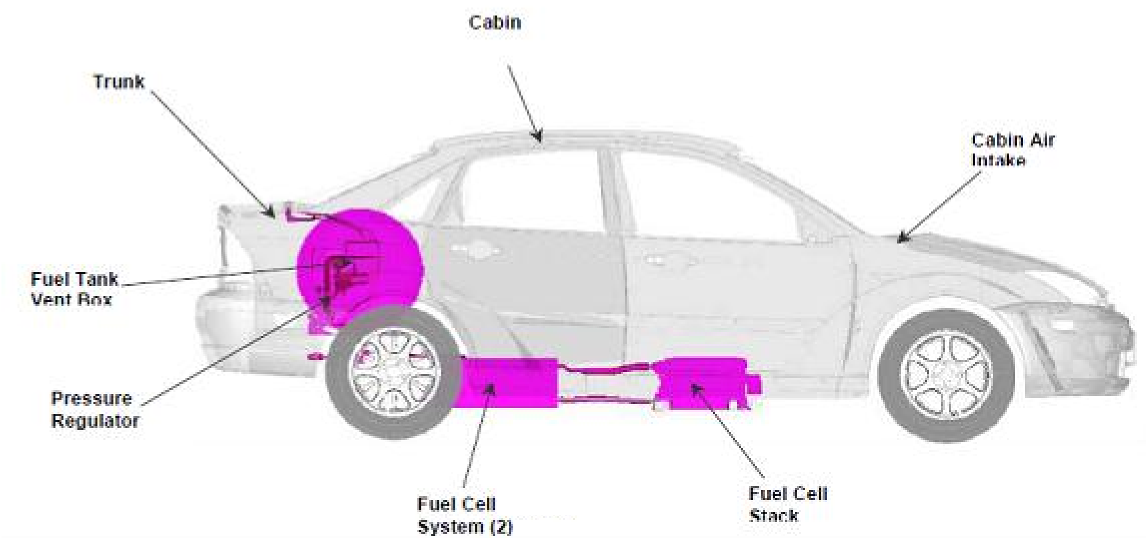


Figure D2: Hydrogen Sensor Locations

Hydrogen flows from the storage tank to the Fuel Cell Systems Module (Sys Mod), which regulates pressure and supplies it to the Fuel Cell Stack (Stack). Simultaneously, an air compressor in the Sys Mod begins to compress air and supplies it to the Stack. The stack begins to generate electricity, which is supplied to the High Voltage Bus. When the system stabilizes, the indicator points to "RUN" and the vehicle is ready to drive. This start up cycle takes about 10 to 20 seconds at normal operating temperatures but may increase to about one minute at lower temperatures.

During the startup interval, the brake-transmission interlock remains engaged to prevent the vehicle from being removed from "Park." The vehicle operator is provided indication of the startup process via the condition gauge on the instrument cluster indicating "Startup," once the vehicle is able to be driven, the condition gauge will indicate "Run" and the brake-transmission interlock will be disengaged to allow the operator to select a gear position. The startup process is essential to allow the fuel cell system enough time to begin providing proper voltage to meet the impending demands of the high voltage bus. Without this process, an operator could potentially demand more power from the fuel cell system than is available immediately following a startup.

The fuel cell system may be unable to respond to driver power demands, such as acceleration events, and battery power may be initially provided to the IPT, thus allowing the Fuel Cell system adequate time to ramp up it's power to meet the full power demand of the vehicle.

During deceleration the electric motor (IPT) works as a generator. Using the mechanical input from the drive wheels to rotate the electric motor, polarity of the windings is reversed to produce electricity. The electricity is directed to the high voltage system, storing energy in the HVB, or if the battery is fully charged, to other HV system components.

Vehicle shutdown is accomplished by placing the gear selector in "Park" and removing the key from the ignition tumbler. This initiates a "Shutdown" procedure in the programming of the vehicle that will take approx. 30 seconds to complete. The driver may exit the vehicle at this time as the shutdown process is fully automated. The vehicle may not be restarted during the shutdown process and the operator is informed that the process is running based on the condition gauge pointing to "Shutdown". Following the completion of the "Shutdown" procedure, the vehicle may be restarted. During the shutdown procedure, ambient gasses are expelled from the Fuel Cell system in order to condition the system for non-operational soaking and prepare it for it's next startup event.

This combination of systems for power generation results in a fuel economy that is comparable to 50 MPG (21.3 kilometers/liter) of gasoline.

If there is high voltage leakage to the chassis or a hydrogen system problem, a warning light illuminates and the vehicle will not restart.

Physical Architecture

The 4kg hydrogen tank is located in what is normally the trunk of the vehicle, the fuel cell stack is located under the driver and passenger seats, the systems module is located under the rear seat, and battery is behind the rear seat. The electric motor is part of the Integrated Powertrain (IPT) placed between the front wheels. The electrical power converters and the high and low temperature cooling systems are located under the hood (Figure D3).

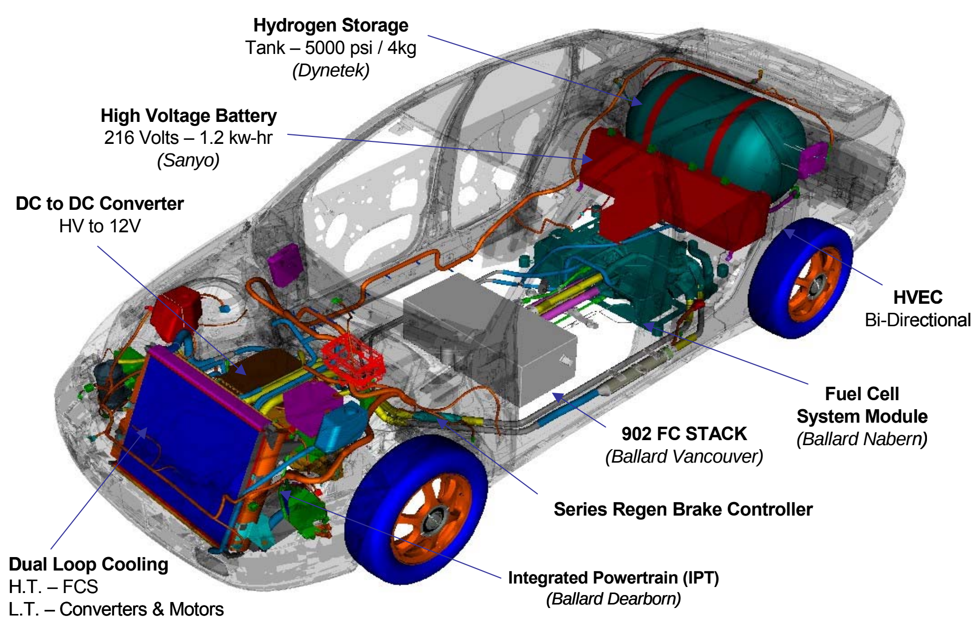


Figure D3 Ford Focus Fuel Cell Vehicle (C264) Architecture

Vehicle Systems

The following sections provide an overview of the purpose and operation of the principle sub-systems of the vehicle:

Fuel Cell Stack

The Fuel Cell system is a Ballard Mark 902 stack and systems module. The stack can produce gross power of 85 kW. The stack consists of four cell rows, each with 110 cells. These are compressed together with bands to make tightly sealed passages for air, hydrogen and coolant which are fed through a manifold. The cells are connected to Cell Voltage Monitors (CVM) to provide state information to the vehicle.

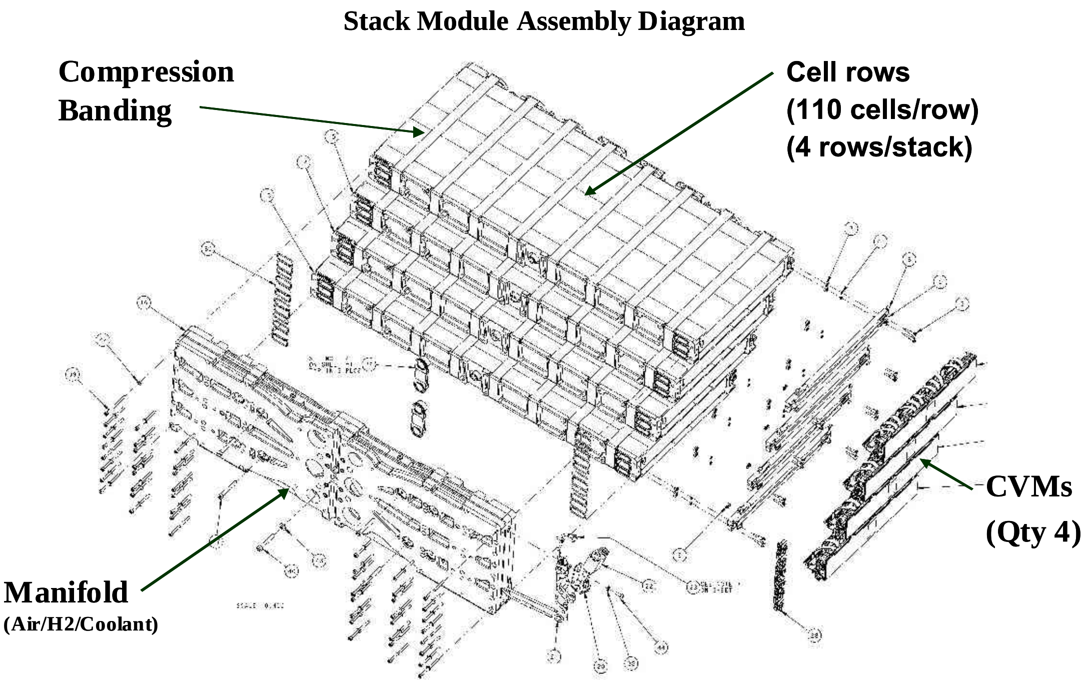


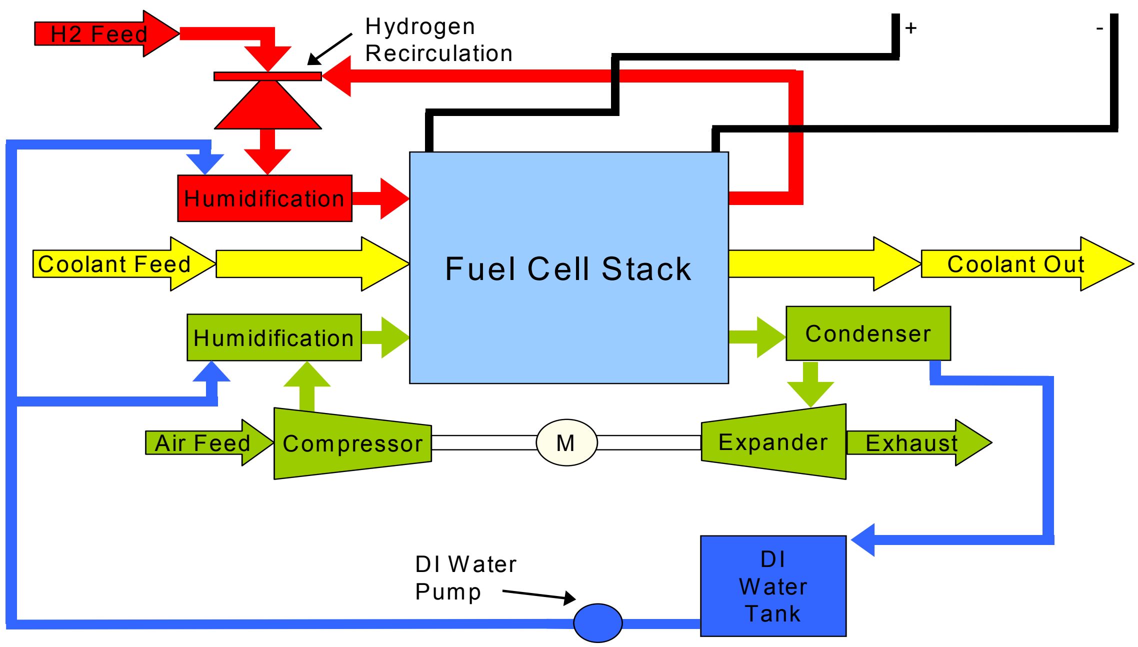
Figure D4: Ballard Mk902 Fuel Cell Stack

Fuel Cell Systems Module

The Fuel Cell Systems Module, sometimes referred to as the "Balance of Plant" (BOP) contains the subsystems that control the flow of hydrogen, air, humidification and coolant for the stack module. The following are the subsystems contained in the systems module:

- Air System (Compressor / Expander)
- Humidification System
- Thermal System
- Electronic Controls

The following flow diagram shows the connections between these elements in the systems module (Figure D5):



- **Air Management Sub-system (green)**
- **Electrical & Controls Sub-system**
- **Water Management (DI) Sub-system (blue)**
- **Thermal Management (DI-WEG) Sub-system (yellow)**
- **Hydrogen Management Sub-system (red)**

Figure D5: Systems Module Subsystems

The physical appearance of the systems module can be seen in the following picture (Figure D5):

Figure D5: Systems Module

The complete fuel cell system is detailed in the following Figure D6:

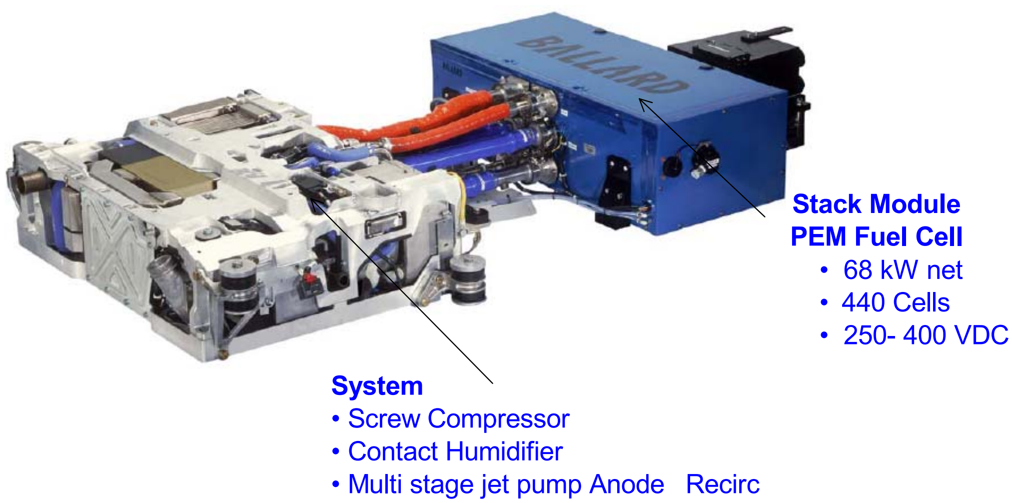


Figure D6: Complete Fuel Cell System

High Voltage Battery System

The HV battery pack is made up of 180 individual Ni-MH (nickel metal hydride) batteries packaged between the rear seat and the hydrogen fuel tank. It is used as a high voltage power source for the vehicle HV components during vehicle start-up, while the FCS is coming up to full power. It is also used to provide additional power (fill-in power) during vehicle transient power increase events (vehicle drive away launch and passing acceleration maneuvers). It provides an energy storage source for the FCS and other HV components (electric drive, brakes, etc.) to store excess energy, for use at a later time.

The battery pack provides additional power which, when used during initial drive away, enables the vehicle to accelerate without delay. The hybrid battery pack assists the fuel cell system for improved driveability providing a smoother overall drive, providing additional throttle response when more power is required, such as when passing other vehicles or climbing hills. The actual battery is shown in the following Figure D7:

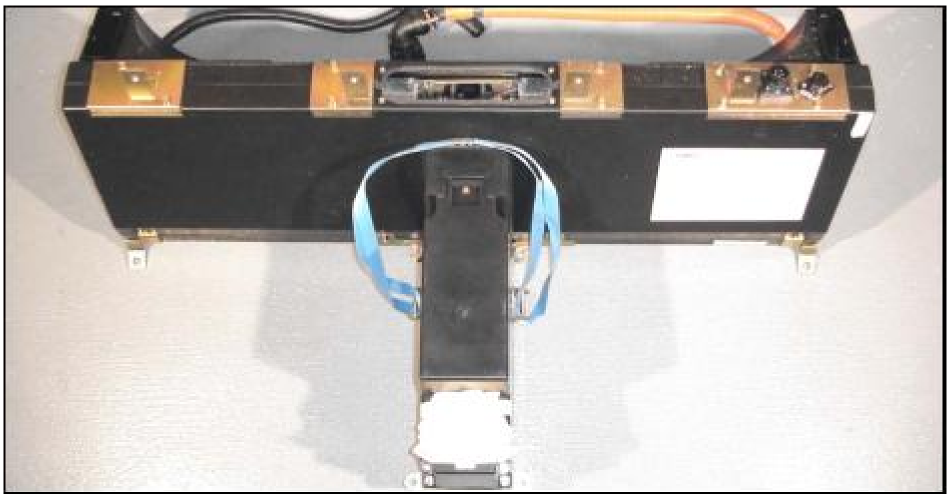


Figure D7: High Voltage Battery Pack

Electronic Control System

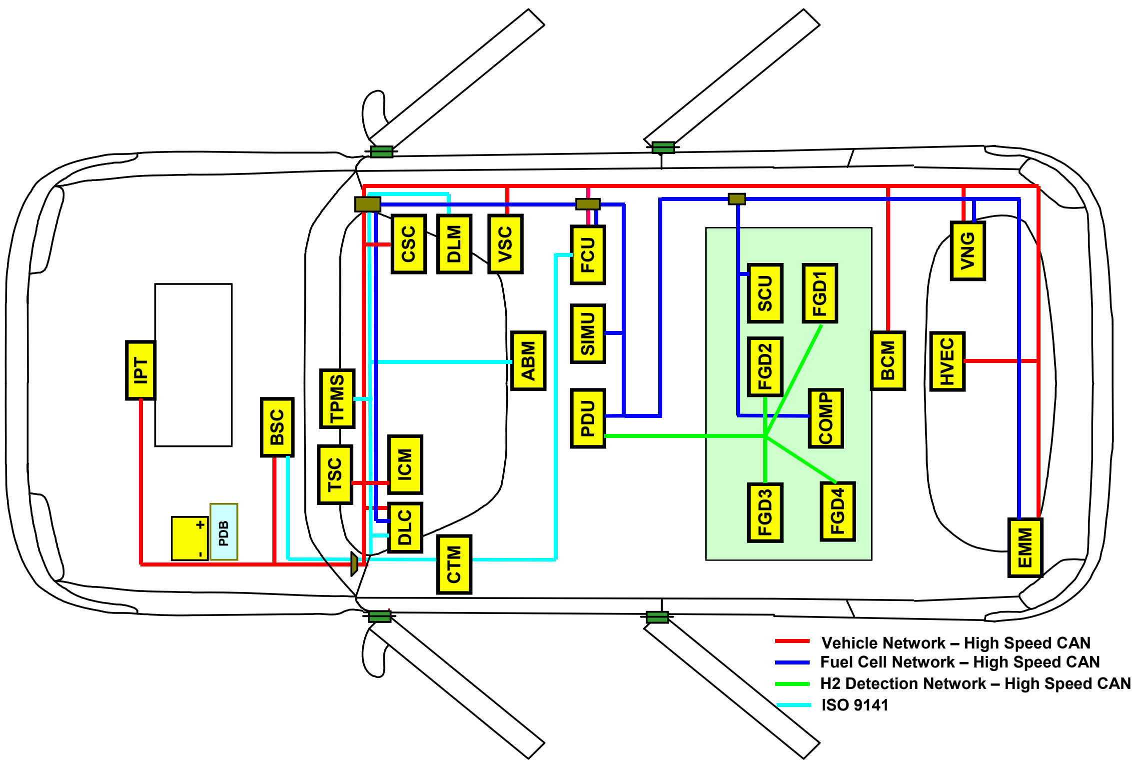
DC/DC Converter

The DC/DC converter, mounted under-hood in the center of the engine compartment, functions as an electronic version of the alternator used on conventional gasoline engines. Like an alternator, the DC/DC converter charges the starting/lighting/ignition (SLI) battery and maintains a regulated voltage on the low-voltage bus for the all 12-volt systems.

Voltage is supplied from the high-voltage bus into the DC/DC converter and is processed into a regulated low voltage of approximately +14.4 volts.

Modules

General systems control is shared between the vehicle systems controller (VSC) and the energy management module (EMM). The electronic controls systems for the Focus FCV is a complex array of communications and control modules depicted in Figure D8.



	ISO 9141 NETWORK
FCU	Fuel Cell Controller
BSC	Brake System Controller
ABM	Airbag Module
TPMS	Tire Pressure Monitor System
DLM	Door Lock Module
CTM	Central Timer Module

	HIGH SPEED VEHICLE NETWORK
IPT	Integrated Powertrain Controller (PCM) (Terminated)
BSC	Brake System Controller (ABS)
TSC	Thermal System Controller
ICM	Instrument Cluster Module (IC)
CSC	Climate System Controller (EATC)
VSC	Vehicle System Controller (PCM)
FCU	Fuel Cell Controller
VNG	Wireless Vehicle Network Gateway
BCM	Battery Controller Module
HVEC	High Voltage Electronics Center
EMM	Energy Management Module (Terminated)
DLC	Data Link Connector (J1962)

Figure D7: High Voltage Battery Pack

The C264 E/E control system is designed to be a fully hierarchical controls system, with the Vehicle System Controller (VSC) as the master controller for the entire vehicle. Each of the subsystem controllers requests resources such as HV Current from the VSC, the VSC arbitrates those requests, and allocates resources as required. The interaction of all of these elements is more complex than can be detailed in this report but a brief description of each element and its function is provided here.

Vehicle System Controller (VSC)
The VSC is the master controller for the vehicle. It is connected to the primary driver inputs (Key, Accelerator Pedal, PRNDL, Brake Pedal, Etc). The VSC processes the driver inputs, requests for resources (e.g. HV Current) from the subsystems, arbitrates those requests, and allocates resources as needed. The VSC also controls the state machine (sequencing) for the entire vehicle, including error detection, and determination of any limited operating strategies.

Integrated Powertrain (IPT)
The IPT is the controller for the electric drivetrain. The VSC issues torque requests (depending on the driver inputs and vehicle speed) to the IPT, the IPT calculates the current (positive to the electric motor, or negative from the electric motor) needed for that torque, and requests that from the VSC. The VSC will then determine the source (Battery or Fuel Cell), or destination (Battery), for that current and allocates that to the IPT.

Battery Controller Module (BCM)
The BCM is the controller for the High Voltage Battery. The BCM monitors the HV battery to determine the State of Charge (SOC), HV Source Current Available, Sink Current Available, and provides this information to the VSC.

Fuel Cell Unit Controller (FCU)
The FCU is the controller for the Fuel Cell System. The VSC will issue Current Requests to the FCU, and the FCU is responsible for controlling the fuel cell subsystem components to provide this power on a timely basis (e.g. within 100-800ms).

Brake System Controller (BSC)
The BSC is the controller for the electro-hydraulic regenerative brake system. The BSC monitors the braking requests, determines how much regenerative brake system force could be provided by the IPT in the form of generator current to put back into the battery, and will provide this information to the VSC. Any braking torque not provided by the IPT will be "filled" in by automatically by friction brakes.

Instrument Cluster Module (ICM)
The ICM controls all of the gauges and telltale lamps in the cluster. It receives all of its primary inputs from the VSC.

Thermal System Controller (TSC)
The TSC is the controller for the thermal fans, pumps and valves. It receives requests for thermal controls, coordinates the high and low temperature thermal loops, and provides this information to the VSC.

Climate System Controller (CSC)
The CSC controls the HV electrically driven air conditioning compressor. The CSC monitors the passenger compartment cooling requests, determines the current needed, and requests this from the VSC.

High Voltage Electronic Converter (HVEC)
The HVEC takes the voltage and current from the HV battery, and boosts it to a higher

voltage as requested by the VSC. The HVEC will also lower the voltage as necessary during regenerative braking to re-charge the HV battery.

Energy Management Module (EMM)
The EMM coordinates the electrically driven heater (WEG) with the HV Battery and HVEC as needed to meet the thermal controls, and also coordinates with the Fuel Cell system on the Fuel Cell Contactors and H2 Detection.

Vehicle Network Gateway (VNG)
The VNG provides 802.11a wireless access to and from the vehicle to support high speed wireless H2 refuelling, error event detection, and network data recording. The VNG also provides wireless diagnostic access to the CAN networks.

Hydrogen Storage System

Hydrogen is stored in a single tank located in what is conventionally the trunk space.

The tank, made by Dynetek, stores 4 kg of usable gaseous hydrogen at pressures up to 5000 psi (350 bar).

Integrated Power Train (IPT)

The Focus FCEV uses an integrated powertrain (IPT) made up of an AC induction electric motor, a power inverter module, power controller module and a single-speed transaxle. The electric drivetrain requires only a single-speed transaxle. The power inverter motor is a three-phase bridge design with a maximum current of 330 amps and a nominal 315 volts.

The transaxle has a final drive ratio of 4:10. The motor produces about 65 kW peak power (45 kW continuous). The IPT stops drawing and/or producing power at the HV bus within 40 ms during an emergency power off (EPO) event.

Regenerative Braking System

The Focus FCEV uses a series regenerative braking system. The regenerative brake system is a brake-by-wire electro-hydraulic design that is the same as brakes on the Ford Escape hybrid electric vehicle. In addition, the Focus FCEV uses the electric drive motor in the vehicle’s integrated powertrain to slow the vehicle. This also works much the same as the Ford Escape hybrid electric vehicle. The system is equipped with hydraulic backup for use in the event of an electrical failure. The operation of the braking system is controlled by the brake system control module (BSCM).

The FCEV has a new electro-hydraulic brake (EHB) system that replaces a portion of the conventional hydraulic brake system. Since there is no vacuum system on this vehicle the EHB system has no conventional brake booster.

The EHB includes a new actuation control unit (ACU), which is similar to a modified master cylinder that includes a pedal feel emulator to provide the familiar sensation of braking. A sensor provides inputs to regulate the amount of hydraulic pressure that is applied to the conventional four-wheel disc brakes, supplied by the HCU.

The EHB system is coordinated with the integrated powertrain management to re-capture energy that would normally be lost to braking (the strategy in the software controls coordination).

Low Voltage Electrical system

The Low Voltage system is a 12 volt system containing many elements of a conventional vehicle electrical system. These include lighting, accessories, some subsystems and the energy for low voltage components during vehicle start up. The battery in this system called the SLI battery (starting/lighting/ignition) maintains a regulated voltage on the low-voltage bus for the all 12-volt systems.

Cooling System Components

The Focus FCEV uses two separate cooling systems:

High-Temperature (HT) Cooling System The high-temperature circuit cools the fuel cell and most of the fuel cell system. It also contains a conventional cabin heater core and a coolant heater that has multiple functions. It is filled with a special mixture of 60% De-ionized Water and 40% Ethylene Glycol (DI WEG) This mixture allows a lower coolant pressure drop across the fuel cell to be realized compared with that which can be obtained with standard 50/50 coolant. This reduces required pumping power but also raises the freezing point of the coolant reducing its freeze protection capabilities. To overcome the relatively high coolant pressure drop of the system, even with reduced EG content, a high power HV electric water pump is utilized. The electrical conductivity of the coolant is maintained at very low levels to ensure isolation of the fuel cell. To accomplish this, DI water is used along with a replaceable de-ionizing filter. Further, the build process calls for a special system cleaning and de-ionization process as part of the initial coolant fill. To control temperatures precisely, a 3 way flow control valve is used in place of a conventional automotive thermostat. The system operates at approximately 70°C (158°F) during normal operation.

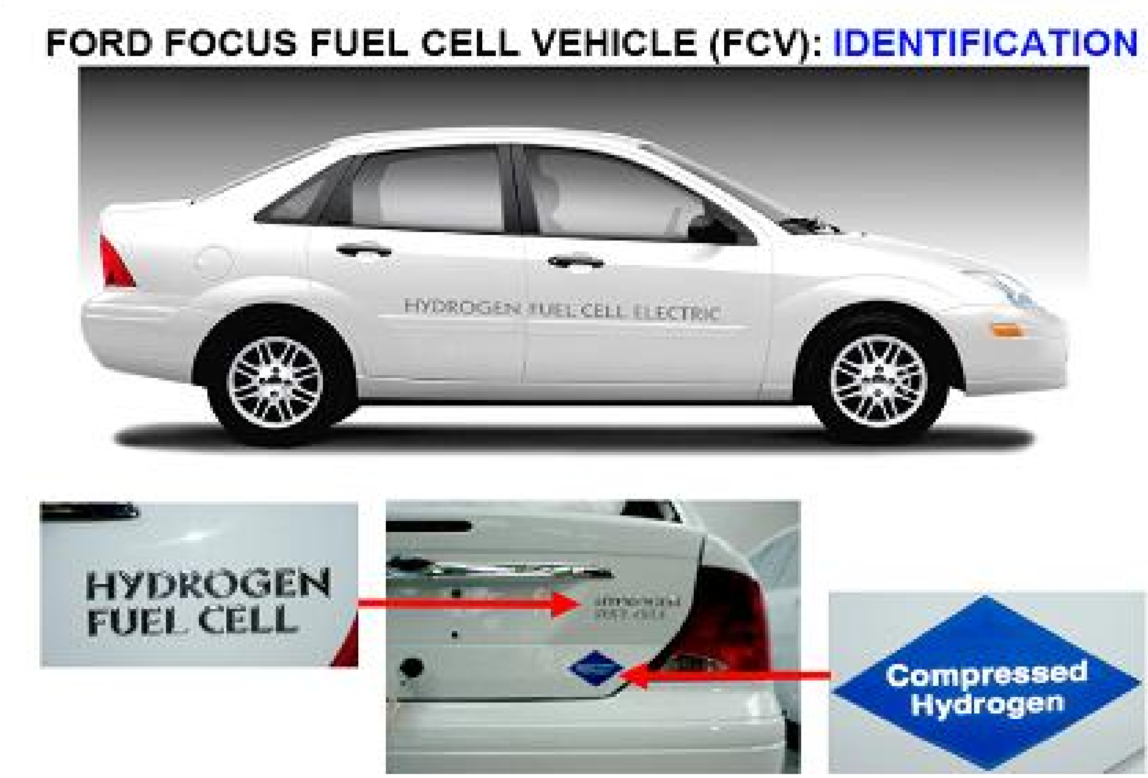
Low-Temperature (LT) Cooling System The low-temperature circuit cools the drive motor, power electronics, and one component of the fuel cell system. It uses conventional automotive coolant (50/50 mix of water and ethylene glycol) and operates between 25°-50°C (77°-122°F) during normal operation. This system utilizes a medium power low voltage electric water pump.

Each cooling system has its own coolant pump, radiator, degas bottle, and sensors. The two radiators are in series airflow with the LT radiator exit air feeding the inlet of the HT radiator. Two HV cooling fans, which utilize the same motor as that used on the HT loop

HV water pump, are utilized to provide additional cooling airflow to these radiators beyond that which ram air cooling can provide.

Vehicle Markings

The Ford Fuel cell Vehicle is clearly marked to ensure that emergency responders, and the general public are immediately aware that the vehicle is a hydrogen car. The markings are made in accordance with industry agreements as shown in this photo.



Vehicle Service & Inspections

In this section of the report, details of vehicle maintenance and repair are presented. Special service procedures for these FCVs were developed throughout this program. A complete list of those procedures is included for reference in Appendix 5 of this report. The following is the reporting order for this section on vehicle maintenance:

1. Standard Maintenance Schedule
2. Technician Repair Order System (TROS)
3. Fleet Maintenance Review
4. Component Part Replacements Review
5. Discussion of Principle Part Failures
6. Stack & Systems Module Repair Details
7. Maintenance & Repair Cost Discussion

Standard Maintenance Schedule

The standard maintenance procedures established for this fleet demonstration included routine service operations performed at 90-day intervals. The checks, inspections and schedule component replacements are summarized in the following table. The complex nature of the fuel cell system, coupled with the state of the technology, made the rather frequent maintenance a prudent approach to maintaining vehicle up-time for the customer.

Fuel Cell Electric Vehicle - Scheduled Care and Maintenance Guide

Item	Intervals				Responsibility	
	90 Days	6 Months	Annually		FC Service Facility	Customer
Check all lamps (including stop/turn signals)	X				X	
Check and fill windshield fluid	X				X	X
Inspect wiper blades	X				X	X
Check DI-Weg conductivity level	X				X	
Check and Set tire pressure (44psi)	X				X	X
Inspect tires for wear	X				X	
Lube door hinges and latches	X					
STM - Vent Compressor Air Filter (4E28-10B778-BA)	X				X	
Inspect and clean Filtration Screen (Air Inlet to Battery) Inspect and clean (Green) air filter element (Battery inlet tube)	X				X	
Inspect FC Air Intake Filter (YF1Z-9601-AB)	X				X	
Inspect IPT for Leaks, Inspect Axle shafts and CV boots.	X				X	
Inspect tie rod ends	X				X	
Inspect front struts	X				X	
Inspect Fuel Cell system module compressor and expander oil levels	X					
Inspect brake pads/rotors, brake lines.	X				X	
Inspect parking brake	X					
Inspect H2 tank and lines	X				X	
Perform 90 Day R-Mode on High Voltage Battery	X				X	
DI-Weg Filter (4E28-8B512-AC)		X			X	
DI tank inlet filter (4E28-10B779-DA)		X			X	
Ion Exchange Cartridge, filled (4E28-10B779-EA or FA)		X			X	
Rotate tires		X			X	
Particle Filter Assy (4E28-8B511-AB)			X		X	
Change Fuel Cell system module and expander oil (HSE 000 449 2390) or Nye lubricants No. 605			X		X	

Originator: Mark Olance/molance | Page 1 of 1 | Date Issued: 100404
C264 MaintenanceCare_Schedule_TROS ver 2-15-06.xls | Date Revised: 2/16/2006

Figure S1 Vehicle Maintenance Schedule

As experience was gained with the vehicle systems, some alternative practices were put in place. For example, the service team developed a procedure for replacing Ion Exchange Filter Media rather than installing a purchased filter, reducing cost from $1300 to around $75. An alternative rebuilding rather than replacing the $2388 3-Way High Temp Valve was also developed. This reduces part cost significantly although a new flat rate cost for the rebuild was not developed.

Technician Repair Order System (TROS)

As previously described, a program specific system was developed for capturing the maintenance and repair information for the demonstration fleet. This system known as TROS (Technician Repair Order system) was an 'in-house' development designed to capture the information desired by the DOE as well as that which would serve the informational needs of engineering management for both this demonstration and future product developments. TROS also provided weekly update reports to assist in the management of the fleet.

The following is a high-level bullet point summary of the DOE fleet maintenance data contained in the TROS file followed by a detailed review of the maintenance performed, and the components replaced. The review of the data is followed by a more in-depth discussion of the key problems associated with the hydrogen related vehicle systems and other systems that were influenced by the characteristic operation of the FCV. Here is the overview:

- Total TROS orders: 1362 tickets with 7728 operations. This means that 1362 repair order documents were written by service technicians, and most of these contained many work operations such as checks, inspections fluid fills etc.

- 52 unique part numbers (or sublet repairs) are contained in TROS that represent the replacement of 175 individual parts for the eighteen car fleet.

- Of the 7728 Regular Maintenance Operations Performed (Figure S2 below) 3547 could be considered to be normal vehicle maintenance and repairs not associated with the nature of the Fuel Cell or hydrogen storage systems. This would include such operations as checking tire pressure, checking or replacing light bulbs, checking or adding windshield washer fluids and routine items such as those that do not provide information about the Fuel Cell Vehicle concept.

- 4311 operations were performed that were directly associated with the fuel cell and hydrogen systems of the eighteen vehicle fleet. These Fuel Cell Vehicle specific operations are detailed in Figure S3 below.

- Cost of Service has been collected using flat rate labor and parts cost established at the beginning of the program. 4607 flat rate hours were assigned to the eighteen DOE vehicles. At the program labor rate of $95/hour, this would equate to $437,684 (per car assessments are presented later in this section).
- Parts costs were $365,783, Stack repairs were $165,070 and System Module Repairs were $886,747.

- Total cost of maintenance, parts, flat rate labor and sublet repair, was $1,855,239.

Fleet Maintenance Review

In all, 7728 maintenance operations were performed on the DOE fleet vehicles. This total included all aspects of vehicle maintenance, much of which would be seen in any vehicle, regardless of the power source. Checks, repairs and replacements of things like tires, windshield wipers and other components like those are normal maintenance items. Other operations such as DI Water checks and FCS oil checks are unique to the fuel cell power system. Figure S2 presents a breakdown of all maintenance operations:

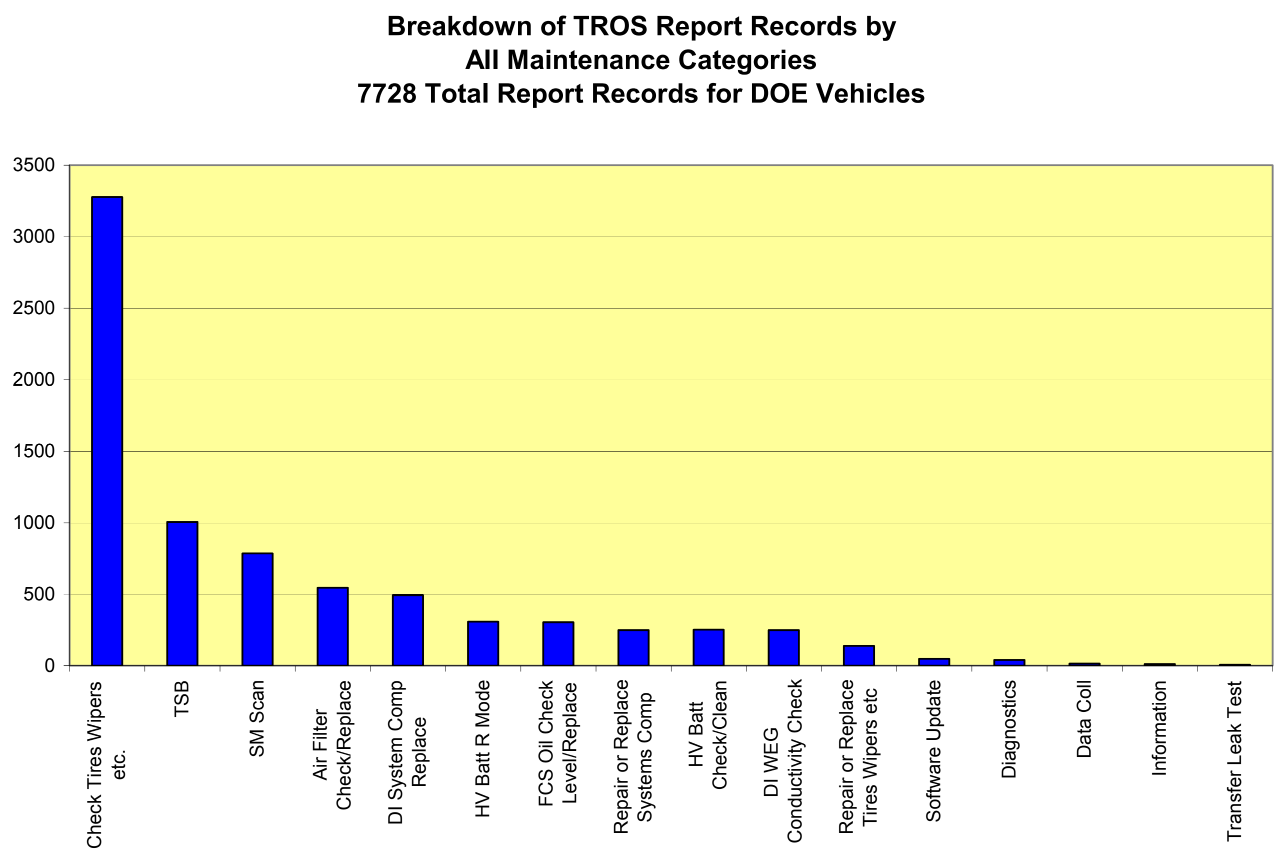


Figure S2 All Maintenance Operations Performed

For a more detailed explanation of what is contained in the largest categories, i.e. Check Tires, Wipers etc, the following provides the specific checks, replacements or work performed:

Check Tires, Wipers etc. (3278 Operations):
Check all lamps (Including turn signals)
Check and fill windshield fluid
Check and Set Tire Pressure
Inspect brake pads/rotors, brake lines
Inspect front struts
Inspect H2 Tank and lines
Inspect IPT for Leaks
Inspect parking brake
Inspect tie rod ends
Inspect tires for wear
Inspect wiper blades
Lube door hinges and latches
Rotate Tires

Replace (139 operations):
Axle seal
Axle shafts
Body Repair
Brakes
Charge HV or LV Battery
Fan motor
Ignition lock/ locks
Lights
PDA
Seats & Trim
Supplemental Heating System
Tire Pressure Monitor
Tires
Windshield
Windshield Wipers

Removing the above operations from the full maintenance record leaves 4311 operations directly related to the hydrogen and fuel cell systems of the cars. Figure S3 presents only those operations.

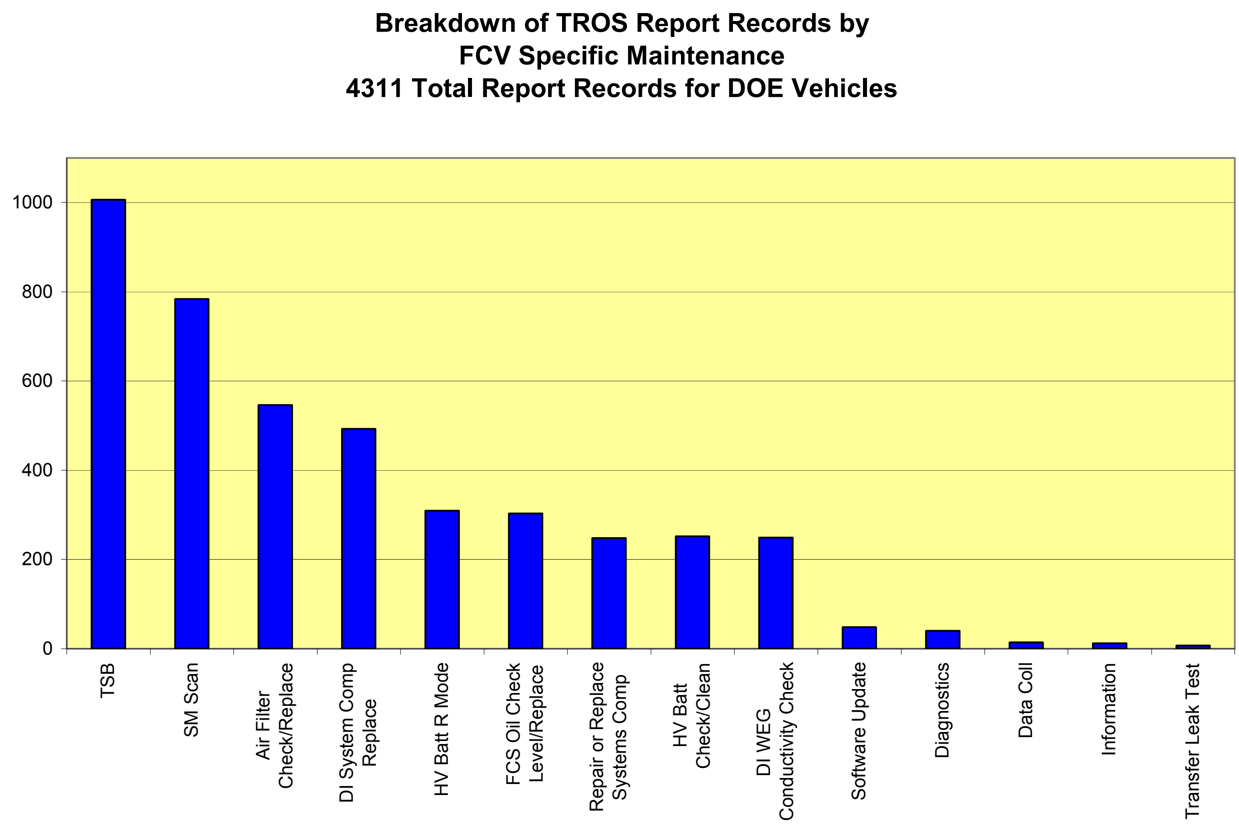


Figure S3 Fuel Cell Vehicle Specific Maintenance Operations Performed

The hours of work required to perform each category of maintenance is not proportionate to the number of operations performed. It is clear that the HV Battery R-Mode requires significantly more hours than other work categories. Figure S3A shows that relationship.

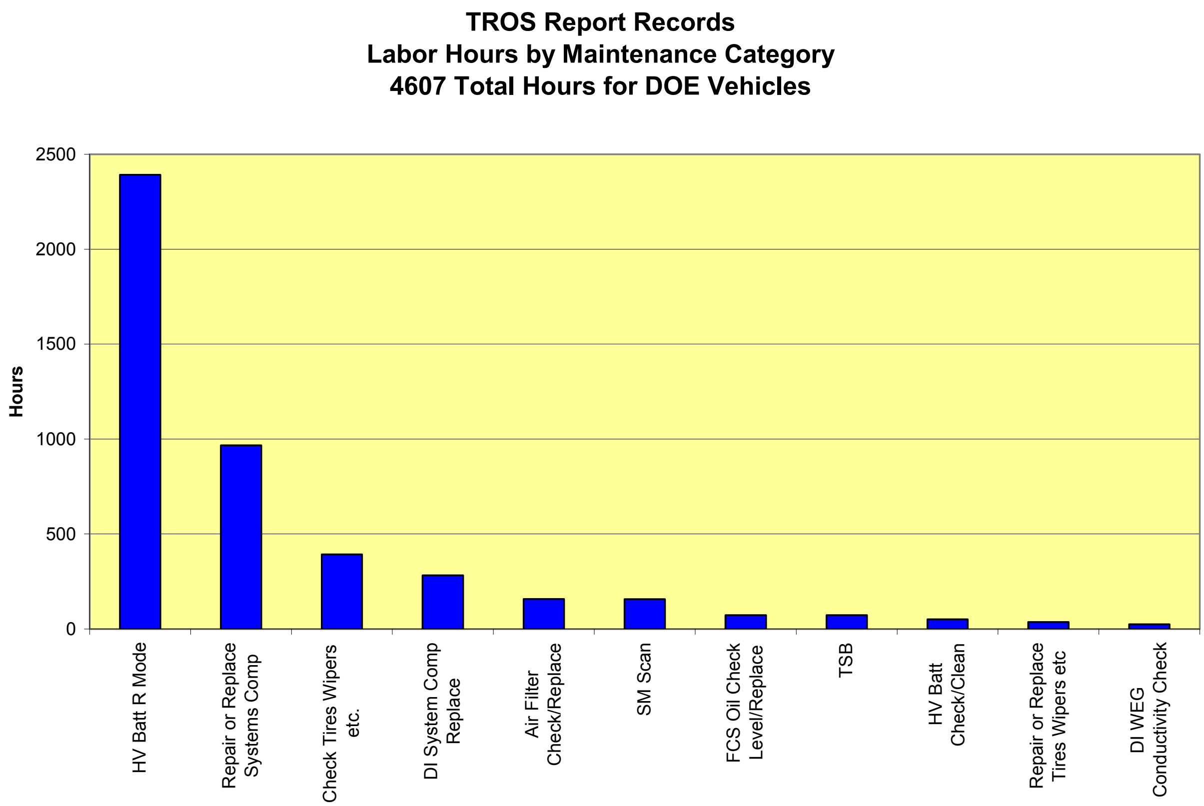


Figure S3A Labor Hours by Maintenance Category

As seen in these charts (Figure S3 & S3A), **Technical Service Bulletins (TSB)** represented the most frequently reported work performed on the FCVs (1006). In total, there were 60 TSBs written for this fleet demonstration covering a range of actions from interior trim problems to important software upgrades in the fuel cell controls. A complete list of these bulletins is presented in Appendix 6 of this report. TSB applications accounted for 21% of all FCV related service and maintenance operations, but only 72 hours (2%) of 4607 labor hours.

Service Monitor Scans were the next most frequent operations (784). These were performed for diagnosis of indicated operational problems. Data collection downloads were done outside of the operations recorded in TROS. The frequency of SM Scans is not unexpected or undesirable. The FCV utilizes a very complex computer operated system of controls. Understanding fault signals in the system can only be done through analysis of Diagnostic Trouble Codes (DTCs) which are stored in the Vehicle Network Gateway (VNG), and these data scans provided the learning events that this demonstration was designed to explore. Hours assigned to this operation were 157 or 3% of labor.

Routine maintenance checks were the most frequent event in the serving of the vehicles. These were generally the checking and replacement of system air filters (540), Fuel Cell System oil level checks and additions (300), High Voltage battery checks and clean (250) and De-ionized water conductivity checks (250). These represented 1340 operations or 32% of total maintenance records for the fleet.

The De-ionized (DI) water system servicing was primarily routine maintenance. In all, service and parts replacement operations totaled 494. Regular maintenance was performed on Ion Exchange Cartridges (127), DI tank inlet filters (127), DI-Weg Filters (127), and Particle Filter Assemblies (62). Total hours assigned to these operations were 283 or 6% of total labor.

DI Water Ethylene Glycol (DIWEG) conductivity checks were performed routinely and accounted for an additional 249 labor operations in the fleet accounting for only 25 hours or 1% of labor.

High Voltage Battery R-Mode (Reconditioning) is a procedure that resets the high voltage battery to optimum operating conditions. The data indicates this operation was performed 309 times in the eighteen-car fleet. As the vehicle operates and experiences a number of start/stop cycles, the state of battery charge is reduced from full power and the ability of the vehicle control systems to accurately recognize the state of charge and regulate re-charge current to the battery becomes imprecise. The R-Mode begins with a complete discharge of the HV battery pack (0% state of charge at 198 Volts) followed by a complete re-charge to a level slightly over the pack voltage to ensure that all cells are equally charged. Then the pack is completely discharged a second time. Finally, the battery is recharged to 60% of normal operating voltage, which establishes the desired state of charge for vehicle operation. This entire process requires four to six hours and is scheduled at 90-day intervals. Other R-modes may be conducted when significant systems problems have occurred.

Figure S3A shows that the R-Mode consumed 53% of total labor. This is because the cycle is long and requires periodic checking and interaction by the technician. It is possible to design the charging system to avoid the need for periodic reconditioning. This has been demonstrated in the current Ford Escape Hybrid. Elimination of this service would, by itself, represent a significant reduction in service requirements and increased availability to the vehicle owner.

Repair or Replace System Components was indicated in 248 records. This number includes all of the FCV specific system work including the hydrogen, high voltage and unique vehicle systems including IPT, brakes and others. Of these repairs, 101 or 41% were specifically identified with the hydrogen and fuel cell systems.

The other categories of repair and maintenance labor are generally self explanatory, and of much lower occurrence rates. These include Software Updates, Non-routine Data Collection, Diagnostic Activities, Non-routine Transfer leak tests and informational submissions. For each of these categories, there were no labor hours assigned, indicating that the work was performed as a part of other operations.

Each of the TROS records identified the principle component that was the focus of the repair operation. However, there are other components that were replaced either as a part of the defined repair process or required because of collateral issues related to the primary problem. For this reason, a different study of replaced components is useful.

Component Part Replacements Review

In the above discussion of maintenance and repair, line items document the replacement of specific components of the vehicle. The following series of plots present some detail to explain what those components were. Following a review of over-all parts replacement, a series of plots are presented that show component part replacements within each vehicle sub-system; Fuel Cell Stack, Fuel Cell Systems Module etc. Some commentary is provided for each of these subsystems. Finally, each of the most significant repairs and replacements is discussed in detail to provide an understanding of the root causes of the problems with the component and what corrective action has been developed for application in future versions of the fuel cell vehicle.

The following chart (Figure S4) identifies the component parts that are contained in the TROS records (excluding fluids) that had four or more incidents of replacements in the eighteen-car DOE fleet.

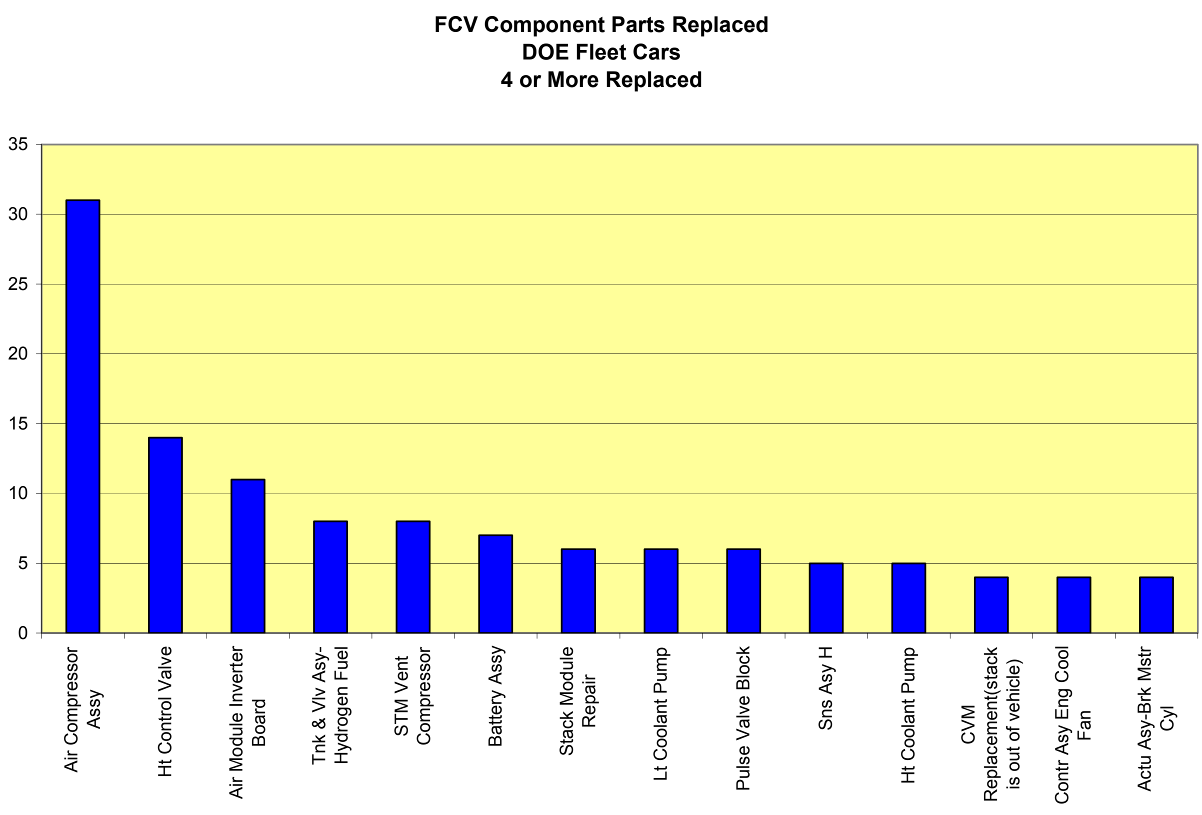


Figure S4 Fuel Cell Vehicle Component Parts Replaced

(Four or more replacements only shown)

In addition to the parts shown in the above plot, the following are components that were only infrequently replaced during the demonstration period in the eighteen-vehicle fleet:

Two each of the following parts were replaced:

- Air Humidifier Nozzle
- Air Module Motor Inverter
- Fuel Cell Monitor
- Hydrogen Pressure Regulating Valve
- Shaft & Joint Assembly-Front Wheel Drive

Only one of each of the following was replaced:

- Anode Air Purge Valve Block
- Back Pressure Regulating Valve
- Brake Assembly-Wheel
- Converter Assembly-Volt Dc-Dc
- DI Re-circulation Filter
- DI Tank 3-way Valve
- DI Tank Level Sensor
- Element Assembly -Cool Heater
- Energy Management Module
- Full Front Floor Carpet
- H2 Humidifier Nozzle
- H2 Isolation Valve
- Hose Fuel Cell Vent
- INTERGRATED POWERTRAIN ASSY
- Lamp Assembly -Front Turn Signal
- Mod Assembly Tire Press Monitor
- Multi Stage Ejector - Jet Pump
- Solenoid Assembly -Fuel Shut Off Valve
- Stack H2 Outlet Pressure Element
- Stack Module Enclosure Replacement
- System Module
- System Module Area Flammable Gas Detector - 1
- Tube Assembly -Fuel Tank Inlet
- Valve Assembly Fuel Fill
- Water Dosing Pump

Focusing on the various sub-systems of the vehicles, the following charts present the component replacements within each subsystem of the vehicle, beginning with the Fuel Cell related sub-systems, hydrogen system and finally the non-FCV sub-systems.

In Figure S5 the Fuel Cell Stack and Fuel Cell Thermal Systems are delineated. The figure shows that only six stack modules were repaired during the demonstration. None of these were complete re-cores of the stack. Only cells that were malfunctioning were replaced, minimizing the cost of repair and providing further experience with the cells that accumulated higher operating hours.

Four Cell Voltage Monitors (CVM) required replacement independent of cell repairs, and one stack enclosure was repaired because of physical damage that occurred during servicing.

Thermal Systems repairs were most commonly associated with control valves and pumps in both the high and low temperature systems. The details of these problems are presented in the discussion section following these component breakdown plots.

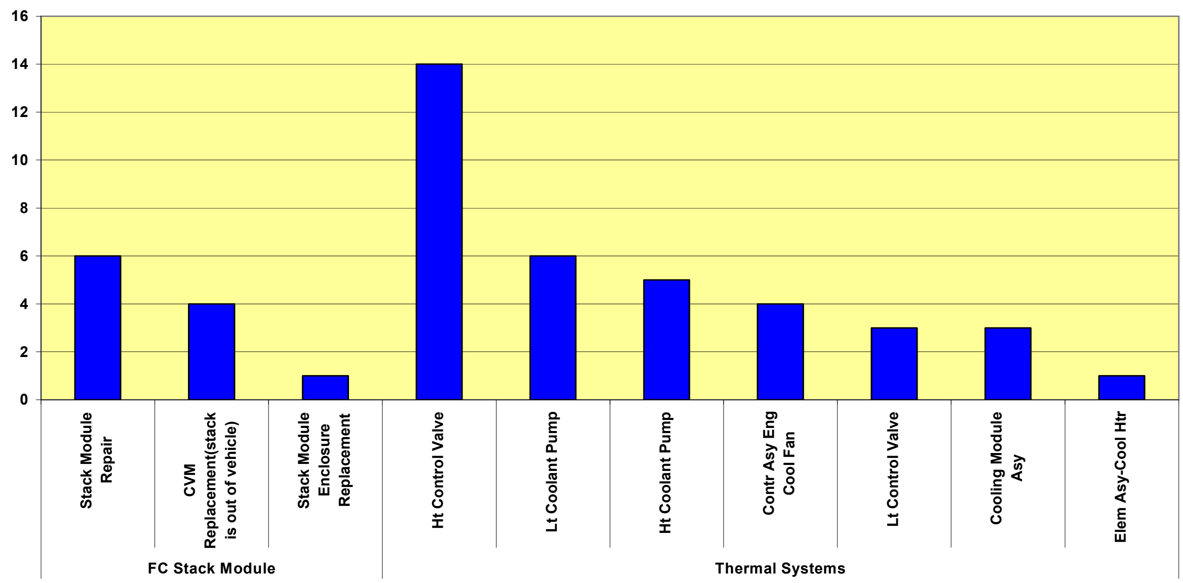


Figure S5 Fuel Cell Stack and Thermal Systems Component Replacements

Figure S6 below shows the components of the Fuel Cell Systems Module that were replaced. In the Air System, two components are obvious problem areas: air compressors and air module Inverter Boards. The air compressor provides pressurized, humidified air to the stack. The support bearing seal design was not adequate leading to water ingestion into the bearings resulting in premature failure. The Inverter board issue was related to the board manufacturing process. The details of these problems are also presented in the discussion section following these component breakdown plots.

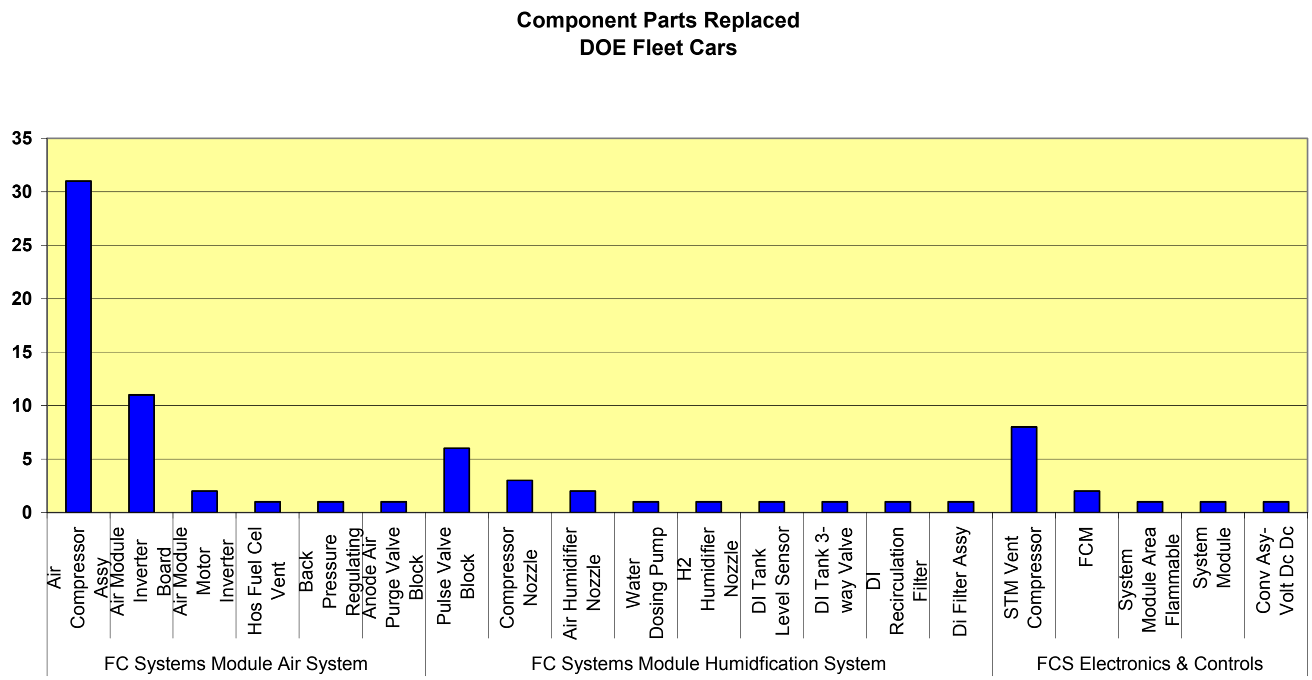


Figure S6 Fuel Cell Systems Component Replacements

Figure S7 below shows the components of the Battery & Hydrogen Storage Systems of the vehicles. The principle battery issue was associated with the low voltage Starting, Lights & Ignition (SLI) battery which, in some locations was not large enough to keep the low voltage systems operating. This was corrected by installing a larger automotive type 12 V Battery replacing the original smaller size, an ATV/Motorcycle sized battery. Only five batteries of the eighteen cars were upgraded. Of these, four were California cars and one was in Florida.

The Hydrogen Tank replacements were the result of an initial build issue. An improper bolt/torque was used and there was concern about fuel tank integrity. All tanks were checked and eight of the eighteen DOE cars were changed out.

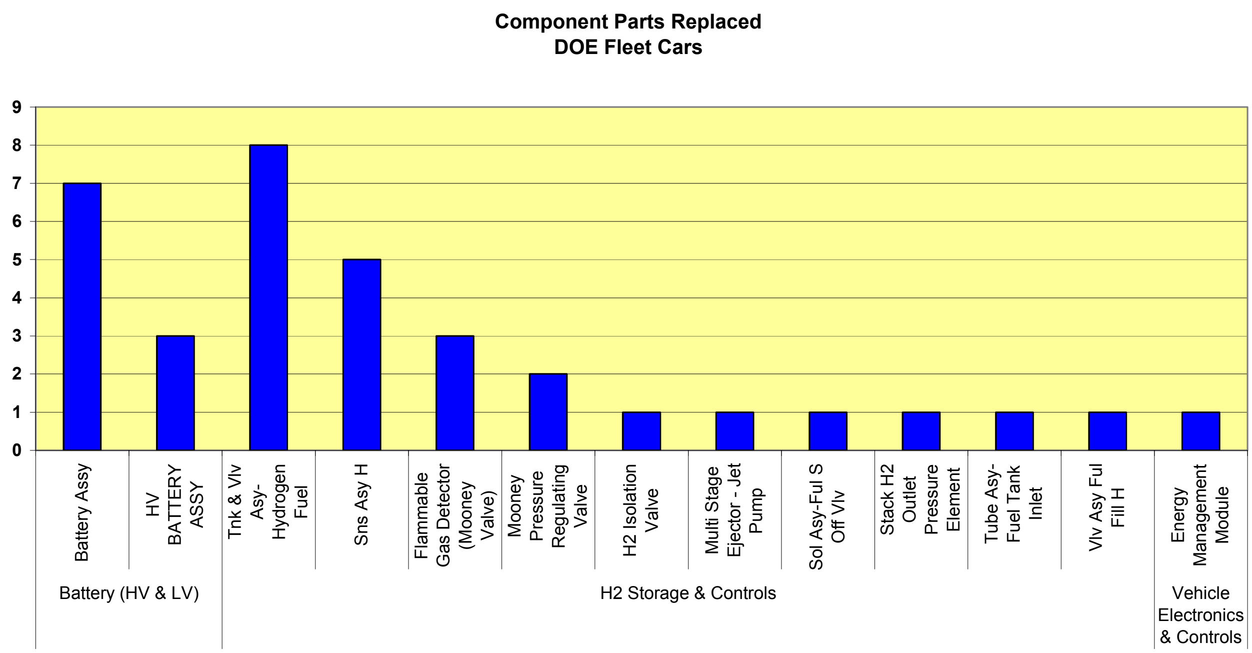


Figure S7 Battery, Hydrogen Storage & Vehicle Electronics Component Replacements

For the non Fuel Cell Vehicle related sub-systems (Figure S8), there were no significant replacement activities. A problem with Constant Velocity Joint and Shaft assemblies was experienced in the larger fleet. This problem resulted in clicking noise emanating from the axle shaft spline-to-hub interface caused by a rapid wearing of the spline. In some cases the shaft broke. The rapid wear was caused by relatively higher torques from the electric motor drive system than the shaft was designed for in the gasoline engine version of the Focus model.

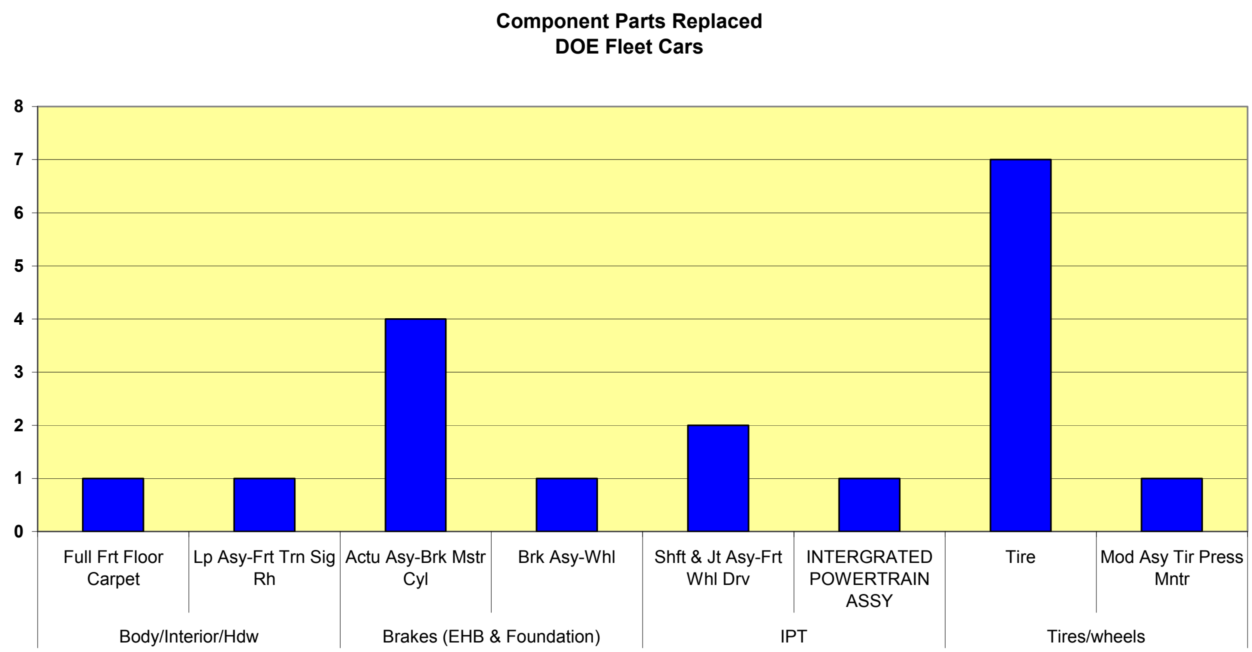


Figure S8 Other Vehicle Systems Component Replacements

Discussion of Principle Hydrogen System Part Failures

Air Compressor

The purpose of this device is to provide pressurized air to the cathode of the fuel cell stack.

A critical concern for the air that is pumped through the stack is the moisture content. The membranes in the stack operate best and have longest life if the relative humidity in the stack is held an optimal humidification value. Improper humidity control can lead to rapid deterioration of the cell membrane, which in turn permits hydrogen gas to pass through the membranes in a physical failure.

To ensure proper relative humidity, a humidification system is built into the systems module to mix DI water into the air (as well as into the hydrogen). In the Mark 902 system, some of the DI water is injected into the compressor to be pressurized and humidify the air stream ahead of the humidifier. In this fleet, after 25-30,000 miles of operation, compressors began to fail as evidenced by excessive noise followed by catastrophic failure of the compressor screw elements caused by contact between the rotating screws. Contact was permitted when the screw support bearing adjacent to the air inlet failed, permitting the screws to move out of designed position.

The root cause of the bearing failure was water ingestion into the bearing. This support element, a single row deep groove ball bearing, is a sealed, permanently lubricated design. The lubricant selected was to be tolerant of low levels of moisture but the selected seal was ineffective in providing protection from water ingestion, causing the lubricant to fail followed rapidly by rusting and spalling of the rolling contact surfaces of the balls and races.

The three other bearings that support the screws did not exhibit the same degree of degradation and failure. From this experience, it is now understood that water injection into the compressor as well as the compressor bearing seal selection are critical elements of the design.

In the newest system designs, this problem is avoided all together by the elimination of water injection at the compressor. In newer systems, moisturizing takes place after the air is compressed.

HT Control Valve

These valves exhibited two unrelated problems; one with an internal controller circuit board and one with drive gears.

Early in the program, circuit board failures were identified. These early failures were caused by water intrusion. This valve is located where road splash can wash over the valve. The joints in the pump were not sealed sufficiently to keep out the environmental water, permitting ingress and subsequent board corrosion and failure. Applying a silicone seal material to all external seams of the pump rectified this and stopped further occurrences of this failure mode.

A more common failure was a breaking of the drive gear teeth within the valve. The largest of the four gears was the element that failed. The tooth design was not robust, but because of the low volume of valves produced for this program, the practical solution was to rebuild the pump gear train with replacement parts. Recurrence of the problem will be avoided because this information has been included in the DVP&R and in an updated FMEA for this type of valve.

Hydrogen Storage Tanks

Some concern was raised about fuel tank integrity when a wrong size bolt was used during the assembly operation. Checks were made on all tanks, and a Technical Service Bulletin (TSB 06-08-02) was issued for all fleet cars. The bulletin instructed technicians to collect and submit specific information prior to any tank repair or replacement.

Subsequently, eight tanks were changed out (fifteen in the larger fleet), either because of unrelated valve concerns or concern about the original installation. In no event did the tank issue present a safety concern for the operators or technicians. All replacements were made to ensure a complete understanding of the tank system.

Air Module Inverter Board

The Air Module Inverter board is a component of the electronic control system in the systems module. The problems identified in early failures of this board were the result of a manufacturing process that lacked proper cleaning during the circuit board fabrication, leaving components susceptible to oxidization and eventual failure.

The correction took place with two replacement versions of the boards. The first version was a carefully produced replacement board, but not one made with the desired shielding during processing. The second version was made with all desired controls.

After replacement, neither version of board experienced subsequent or repeat failures. The correction of the process is thought to be a proper solution to avoiding this type of problem in future designs.

Low Temperature Coolant Pump

Problems that were experienced with these pump assemblies were related to both assembly issues and operational damage. Early in the program, leaks between metal motor housing and plastic exhaust stack housing occurred. The cause was either:

- Plastic housing cracked due to possible over-torque of mounting bolts and/or impact on curb during parking maneuvers.
- Gasket rolled out of place during assembly process (early failure fixed while still in the plant).

Early in the demonstration, Low-Temp pump wiring damage was identified caused by abrasion. A Technical Service Bulletin (TSB 05-05-03) was written to preclude continued failures.

High Temperature Coolant Pump

High temperature pumps experienced failure related to two causes. Leaks between the metal motor housing and metal exhaust stack housing were caused by inadequate sealant at the time of assembly and/or occurred later due to contaminants in the coolant loop. The other failure mode was pump rotor lock-up due to long periods of non-use (usually more than one week). The rotor would lock in place and require disassembly/re-assembly to free it. Some units were replaced in the field due to this before it was determined that simply disassembling could rectify the problem.

Non-Hydrogen System Failures

Low Voltage Battery

After the fleet was deployed, some instances of SLI (low voltage) battery failure occurred. This was most prevalent in vehicles that were operated in California. The result of the low battery condition is that the fuel cell system could not be started.

The original SLI battery was a small size, similar to a motorcycle battery, since the demand on this battery was expected to be very small once the vehicle was started. Only seven of the eighteen DOE fleet (14 of the 30 car fleet) batteries were involved during the 48-month demonstration drive period.

The correction for this failure, when it happened, was the installation of a larger, automotive battery. This change required the replacement of the battery mounting tray and hardware. No additional changes were necessary.

CV Joint & shaft

In some vehicles, the front outer CV joints could exhibit a clicking sound during drives. Investigation identified excessive wear on the internal splined surfaces of the outer CV joint and on the outside of the mating splined shaft.

Assessment by the supplier of the component identified a sizing problem that was the result of a misunderstanding of the maximum expected torque loads on the shaft. The FCV version is significantly heavier than the internal combustion engine version of the vehicle. In the design of the shaft assembly, in an effort to use available components to avoid very high cost special part manufacturing, it was judged that the production ICE sized (high volume production) version would be capable of the expected torques in the drive train. Although the CV joint itself was in fact capable of transmitting the toques, the supporting shafts did not stand up to the higher torques.

The higher torque was related to two factors: 1) heavier vehicle and 2) high starting torques of the electric motor drive.

With this understanding, it is very feasible to design a driveshaft that will meet all of the design requirements in future FC vehicles. This is not considered a serious problem for the implementation of FC drivetrains.

Tires

The Ford Focus FCV was originally designed with special low rolling resistance tires to optimize the fuel economy of the vehicle. These special tires did make a contribution, but also exhibited wear characteristics that were unacceptable.

As a result, when tire replacements became necessary, a standard production tire was used. No identifiable effect on fuel economy could be seen in vehicle data when these changes were made.

Other investigations

High Voltage Battery State of Charge

The hybrid fuel cell and battery system presents technical challenges, one of which is developing systems that can accurately measure the state of charge (SOC) of the high voltage battery. In the fuel cell car, over time the nickel metal hydride voltage can drop to levels that are too low to support the start-up and drive system of the car. Although the fuel cell charges the high voltage battery, it must know what the state of charge is to set a charge rate. This SOC identification deteriorates over time requiring a periodic battery reconditioning. This is normally done at 90-day intervals and the vehicles perform satisfactorily.

Under driving conditions that include heavy use of the defrost system (such as in cold environments with high humidity) the error in estimating actual SOC increases. This leads to long periods of high frequency current modulation due to the PWM character of the WEG heater. Under these conditions the current integration algorithm causes higher levels of error in SOC estimation.

When the drive cycle is predominantly urban driving, faster transitions to high error states occur, faster than the expected 90-day cycle. Investigation of the data indicated that the anticipated average event timing in the range of 1 second when in these drive cycles the actual measured event timing was approximately 100 ms. This variance has a major impact on the estimated efficiency of charge acceptance. Subsequent lab testing demonstrated that charge acceptance is much lower during short duration charge events regardless of current level.

Fleet data analysis demonstrated that the error was limited to regions where the combinations of the two issues (urban driving, especially with hilly terrain, and in high humidity) were dominant. For example the California fleet showed high accuracy over the 90 day period whereas vehicles operating around Vancouver, Canada did not.

Corrective actions for the demonstration fleet were developed using modification of the operating software. A proprietary algorithm, which corrects SOC estimation error during vehicle shutdown, was developed. The algorithm allows the battery to evaluate energy content under known and stable conditions. It also allowed for greater correction than was originally envisioned. This involved some risk. There is some difficulty in ensuring accuracy over the entire temperature range and over the full life of the battery. Because of the duration of this demonstration, there was not sufficient opportunity to fully calibrate the algorithm. As a result, the change was limited to areas where SOC inaccuracy was demonstrated to be an issue.

This was valuable learning for application to future designs that use a wide SOC range (not as useful in a traditional hybrid). As a point of interest, Ford has used a very similar approach in the Southern California Edison Plug-in Hybrid Electric Vehicle fleet and it has been very successful.

Stack Warming Blankets

Stack warming blankets were used in some cold climate applications. This was a simple step to extend the range of temperatures in which the cars could be used by installing an electrically powered heating pad under the stack. The pad was plugged into a120V current source to supply heat to the stack. This was only used in over-night storage situations where temperatures were expected to be near freezing and where the vehicles were parked in an unheated facility or area. This approach was effective in the few vehicles in which it was used.

False H2 Sensor signals: humidity related

All five vehicles in Florida reported a hydrogen (H2) high-level alarm from the vehicle gas sensor at the climate control location. The vehicle's Energy Management Module (EMM) will set a high-level alarm if the hydrogen output from any vehicle gas sensor is greater than 1.5%. If the level is above 1.5% when a vehicle start is attempted, the EMM will prevent the vehicle from being started and set a service reset.

The alarm occurs only after the first start of the day after an over-night rain and high humidity. It was determined that no hydrogen was present after a detailed investigation at the customer site. The investigation utilized multiple redundant vehicle and handheld gas sensor devices. Therefore, the alarm was determined to be a false-positive issue within the gas sensor.

The false positive occurred due to water condensation on the internal sensor detection circuit, which caused a delay in the sensor providing the correct reading. The internal sensor detection circuit consists of two elements, a Detecting Element and a Compensating Element.

When both of Detecting Element and Compensating Element have water condensation on them before turning on the power, the Detecting Element is faster to dry out the water condensation than Compensating Element because, the catalyzer on the Detecting Element is porous material, and it has more area to vaporize water condensation than Compensation Element. If the Detecting Element is dried out faster than Compensation Element, it makes the resistance difference between Detection Element and Compensation Element produce a signal, which it what happens when H2 is present. This is reason why the H2 sensor gives false-positive output when it gets water condensation.

The climate control vehicle sensor is located under hood and is directly exposed to the humidity and environmental effects. The other vehicle hydrogen sensors are located within the vehicle and are not directly exposed to external environment. The climate control sensor is positioned within the drain trough for the front windshield. It was observed for all of the occurrences that the dew point temperature was within a few degrees of the ambient temperature, which supports the condensation explanation.

After review of the vehicle data and the supplier test lab data, a permanent corrective action to change the warm-up time to 10 seconds was implemented in the software. To prevent reoccurrence, the H2 Sensor FMEA was updated to account for water condensation while the sensor is not operating. Also, water condensation warm-up testing was added to H2 sensor DVP&R.

Stack & Systems Module Repair Details

Stack Issues and Repairs (Ballard)

Although there were some stack repairs performed during the demonstration, the overall performance of the stacks exceeded the original expectations. A target assumption for the program was 1500 hours of vehicle operation. Based on high mileage durability testing conducted on earlier versions of the Focus FCV with the Ballard Mark 902 stack and predicated on an assumption that a 10% reduction in stack power would constitute unacceptable performance for drivers, it was expected that stack refurbishment would be required after around 500 hours of operation. Refurbishment generally would consist of a re-core replacement of all of the cell rows in the stack. Allowances were made for one stack re-core during the demonstration period.

However, as the vehicles accumulated operating hours, driver reaction was different than expected. The fuel cell stacks did experience power degradation over time, but it appears that the hybrid stack/battery concept employed in the cars assisted any reduction of fuel cell power. The battery was able to provide necessary power to accelerate the vehicles so that the driver did not recognize the reduction in stack power. Although top speed may have been reduced, the vehicles were not driven in duty cycles that demanded frequent high speeds, reducing the effects of the stack power reduction.

Stacks were exchanged at different times for a variety of reasons during the demonstration, but within the DOE fleet, there was little movement. In all, 19 different stacks were used during the demonstration. On four stacks, there were no repairs. A total of 23 repairs were made on 16 stacks. Excluded from this list are 8 Stack Module Vent Compressors replacements. These are mechanical items outside the stack and are removed to show the true stack issues. Ballard performed six complex stack repairs. Changes to stack design resulting from this demonstration are highlighted later in this review. The following chart (Figure S9) summarizes all of the repairs associated with the stacks in the DOE fleet cars presented in vehicle number order:

Vehicle	Stack No.	Type of Service to Stack
2	3508	CVM
		Stack Enclosure & Repair
		Vent Compressor
3	3330	None
9	3551	Stack 4 cell replace
10	3563	CVM Stack
11	3356	None
12	3334	Stack Repair
	3536	Stack Repair two cell rows
13	3537	CVM Replace #2
		H2 Sensor
16	3347	Stack Water Mainfold Leak
17	3332	None
18	3354	Stack #1 CVM
19	3554	None
20	3497	CVM Board Assm.
21	3499	None
22	3331	AM Inverter Board
23	3322	Stack, water
24	3568	Stack Change
25	3560	STMo H2 sensor
26	3801	H2 Sensor
		Stack Coolant to Air leak

Figure S9 Fuel Cell Stack Repair Summary: By Vehicle

In the 18 vehicle fleet, 7 used the same stack throughout the demonstration. These are shown below:

Vehicle	Stack No.	Total Stack Miles
11	3356	35264
13	3537	44177
18	3354	47817
19	3554	47058
21	3499	32719
24	3568	46222
26	3801	30975

Figure S9A provides a summary of the cost for the above repairs, which totaled $184,964. Ballard technicians completed nearly all of this repair work. However, in the later months of operation, some Ford technicians assisted in repair operations. Here is the cost summary:

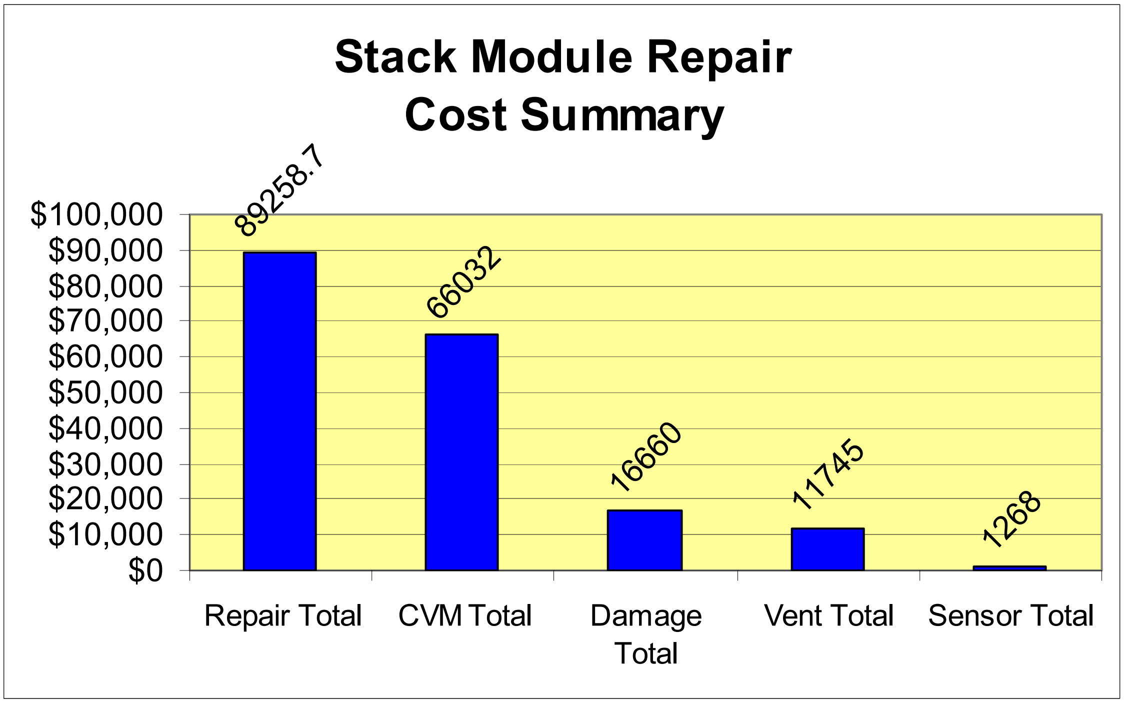


Figure S9A Fuel Cell Stack Repair Cost

Systems Issues (NuCellSys)

Systems modules, a complex assembly of mechanical and electronic controls, required the most service and attention during the fleet demonstration. In the eighteen car DOE fleet, 30 different system modules were used. These 30 modules were rotated between vehicles to return vehicles to customers as quickly as possible when repairs were required. Some of these modules were originally installed in non-DOE program vehicles, and all were used as "refurbished" parts from Ford inventory when required. In total, 87 system module repairs were made during the demonstration.

Chart (Figure S10) provides a breakdown of the number of repairs performed on each of the 30 systems modules:

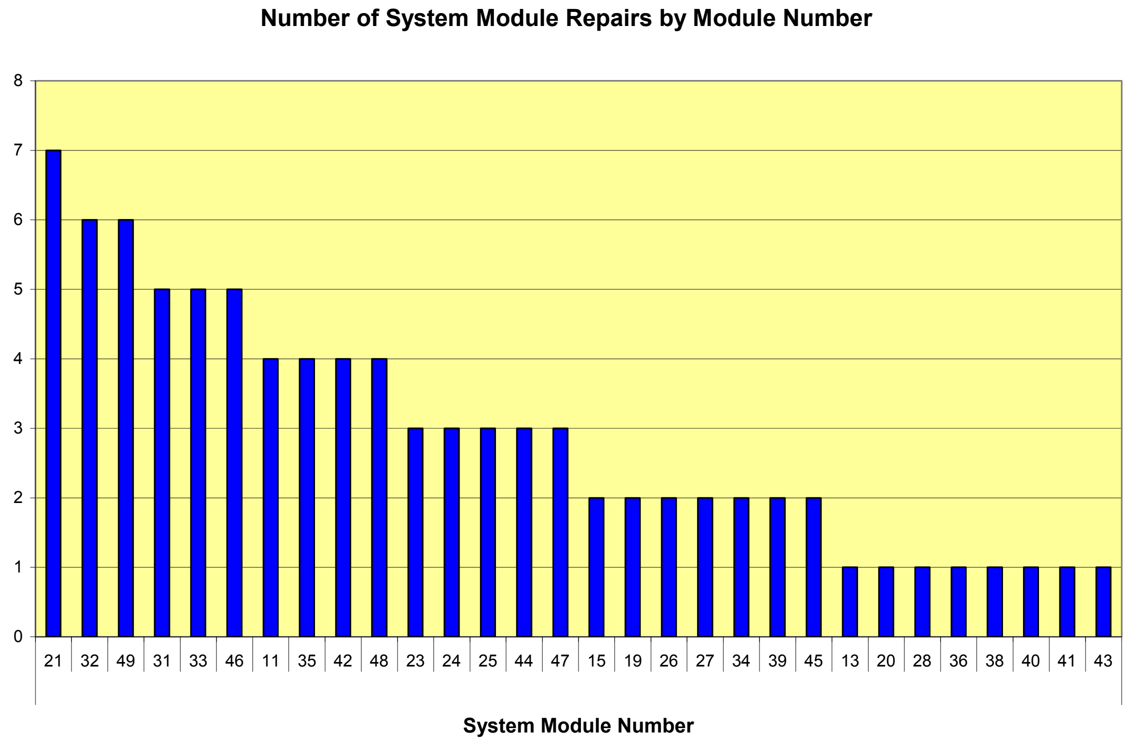


Figure S10 Number of System Module Repairs: By Module Number

The repair data is presented in detail by system module in the following table (Figure S11):

Systems Module	Root Cause
11	Aux Drv Control Board
11	Air Compressor
11	DI Water Pump
11	Air Compressor & Control Board
13	Air module motor inverter
15	H2 Leak- repaired locally
15	Air Compressor
19	Pulse Valve Plugged Nozzle
19	Air Compressor Air Compressor Noisey
20	Nozzle block
21	Plugged nozzle
21	HT Control Valve
21	Plugged nozzle
21	Plugged Nozzle & Purge Valve
21	Plugged Nozzle Pulse Valve
21	Auxdrive (ongoing)
21	Air Compressor
23	Sys Mod
23	DI Filter plugged
23	Air Compressor
24	Air Compressor
24	Blocked Nozzle
24	Air Compressor & AM Comms board
25	Air Compressor & Aux Drive Mtr
25	Air module motor inverter, Air Valve
25	Anode air purge valve
26	Air Compressor
26	Pressure Reg Valve
27	Air Compressor
27	Comms Board
28	Plugged Nozzle Pulse Valve
31	Air Compressor Air Mod & Anode Line Leak
31	Contamination
31	Pluged Nozzle
31	Nozzle Repair
31	Air Compressor & Control Board
32	Air Compressor Compressor Noise/Failure
32	Air module motor inverter
32	Air Compressor
32	Air Compressor
32	DI Hose burst
32	Air Compressor Sys Mod

Systems Module	Root Cause
33	AM Board
33	H2 sensor
33	Air Compressor & Bus Bar Board
33	Water Injector Valve
33	Sys Mod
34	Blocked Nozzle
34	TPMS Module
35	DI Water Leak
35	Plugged nozzle
35	DI Pump Leak
35	Plugged Compressor Nozzle
36	Air Compressor AM Noisey
38	Air Compressor
39	Air Compressor
39	Humidifier Sensor
40	Air Compressor Air Mod Siezed
41	Air module motor inverter
42	Comms Board & plugged
42	DI Tank three way valve YV 3000
42	HVEC Sensors
42	Air Compressor
43	Compressor Local repair
44	HV Battery Pack
44	Air Compressor
44	Air Compressor Air Mod Noisey
45	Air module motor inverter
45	Air Compressor
46	DI System
46	HT Pump
46	Air Compressor
46	Air Compressor & Air module motor inverter
46	HT Pump
47	Air module motor inverter
47	Mooney Valve
47	Jet Pump
48	Air module motor inverter
48	Air Compressor & Bus Bar Board
48	HT Pump
48	Plugged nozzle
49	Air Compressor repair & Belt failure
49	HT Pump
49	Air Compressor
49	Expander Control Valve
49	Jet Pump
49	Air Compressor

Figure S11 Detailed System Module Repairs: By Module Number

The following table (Figure S12) summarizes all of these repairs <u>by vehicle</u>:

Vehicle	Systems Module	Root Cause
2	31	Air Compressor Air Mod & Anode Line Leak
	44	HV Battery Pack
		Air Compressor
		Air Compressor Air Mod Noisey
3	42	Comms Board & plugged
	20	Nozzle block
9	15	H2 Leak- repaired locally
		Air Compressor
	19	Pulse Valve Plugged Nozzle
	27	Air Compressor
	39	Air Compressor
10	35	DI Water Leak
		Plugged nozzle
	47	Air module motor inverter
	48	Air module motor inverter
		Air Compressor & Bus Bar Board
	45	Air module motor inverter
11	21	Plugged nozzle
	11	Aux Drv Control Board
	25	Air Compressor & Aux Drive Mtr
	42	DI Tank three way valve YV 3000
		HVEC Sensors
12	32	Air Compressor Compressor Noise/Failure
	33	AM Board
		H2 sensor
		Air Compressor & Bus Bar Board
		Water Injector Valve
	25	Air module motor inverter, Air Valve
		Anode air purge valve
13	19	Air Compressor Air Compressor Noisey
	36	Air Compressor AM Noisey
16	32	Air module motor inverter
	42	Air Compressor
	26	Air Compressor
	39	Humidifier Sensor
	28	Plugged Nozzle Pulse Valve
	38	Air Compressor
17	21	HT Control Valve
		Plugged nozzle
	32	Air Compressor
	11	Air Compressor
	24	Air Compressor
	34	Blocked Nozzle
		TPMS Module

Vehicle	Systems Module	Root Cause
18	31	Contamination
		Pluged Nozzle
	24	Blocked Nozzle
		Air Compressor & AM Comms board
19	31	Nozzle Repair
	46	DI System
		HT Pump
		Air Compressor
		Air Compressor & Air module motor inverter
	26	Pressure Reg Valve
20	49	Air Compressor repair & Belt failure
	31	Air Compressor & Control Board
	33	Sys Mod
	23	Sys Mod
	48	HT Pump
		Plugged nozzle
21	21	Plugged Nozzle & Purge Valve
		Plugged Nozzle Pulse Valve
	32	Air Compressor
	35	DI Pump Leak
	27	Comms Board
	41	Air module motor inverter
22	21	Auxdrive (ongoing)
		Air Compressor
	49	HT Pump
		Air Compressor
	40	Air Compressor Air Mod Siezed
23	32	DI Hose burst
	35	Plugged Compressor Nozzle
	23	DI Filter plugged
	47	Mooney Valve
	43	Compressor Local repair
24	49	Expander Control Valve
		Jet Pump
		Air Compressor
	11	DI Water Pump
	23	Air Compressor
	45	Air Compressor
	13	Air module motor inverter
25	32	Air Compressor Sys Mod
	11	Air Compressor & Control Board
26	46	HT Pump
	47	Jet Pump

Figure S12 System Module Repairs: By Vehicle

Finally, the breakdown of the $865,504 cost by major categories of repair is shown in Figure S13:

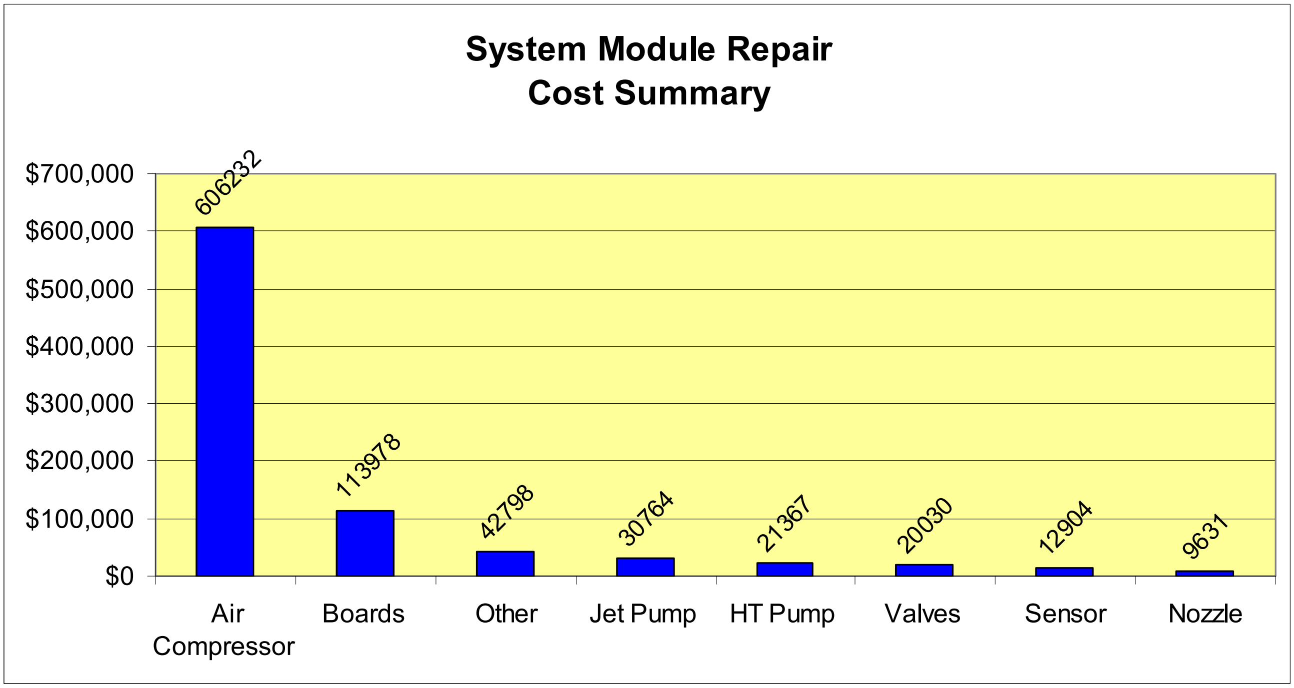


Figure S13 Cost Summary of System Module Repairs by Major Category

Maintenance & Repair Cost Discussion

Cost of Service has been collected using flat rate labor and parts cost established at the beginning of the program. These costs are indicative of the cost associated with the operation of the fleet, but cannot be considered exact. For example, for a given problem, flat rate labor may allow a certain number of hours to complete the repair, but in reality, the diagnosis procedure may have taken many more hours, just owing to the newness of the technologies being used. The building of an experience base on which to improve vehicle diagnostics and repair was a significant accomplishment in this demonstration. It is anticipated that, although future FCV designs will differ from these cars, some of the learning will carry forward to the next generation of vehicles.

With the above discussion about the relative value of the cost information, here are the highlights of the maintenance costs recorded in TROS:

- 4607 flat rate hours were assigned to the eighteen DOE vehicles.
- At the program labor rate of $95/hour, this would be $437,684.
- On a per vehicle basis, this is $24,316/vehicle.
- Cost of all parts $357,228.
- Sub-let services: System Module repairs were $865,504
- Sub-let services: Stack repairs were $184,964.

Total maintenance and repair cost as summarized above was $1,845,380 or $102,521 per vehicle, or $25,630 /year/car. The breakdown of this cost on an annual cost per car basis is summarized in Figure S14:

	Cost/Car/Yr
H2 & Fuel Cell Repair	$19,633
H2 & Fuel Cell Maintenance	$5,070
Non Fuel Cell Related	$928
Grand Total	$25,630

Figure S14 Cost per Car per Year

Charted labor cost by maintenance category provides an important understanding of the relative costs of the operations detailed earlier. Although some operations occurred frequently, their cost was low compared to the major cost elements. Figure S15 provides this analysis:

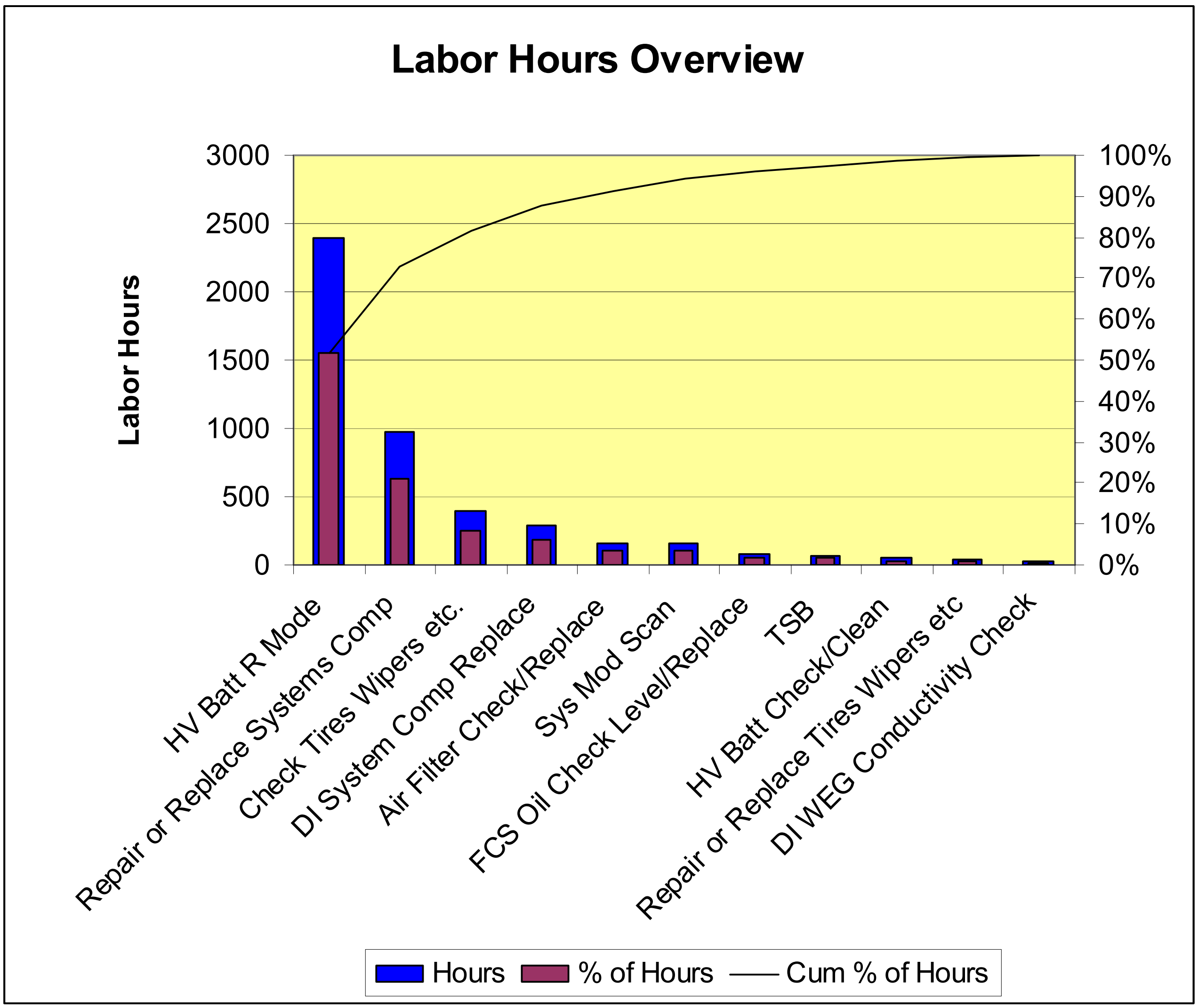


Figure S15 Labor Hours by Maintenance Category

This chart highlights the importance of improvements in the two areas of HV Battery reconditioning and DI System maintenance. There are no parts associated with the HV Battery R Mode, but $176,000 in parts for DI system maintenance. Significant reductions in these two categories of maintenance could reduce overall maintenance (parts & labor) cost up to $430,000, the equivalent of $5975/year for each car.

The following chart (S16) is a summary of total cost of Parts, Labor and Sublet Stack and Systems Module cost:

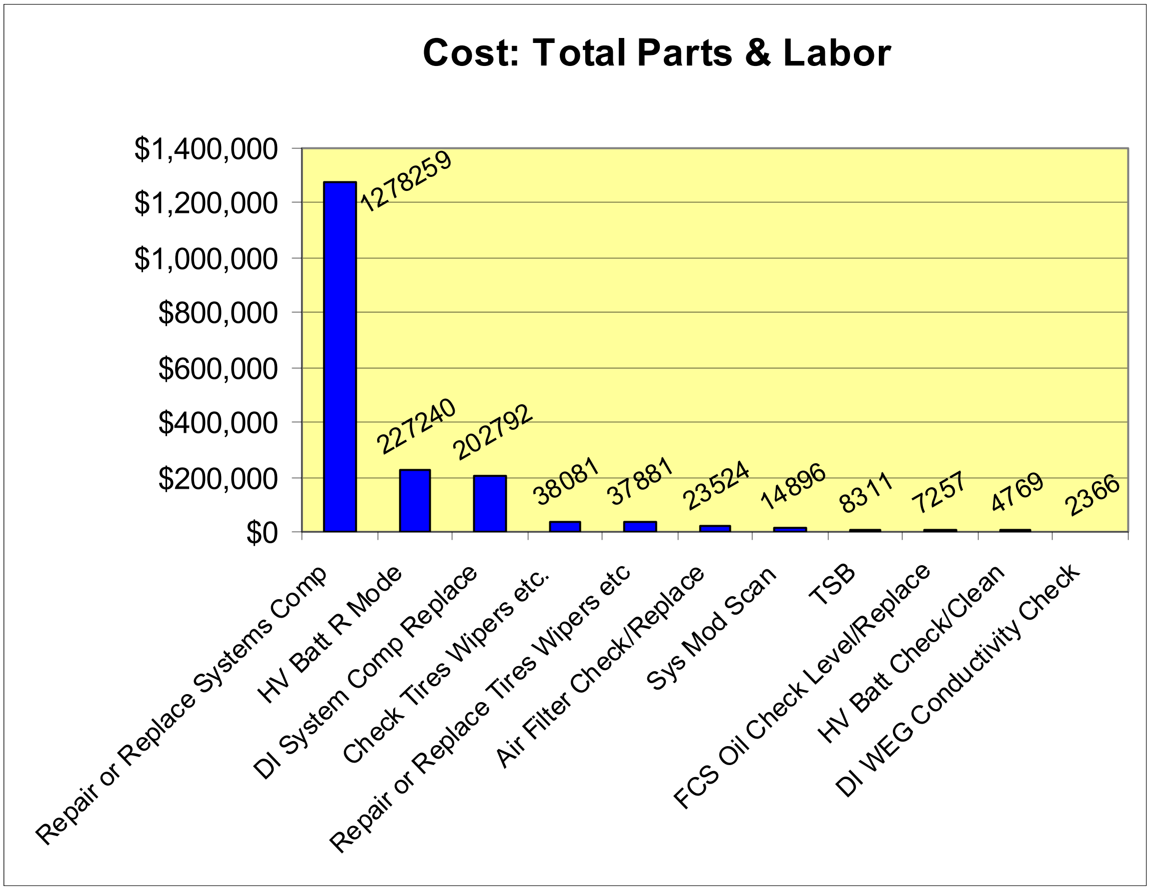


Figure S16 Total Cost of Parts, Labor and Sublet System Repairs

For clarity, the next chart (S16A) shows Total Cost excluding the known expense of the Systems Module and Stack repairs:

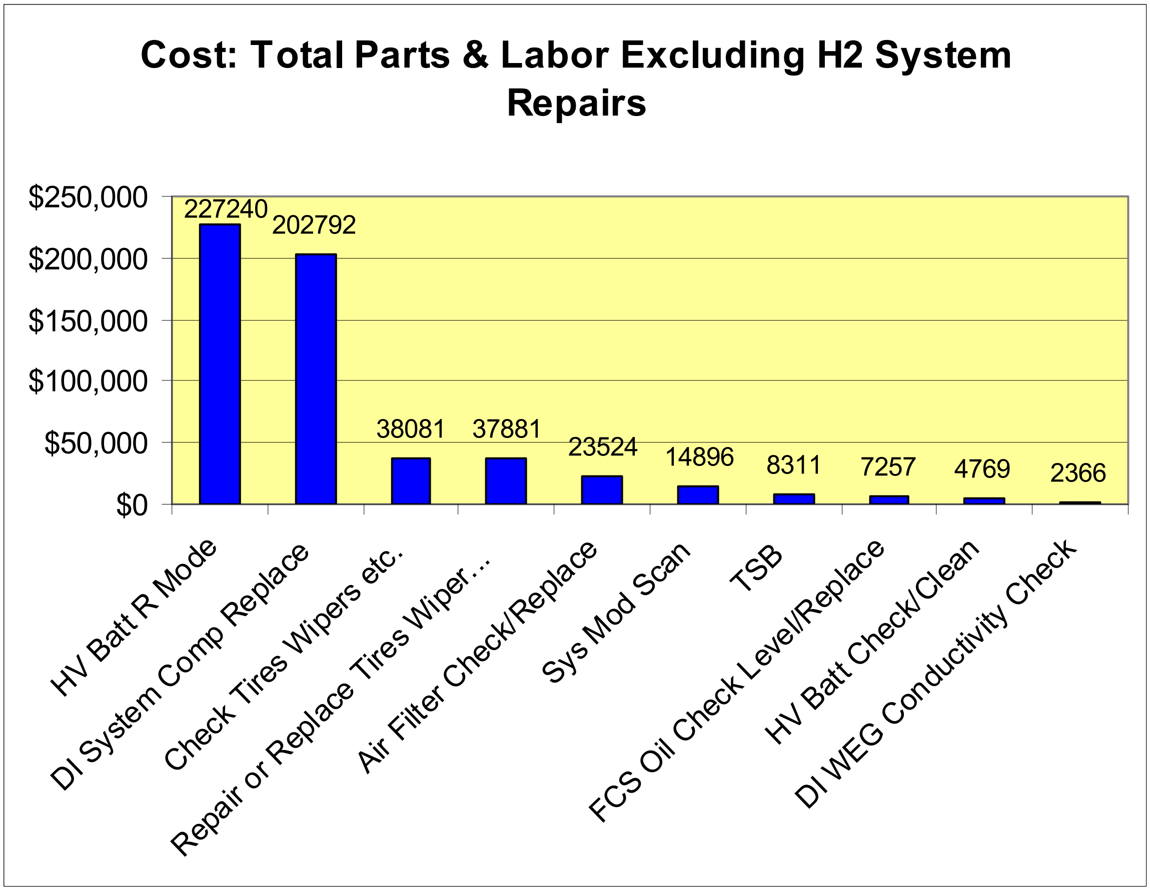


Figure S16A Total Cost of Repairs Excluding Hydrogen Systems (Storage, Stack, Systems Module)

It is reasonable to think that this cost for maintenance would make the vehicle non-viable for commercial sales. Allowing for improvements in components/systems that have already been identified and which will reduce the need for maintenance, or avoid repair, the cost will be substantially lower.

New systems do not inject moisture into the expensive air compressor. The resultant failures, which accounts for nearly 20% of the repair cost per vehicle, would be eliminated. This single item would provide an average $5000/year cost savings.

Refilling Ion Exchange filters rather than replacement would result in $2400/year savings.

Elimination of HV Battery R-Mode would reduce maintenance labor by 53%, a savings of $3156/year.

Improvement in DI water system and service procedures would reduce cost $2816/year. Overall, most "nuisance" problems from these vehicles are a direct result of an issue pertaining to the DI water loop (be it low water levels, high water levels, pump pressure…etc). Future programs already plan to eliminate the DI water loop.

Avoiding poor quality Inverter Boards would have saved $2500/year.

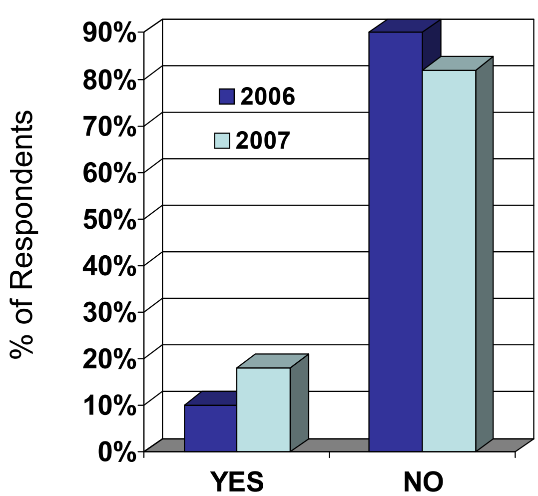
More robust stacks could reduce cost $2700/year although the platinum used in stacks remains an expensive element of cost. New designs have removed the Cell Volt Monitors (CVM), which eliminates repair cost associated with them.

Total potential reduction in maintenance cost is estimated at $18,600/year. The remaining $6800 per year, although still too high for commercially viable use, would likely be lower in a production version since in this demonstration, many checks and inspections were done at 90-day intervals that would be much less frequent in normal use. Assessing how those operations contributed to overall cost of the demonstration cannot be done with any level of certainty given the early stage of technology that this fleet represented. However, it is reasonable to forecast that ongoing maintenance requirements and subsequent cost could be significantly reduced.

Customer Survey

Ford conducted an operator survey twice during the demonstration to assess customer opinion about the performance of the vehicles, the acceptability of hydrogen and hydrogen fueling. As many as 58 questions could be answered, however, not all questions applied to all drivers. The survey focused on issues related to the vehicles, fuel stations, service and program related training. The following illustrations are reasonably self-explanatory. Each represents a key vehicle related question.

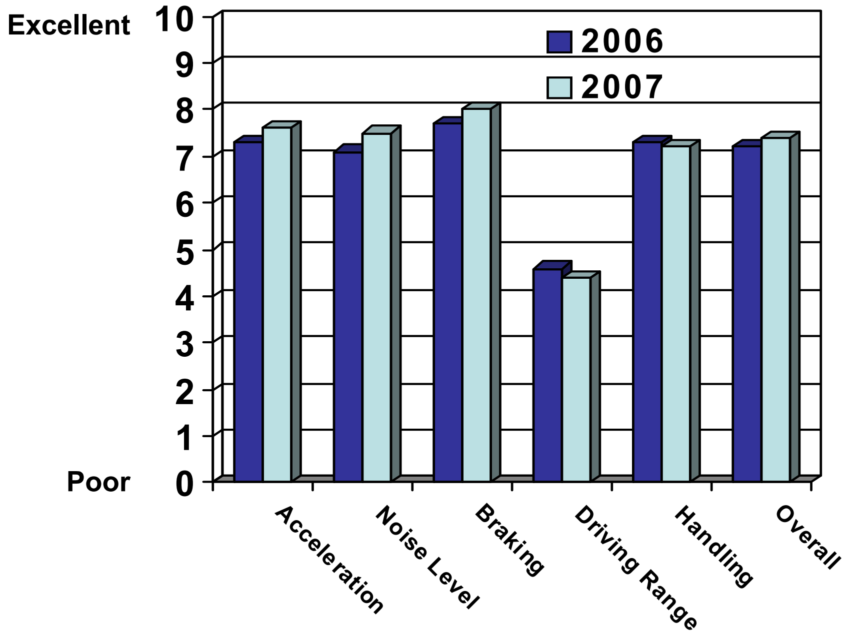
Do you currently have any HESITATION in driving the vehicle?



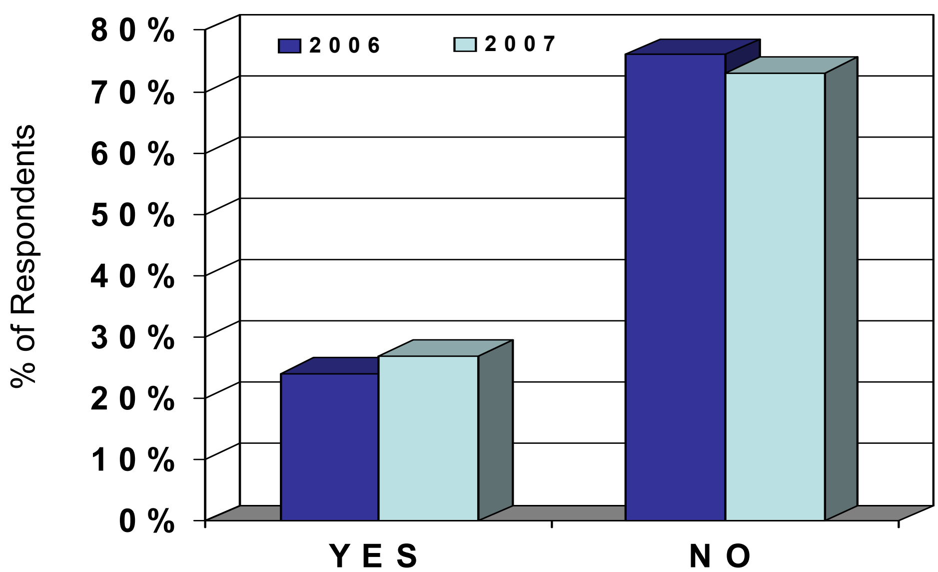
Those who answered YES (16):

- Vehicle range (8)
- H2 Station availability (6)
- Cold weather storage restrictions (4)
- H2 Station reliability (3)
- Lack of regular exposure to the vehicle
- The ability to fuel-up without causing too much delay in my work day
- Hassle of getting the vehicle out of storage (multiple padlocks, doors, three sets of keys)
- Vehicle reliability
- Afraid of a crash

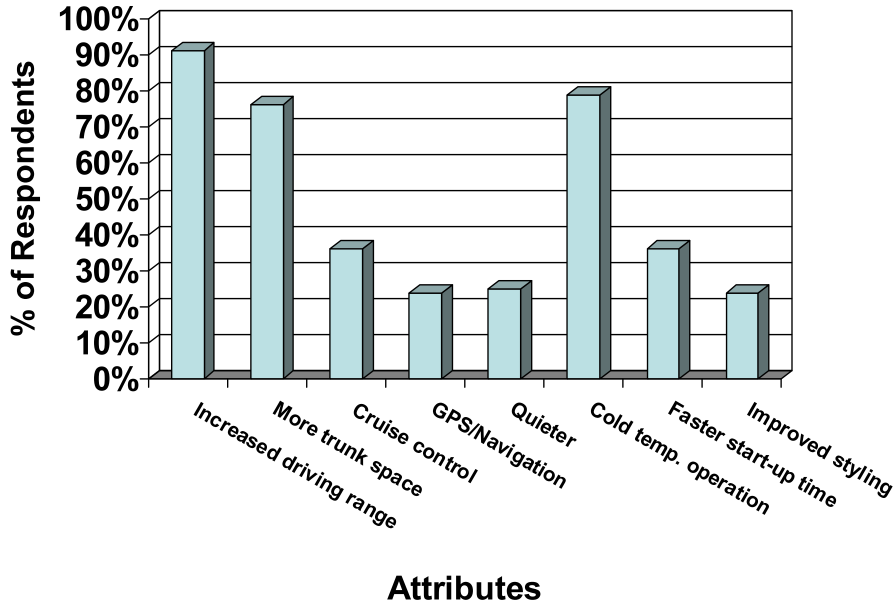
How would you rate the vehicle's performance?



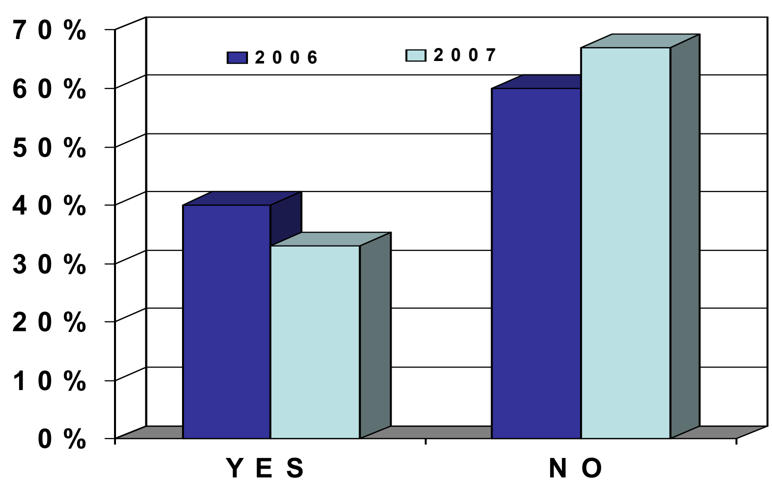
Does the vehicle's start-up process take too long?



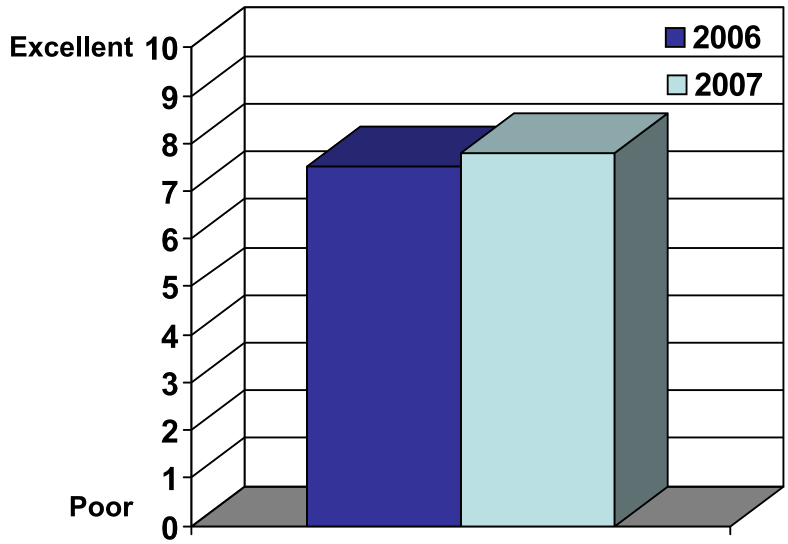
What features would you like to see on Ford's next generation Fuel Cell Electric Vehicle?



In your opinion, does the current number of available stations meet the hydrogen fueling needs of your organization?



To date, how would you rate your overall vehicle experience? This includes driving, fueling, etc.



The survey provided a representative sampling of the general driver and, although the sample is small size, may be extended to represent the consumer in general. As the figures show, drivers provided higher marks for the vehicle and overall program in both years, and were slightly more positive in the second survey.

As the vehicles were driven and became more reliable, fueling issues became more prevalent in customers' critical responses.

Drivers became more comfortable with the vehicle and were more likely to drive them more frequently. However, it was clear that vehicle driving range was an important issue and did cause some driver concern. Infrastructure issues, especially the reliability of the fuel station, became more pertinent.

Overall the customers and drivers were satisfied with the vehicles and the program.

Conclusions & Recommendations

The fleet demonstration portion of this project was successful in demonstrating that the hydrogen FCV can be developed into a reliable, durable alternative to conventional fuel vehicles. The eighteen car fleet had reasonable up-time (94%, discussed in the Data Collection section of this report) meaning the cars were available to the users most of the time that they were needed. Although this up-time is short of commercially viable performance, the demonstration provided learning that will lead to further improvements.

The cost of maintenance was expectedly high since the components for these cars were still expensive low volume parts. The level of service hours was also high, driven by the objective of maintaining vehicle up-time for the users. Here again, the demonstration provided valuable learning that identified ways to reduce these cost elements. Such things as eliminating regular battery reconditioning, and changing the humidification logic will make significant reductions in the time required to keep the vehicle operational.

Drivers were favorably impressed with these cars and used them in daily work assignments. The survey results indicate that their overall assessment of the driving experience was very high, and actually improved over time in the demonstration.

It is also clear from driver comments and logical assessment of the vehicles storage capability that significant work remains to be done for implementing a hydrogen storage system that will provide adequate range while still fitting into a useable vehicle package. This is identified as one of the most critical requirements in future FCVs.

Data Collection and Analysis

Vehicle Data Plan

In response to the defined program requirements, Ford provided a comprehensive plan that detailed the specific data that would be collected during the FCV demonstration program. This plan included static data that described the vehicles in detail, operational data from both real world driving and dynamometer testing, and maintenance and repair data.

The detail of the data reporting structure developed by Ford is shown in Appendix 7 of this report. The following identifies the various data tables that have been addressed in the project and included in the appendix:

- Table D1 Performance Summary[1]
- Table D2 Fleet Summary[1]
- Table D3 Stack Durability Summary[1]
- Table D4 Maintenance Summary[1]
- Table D5 Safety Summary[1]
- Table D6 On-Road Fuel Economy[1]
- Table D7 Dynamometer Test Data[1]
- Table D8 On Road Data[1]
- Table D9 Vehicle Parameters
- Table D10 Consolidated NREL Data Reports

Note 1: Provided to NREL every quarter

Because detailed data has been submitted throughout the program, this report will not include what has already been supplied. However, a summary overview of each area is provided in the following sections of this report. The overview of the fleet demonstration vehicle maintenance is provided in the section on Fleet Operations.

Fleet Vehicle Data Collection and Submission

The DOE has assigned the task of data collection to the National Renewable Energy Laboratories (NREL) in Golden, Colorado. In concept, NREL sought to obtain data on a regular basis that permitted the overall assessment of fleet vehicle operation. The objective was to receive data collected at one-second intervals from the vehicles' on-board data resources.

Early in the discussions with NREL, it was determined that the Ford methodology for data logging on the vehicle would make the one-second interval very feasible, and permitted flexibility for Ford to supply the data. Figure DC1 shows in graphic format, the approach that Ford determined to use.

Each vehicle is equipped with a data collection device that is capable of receiving data from all of the vehicle systems electronic signals. This device is the Vehicle Network Gateway (VNG). The VNG is located in the right rear of the trunk in the vehicle. Signals are received from the vehicle CAN bus, the Fuel System CAN bus, and the fueling system of the hydrogen and drive subsystems.

The VNG also has the ability to monitor both CAN channels for an event to trigger a Diagnostic Trouble Code (DTC) and capture the fault information and freeze frame data as well. It is capable of communicating wirelessly with an off-board computer that is equipped with communications software. These computers are "Service Monitor" machines and are located at the fleet garage or service center.

Because the expected amount of data was large, and to provide effective security for Ford's corporate computers, a third party was contracted to operate file servers as a Central Program Database for the field demonstration. ASG Renaissance of Dearborn, MI provided this service. The service monitors communicated data downloads for each vehicle through an Internet protocol. Generally, the data was retrieved on a weekly basis and monitoring reports were created to facilitate the management of the fleet, and to provide accurate information for use in analysis and problem resolution activities.

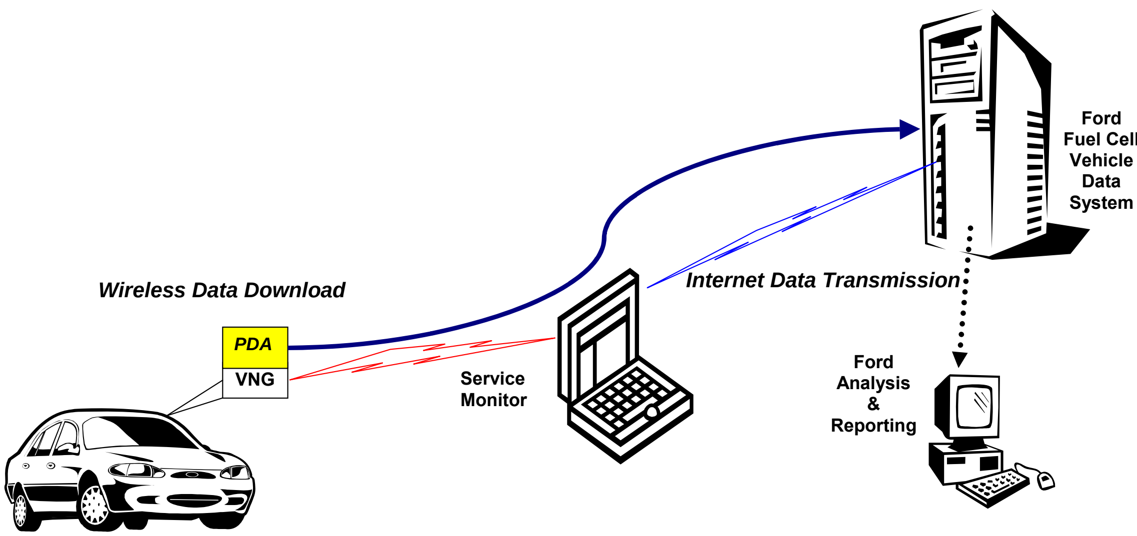


Figure DC1: Data Collection Architecture

As shown in this diagram, the vehicles were also equipped with PDAs (shown below) that were capable of sending limited data directly from the vehicle. However, because of a telephone systems change during the program, this service was removed from the cars in 2006.

In total, FORD submitted over 270 gigabytes of operational data from the 18 demonstration vehicles that was used for NREL analytical work. The total collected was a significantly larger data set that encompassed over 1.4 terabytes of data. The volume of data reported to NREL was in accordance with their requests, but other data was also shared for special projects and investigations.

In addition to the operational data, the DOE required details about the maintenance; repairs, both scheduled and unscheduled, and parts information. To accomplish this, Ford designed a program specific repair information system known as the Technician Repair Order System (TROS). This data system provides a number of reporting capabilities to permit detailed analysis of the fleet, individual vehicles, part numbers and sub-systems. The required maintenance data from TROS was reported to NREL in quarterly data reports and is reviewed in the section Fleet Vehicle Operations of this report.

No detailed are provided in this report because the DOE has specified that operational data is only to be provided to NREL for use in developing publicly available consolidated data products, combining the Ford data with that submitted by the other program participants,

Special Stack Degradation Work with NREL

In addition to the originally scheduled reports, Ford engineers worked with NREL in several discussions designed to enhance the understanding of the contribution of key data elements in both analysis and end of life predictive applications.

To this end, Ford engineers met with NREL personnel in a three-day session in which detailed data was analyzed to determine the principle characteristics of the fuel cell that correlated with system degradation. These meetings were held in March, 2008 and resulted in ongoing data sharing between Ford and NREL with Ford providing select data from all thirty of the fleet vehicles as a way of enhancing the NREL analytical approach.

Stack Degradation Estimation & Analysis

A concern for FCVs is the long-term durability of the PEM fuel cell stack under the dynamic loading conditions required for automotive applications. Under constant operating conditions, the reliability of PEM fuel cell is quite high but under dynamic loading conditions a number of failure modes related to oxygen starvation, membrane hydration cycling, and thermal gradients are introduced. Through hybridization, it may be possible to reduce the dynamic loading requirements; however, these solutions are likely to add cost and weight to propulsion systems that are already expensive and heavy.

Using the data that was collected from the DOE demonstration fleet combined with data from other Ford fleet cars, a method for extracting meaningful voltage degradation estimates, using current and voltage data taken from fuel cell vehicles, was developed. In all, data from 21 fuel cell Focus vehicles that have been operating at various locations around the world was used.

As previously described, the demonstration vehicles were instrumented and operating conditions were collected on a second-by-second basis. Analysis of this data allowed the estimation of the polarization curve of the PEM fuel cell during normal operation, and with that, estimate the voltage degradation rate over time.

Some of the vehicles were not considered in this analysis. Some were eliminated because a stack had been replaced; the vehicle had been used in engineering studies and was subjected to stress-conditions outside of normal operation ranges, or didn't have enough hours of operation to give a reasonable estimate of the voltage degradation. (Note: of the vehicles that had a stack replaced, none were replaced because of voltage degradation). The data was filtered to eliminate data from start-up and other transient operating conditions. The filtered data was used to estimate polarization curves over the life of the vehicles.

Analytical Approach

A least-square error-fitting algorithm was developed to fit a parametric form of the polarization curve that included terms for an effective open circuit voltage, effective stack resistance, and activation voltage.

Once a suitable polarization curve is calculated, the values for the best-fit curve along with the mid point of the data collection time interval are stored. This provides a set of polarization curves as a function of time. An example of these polarization curves is shown in figure SD1.

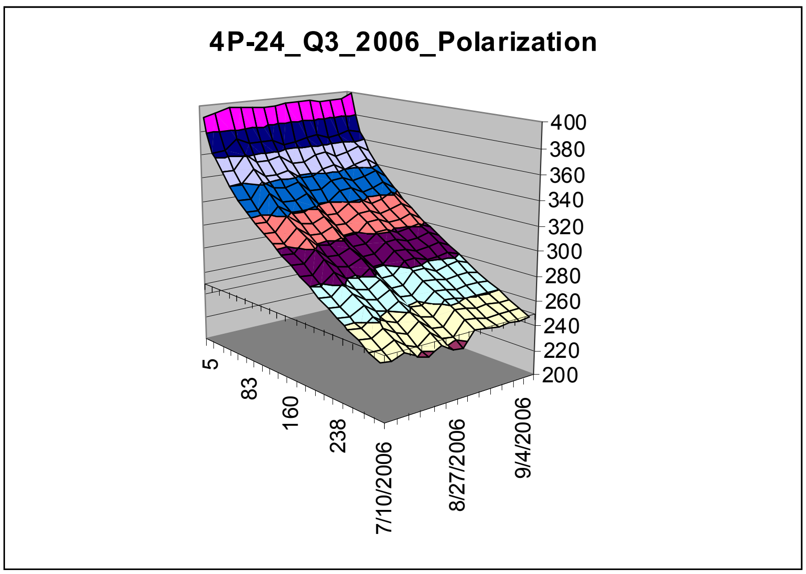


Figure SD1 An example of polarization curves as a function of time for a vehicle (4P-24)

Even in cases where the scatter in the voltage is quite large, the uncertainty in the best-fit line reduces quickly as data is accumulated. It does not take very much data to get a good estimate of the polarization curve.

The algorithm is applied in an adaptive manner by collecting 250 data points and fitting the curve. If the uncertainty bounds of this fit at the high current end of the polarization curve are larger than a specified value, more data is collected until the uncertainty is brought into the desired range. Since the data is already filtered to remove data from transient operating conditions, the only time a problem with the uncertainty bounds is seen is when the first 250 data points do not contain any high current data. The uncertainty band can be quite wide at high current until there are at least a few high current points to pin the upper end of the polarization curve.

The polarization curve information is used to estimate the voltage degradation for each vehicle in the study. This is done using the stored polarization coefficients to reconstruct the voltage at the desired current as a function of time, and using linear interpolation to estimate the degradation rate with time in service. Estimates of the degradation rate per day of calendar time in service as well as per hour of stack operation time are possible. It was discovered that degradation rates were not strongly dependent on the current so degradation rates at a single current, 250 amps, are discussed.

The voltage degradation estimations at 250A are shown in
Table SD1. The first column shows the degradation rates with respect to hours of operation in milli-Volts per hour of operation. The second column shows the degradation rates with respect calendar days in operation in units of Volt per day.

Vehicle	Degradation rate w.r.t operation time(mV/hr)	Degradation rate w.r.t calendar time(V/day)
1	7.79	0.010
2	8.60	0.014
3	9.45	0.014
4	10.05	0.011
5	10.25	0.011
6	10.66	0.015
7	10.70	0.009
8	11.73	0.017
9	11.92	0.015
10	14.40	0.014
11	14.99	0.019
12	17.33	0.015
13	18.65	0.015
14	20.21	0.026
15	21.58	0.026
16	23.00	0.014
17	25.05	0.023
18	27.28	0.010
19	38.99	0.016
20	48.19	0.035
21	53.67	0.023

Field Demo Vehicles

Engineering Test Vehicles

Table SD1: Degradation rates for 21 vehicles included in this study.

End of Life Discussion

An often-used surrogate for end of life is 10% degradation of stack voltage. Many of the degradation curves that were developed show a steeper decline in the first few hours of operation followed by a long slower degradation over the rest of the time. The data from vehicle P-24 presented in Figure SD2 is a good example of this. The slope of the degradation curve decreases after about 100 hours of operation.

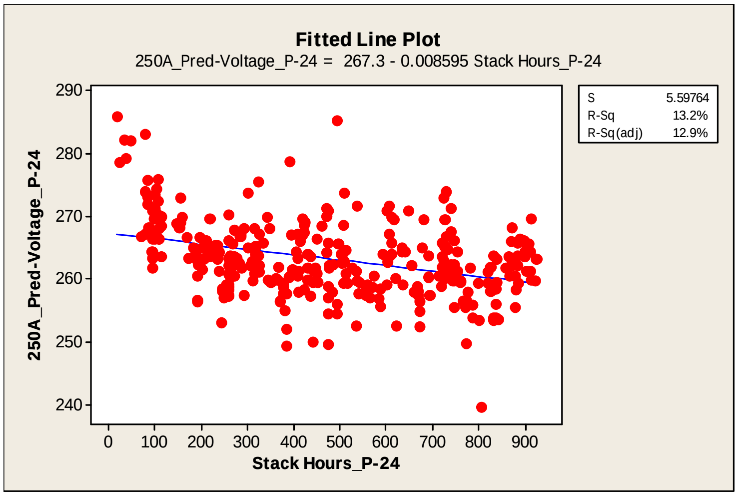


Figure SD2. Degradation curve for vehicle P-24 showing the sharp drop in voltage early in life followed by a slower decay for the rest of the time.

Because of this, the time to 10% voltage degradation numbers can be somewhat misleading. Based on this work it is proposed that future degradation estimates use a bilinear fit to capture the early life degradation. This will give a more accurate estimate of the true degradation rate during the working life of the vehicle.

The distribution of degradation rates with respect to stack operating hours and with respect to calendar days are fit well by three different distributions: 3-parameter log-logistic, 3-parameter log-normal, and 3-parameter Weibull. The parameters for these best fits are shown in Table SD2.

	Degradation rate w.r.t operation time(mV/hr)			Degradation rate w.r.t calendar time(V/day)		
Distribution	**Loglogistic**	**Lognormal**	**Weibull**	**Loglogistic**	**Lognormal**	**Weibull**
Location/Shape	1.963	2.025	0.9105	-4.846	-4.774	1.164
Scale	0.7062	1.078	11.51	0.3878	0.6176	0.008169
Threshold	7.535	7.098	7.713	0.007211	0.006605	0.00898

Table SD2: Best fit parameters for distribution of degradation rates.

An assumed end of life power loss target of 10% corresponds to a voltage degradation of about 27 volts at 250A. Using the distributions above, we can estimate the distribution of times to 10% voltage degradation.

From Figure SD3 we see that 80% of stacks last more than 1000 hours before degradation reached 10%. The median time to 10% degradation is projected to be about 1800 hours. The minimum acceptable lifetime for a commercially viable propulsion system is 5000 hr. This corresponds to approximately 150,000 miles.

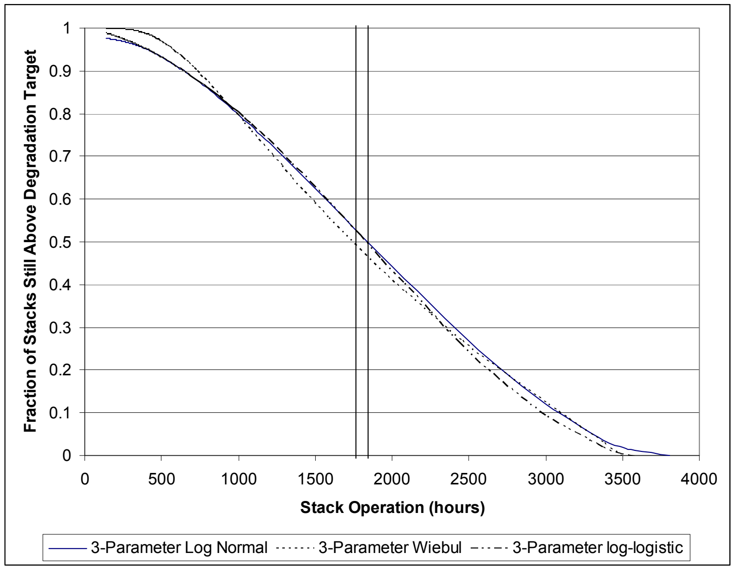


Figure SD3. Cumulative plot of for time to 10% voltage degradation in hours of operation

Looking at the number of years the stacks would continue to function before reaching the 10% degradation level, Figure SD4 presents the estimates using the three distributions.

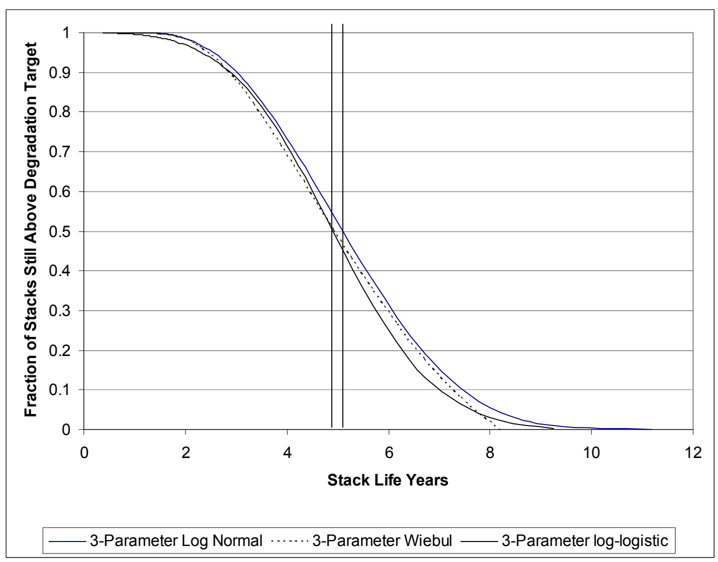


Figure SD4 Cumulative plot of for time to 10% voltage degradation in calendar years.

From this plot, we see that 90% of stacks last more than 3 years in the field before degradation reached 10%. The median time to 10% degradation is projected to be about 5 years.

Correlation Studies

To investigate the correlation of these degradation rates with various operating condition and environmental factors, the degradation rates are transformed with a lognormal transformation using the parameters identified for the lognormal distributions in Table SD2. Correlation coefficients are then calculated for these transformed degradation rates with a large number of operating conditions to identify factors that might either aggravate or mitigate stack degradation.

The qualitative results of these correlations are shown in Table SD3. In this table, correlations with significant operating conditions (with a p value less than 0.05) have been identified. These are labeled as “positive” if the degradation rate increases as the parameter increases, and “negative” if the degradation rate decreases as the parameter increases. Factors investigated that showed “no significant” correlations are also shown in the center row of the table.

Correlation	Degradation rate w.r.t operation time(mV/hr)	Degradation rate w.r.t calendar time(V/day)
Positive Correlation	• Degradation rate w.r.t calendar Time • Average Soak Time	• Degradation rate w.r.t. operating time • Average ambient temperature
No Statistical Significant Correlation	• Days in the field • Average start up time • Average operating current • Average length of drive (sec) • Latitude • Average Ambient Temperature • Time with minimum cell voltage < 0.0V • Time at minimum bus voltage	• Hours of operation • Days in the field • Duty Cycle • Average Soak Time • Number of soaks > 2 hrs • Total time at idle • Number of warm or hot starts • Total number of starts • Average start up time • Number of 2 tier shut downs • Total energy generated • Average length of drive (sec) • Longitude • Average stack operating temp. • Time with stack inlet temp between 60-70C • Time with minimum cell voltage < 0.2V • Time with minimum cell voltage < 0.0V • Time at minimum bus voltage
Negative Correlation	• Hours of operation • Duty cycle • Number of soaks > 2 hrs • Total time at idle • Number of starts (all types) • Number of 2 tier shut downs • Total energy generated • Longitude • Average stack operating temp. • Time with stack inlet temp between 60-70C • Time with minimum cell voltage < 0.2V	• Number of cold starts • Average operating current • Latitude

Table SD3: Correlation of environmental and drive cycle factors to stack degradation.

Degradation with respect to Calendar Time

It is impossible to draw definitive conclusions from this data without the ability to do controlled experiments, but it is instructive to point out some interesting trends in the data. Looking first at the degradation rates with respect to calendar time, we see that there is a correlation between increased degradation rate and the following three factors: increased ambient temperature, decreased number of cold starts, and more southerly location of the vehicle. There is also a somewhat weaker negative correlation with average operating current. The ambient temperature, cold start, and latitude all correlated with each other. Most likely, these are all surrogates for each other.

In the analysis of the data, degradation rate with respect to calendar time for the four factors identified (Average Ambient Temp, Number of Cold Starts, Average Operating Current and Latitude) appear to be most meaningful for vehicles that are located in Florida. If these vehicles are removed from the analysis, the correlations with degradation rate are no longer significant. Clearly, something is different about the vehicles in Florida. One possibility is that these vehicles see much higher ambient temperatures and fewer cold starts. It is possible that hot weather causes degradation even when the vehicles are not in operation. However, it is impossible to tell whether these are causal factors or if there is some other factor unique to the Florida fleet that caused higher degradation rates.

Degradation with respect to Operating Time

A large number of factors have significant correlations to degradation with respect to hours of operation. Many of these predictor variables are so strongly correlated with the hours of stack operation, their effects can't be determine or isolate. Number of starts, number of 2-tier shut downs, number of soaks, total time that stack inlet is between 60 and 70 degrees and total energy generated all increase as total hours of operation increase, so there is no way to separate these effects.

Since all the vehicles have been in operation for about the same amount of time, duty cycle and hours of operation are essentially the same variable. If correlation with duty cycle can represent the correlation with all the related predictors, then the following can be observed:

- Degradation decreases as duty cycle increases. The more you use the fuel cell the lower the degradation rate.
- Degradation decreases as longitude increases. This is most likely due to the fact that some of the vehicles in the study were operated in Germany where they experienced very low duty cycles and the highest duty cycle vehicles were operated in Vancouver, Canada. For this reason, longitude just happens to correlate well with duty cycle.
- Degradation rate decreases as the number of 2-tier shut downs increase.
- Degradation rate decreases as the amount of time spent with the minimum cell voltage less than 0.2 V increases.

The last two points seem counter intuitive. This may result from a duty cycle effect that is so strong that the impact of other stressors that scale with time in service cannot be seen. Another way of saying this is that those vehicles which have experienced more shut-downs and start ups and other stressful conditions, and which might show some increased degradation because of these stressors, are also the vehicles with the highest duty cycles. Because of this they show a negative correlation between the stressors and degradation rate. This may simply be due to the fact that those stacks that are used most frequently are the stacks most likely to be in an ideal state of conditioning and therefore more robust to stressors

Conclusions from Stack Degradation and Analysis Discussion

A statistical method used by Ford's fuel cell development group can be used to extract small voltage degradation rates out of relatively noisy data from fuel cell vehicles being operated in the field. This method has been shown to be a useful diagnostic of the fuel cell stack and can be used to estimate expected stack life. Vehicle degradation rates for vehicles in fleet operations range from about 7 mV/hr to around 25 mV/hr. Ford believes this method of degradation estimate, with some adjustments to deal with the higher degradation rates early in the stack life, can be adopted as the standard for estimating stack life from field data. A list of factors that have been checked for correlation with the degradation rate has been developed.

Conclusions & Recommendations from Data and Analysis Discussion

This demonstration program was able to provide over 1.4 terabytes of data, extracted from vehicles at one-second intervals during the complete four years of fleet operation. The data was finely detailed and met all requirements defined for the program by NREL at the initiation of the project. Valuable learning came from this data. All required data files were submitted to NREL on a regular basis for consolidation with other program participants, helping to produce broadly meaningful information for public use in the further development of these technologies.

The fleet data collection methodology proved to be effective in accessing data from across the country and around the world. This success has provided an approach that Ford will utilize in future vehicle development programs.

This report does not draw conclusions from the data as agreed at the outset with the DOE and NREL. However, from the information that is reported here, it is clear that, within the climatic/environmental operational parameters of this demonstration, the Ford Focus FCV vehicle performance has proven to very nearly meet driver and operator expectations. The data defines those areas where further improvements are necessary.

Technology Demonstration Vehicle (TDV) Program

The objectives for this project included the development and test of evolving fuel cell technologies for incorporation into vehicle platforms. Fuel Cell designs, hydrogen storage concepts and electric vehicle components are each being enhanced for improved performance, lower cost and acceptability in commercial use. It was clear as this program started, that Ford Motor Company could make valuable contributions to technology implementation, providing leading indicators of future concepts.

In the program, Ford planned to prepare three distinct Technology Demonstration Vehicle concepts as Phase II of the project. These vehicles are separate from the 18 deployed Phase I demonstrators and have been used only as Ford controlled engineering prototypes. The original Work Plan reflected the most current program direction. However, the decision to build specific technologies in the TDV's and the number of vehicles became contingent upon available Ford resources and DOE funding and approval.

The Ford plan was to develop three vehicle designs as described below, and build eight vehicles. Changes in the numbers of vehicles planned for each type occurred as the program developed. When changes in direction became desirable or prudent, Ford conducted formal reviews with DOE personnel to explain the rationale, assure common understanding of the characteristics and objectives for the vehicle prior to build, and to secure DOE approval for the revised plans.

TDV Rationale

Ford engineering met with the DOE program personnel in June of 2004 to discuss the overall FCV program and the TDV effort in particular. In that meeting, Ford explained the technology drivers that were essential to the development efforts of this 2nd phase of the demonstration. The rationale was explained as follows:

- Fast and Flexible Demonstration of new FC Technologies in a cooperative effort to increase the degree of stretch with suppliers.
- Serve the technology need and not the vehicle in a versatile approach to FC Powertrain technology demonstration, i.e. under hood Stack, Thermal, FC System, Hybridization, H2 Storage.
- Utilize a "Designed Around Hydrogen" approach for 300-550 miles range
- Support platform derivatives easily with a fast turn around to avoid delay in trials of new developments
- Develop flexible powertrain architecture to cover several platform sizes.

TDV concepts were discussed with the DOE prior to the start of the program in a cooperative effort to obtain DOE feedback and level of interest. Ford's resource plan was developed as the next step for the TDV proposal and finally, the number of TDV units was matched to the DOE's interest and Ford's ability to staff parallel efforts, i.e. Phase I fleet plus TDVs.

The following is an overview of the three original vehicle concepts presented to the DOE and incorporated in the Statement of Objectives for the program. Following the overview, a detailed discussion of the characteristics and performance of each of the TDVs that was ultimately built is presented. The TDV program provided the technical input as originally conceived, although the vehicles were markedly different than the original proposal.

1 Robustness Demonstrator

This demonstrator was to incorporate some key improvements to the Ballard fuel cell system installed in one Phase I Focus model vehicle. This vehicle is to demonstrate the impact of improvements in projected stack life and reliability.

2 Design Around Hydrogen Demonstrator

Five vehicles to be developed that utilize totally new physical architecture for more optimal packaging of hydrogen storage and system components, and system improvements. These vehicles were to demonstrate improved stack life with a Second-Generation Ballard fuel cell system, increased range, and improved cold start capability.

3 Freeze Start Demonstrator

Two vehicles were to be built to demonstrate improved low temperature start capability, improved operational capabilities, increased range, anticipated improved fuel efficiency, and quieter operation. These vehicles would have the dedicated architecture developed in the Designed Around Hydrogen vehicle combined with a Second-Generation Ballard fuel cell system and high-pressure hydrogen storage.

A Specifications Summary for these originally conceived vehicles is shown in the following table (Table TD1):

Vehicle Attributes	**Robustness Demonstrator**	**Designed Around Hydrogen Demonstrator**	**Freeze Start Demonstrator**
Platform	Modified Focus	SUV	SUV
Fuel Cell Generation	Gen 2 (Stage 1)	Gen 2 (Stage 2)	Gen 3
Range (miles)	200	>300	>450
Hydrogen Storage (bar)	350	350	700
STACK Life (miles)	30,000	45,000	45,000
MTBF (miles)	5,000	5,000	5,000
Unassisted Cold Start (°C)	2	<0	-25
Assisted Cold Start (°C)	2	-15	-40
Fuel Efficiency (mpg) (*normalized to Focus)	50	50*	55*
FCS Peak Noise (dBA)	90	80	75

Table TD1: Original Technology Demonstrator Vehicle Program Targets

Delay in development of the new generations of fuel cell systems and stacks, emerging technologies and alternative vehicle architecture innovations drove revisions to the plan. Ultimately, the TDVs were able to accomplish the original objectives although the vehicles that were used to meet the objectives were changed. The following chart (Table TD2) documents where each objective was demonstrated (marked with an "X"):

Demonstration Objective	TDV1	TDV2	TDV3	TDV3.2	TDV4	TDV7	TDV9
Fuel Cell Stack Improvements				X	X		
Fuel cell Systems Improvements	X		X	X	X	X	X
Over 300 Mile Range		X			X		
700 bar Hydrogen Storage					X		X
STACK Life (30,000 miles)	X						
Unassisted Cold Start < 0°C				X	X		
Fuel Efficiency (mpg) (*normalized to Focus)	X	X	X		X	X	X
FCS Peak Noise (dBA)		X				X	

Table TD2: TDV Program Target Demonstration

It should be noted that this review has eliminated reference to "Assisted Cold Start". Ford has done all of the development of these FCVs for unassisted starting capability. It is assumed that assisted cold start temperatures, significantly below the unassisted temperatures, are very feasible. Assisted starts were not demonstrated in this project.

In addition, a special vehicle study, referred to as TDV8 was conducted but did not result in a vehicle design. The key elements of that effort will be discussed briefly in this report.

TDV1 Robustness Demonstrator

Figure TDV1-1: TDV1 Focus Durability Dynamometer Test Vehicle

Demonstration Objective	TDV1
Next Generation Fuel Cell	▲
Over 300 Mile Range	
700 bar Hydrogen Storage	
STACK Life (30,000 mile)	X
Unassisted Cold Start < 0°C	
Fuel Efficiency (mpg) (*normalized to Focus)	X
FCS Peak Noise (dBA)	

▲ Advancements, improvements or new concepts

Table TDV1-1: TDV1 Objectives

Goals

The principle goal of TDV1 development was the demonstration of a fuel cell stack that could achieve 30,000 miles of operation as a step toward a viable automotive powertrain. This was to be done by making improvements to the existing Focus (C264) powertrain (the anticipated Gen2 Stage 1 fuel cell system was not available) which could then be proven out on a long-term dynamometer test.

Fuel cell vehicles appear to suffer stack degradation over time and it is suspected that the duty cycle could be a significant factor. The duty cycle determines the vehicle "soak time", i.e. the time the fuel cell system has to cool down or heat up related to the time between test cycle steps, and data indicates that extended soak intervals can lead to stack damage. When hydrogen is depleted from the anode during a soak, a presence of air is possible which can lead to carbon corrosion. Ford's Stack Degradation Task Force identified a soak of 4-7 hours as the critical time required for hydrogen depletion to take place, leading to potential corrosion.

The dynamometer test schedule was developed using driving traces developed at Ford's Michigan Proving Grounds (MPG) to make the testing comparable to accelerated real world use. The test was performed by robot operators, permitting round the clock operation that enabled the completion of the test in less than seven months.

During the dynamometer run, Polarization Tests and Transfer Leak Detection Tests were conducted every 100 hrs to monitor the health of the stack. A battery R-Mode reconditioning was performed every 80 hours.

System development goals were defined within the larger durability goal. These were:

- Improve Anode Reactant Gas Humidity
- Improve water management inside FC

Powertrain Architecture

TDV1 incorporated the C264 HyWay1 stack & system powertrain architecture with improvements to the humidification system. This was done to address the TDV and Fuel Cell System engineering teams' identified strategy to correct improper stack humidity, removing that influence as stressor to stack life. The focus of this improvement was improved Anode Reactant Gas Humidity with improved water management inside stack. In addition, a H2 recirculation blower was added.

How it works

The powertrain functions identically to the C264 except that new hardware was inserted to improve humidification of the air and hydrogen flowing into the stack.

Physical Architecture

Figure TDV1-2 below shows the novel device developed to meet the vehicle durability objectives. The powertrain architecture was modified with the insertion of a Reactant Gas Conditioner, between the stack and the systems module replacing the connector tubes of the C264.

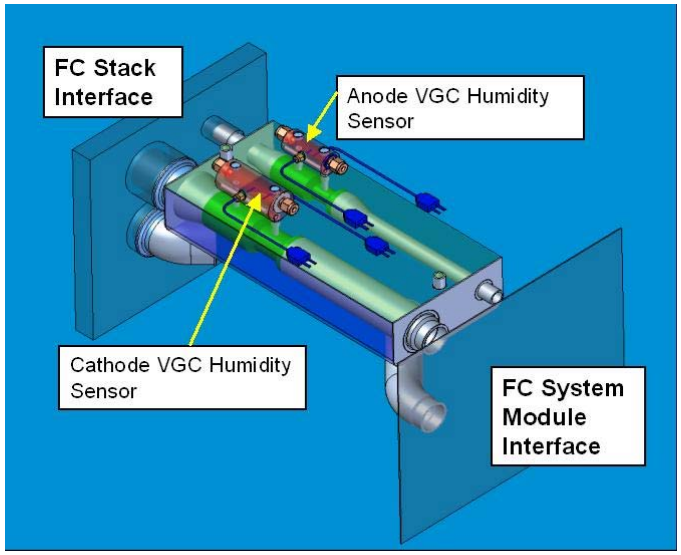


Figure TDV1-2: Ford Reactant Gas Conditioner

Figure TDV1-3 below shows the physical location of these elements in the vehicle, providing a better view of the physical architecture of the vehicle.

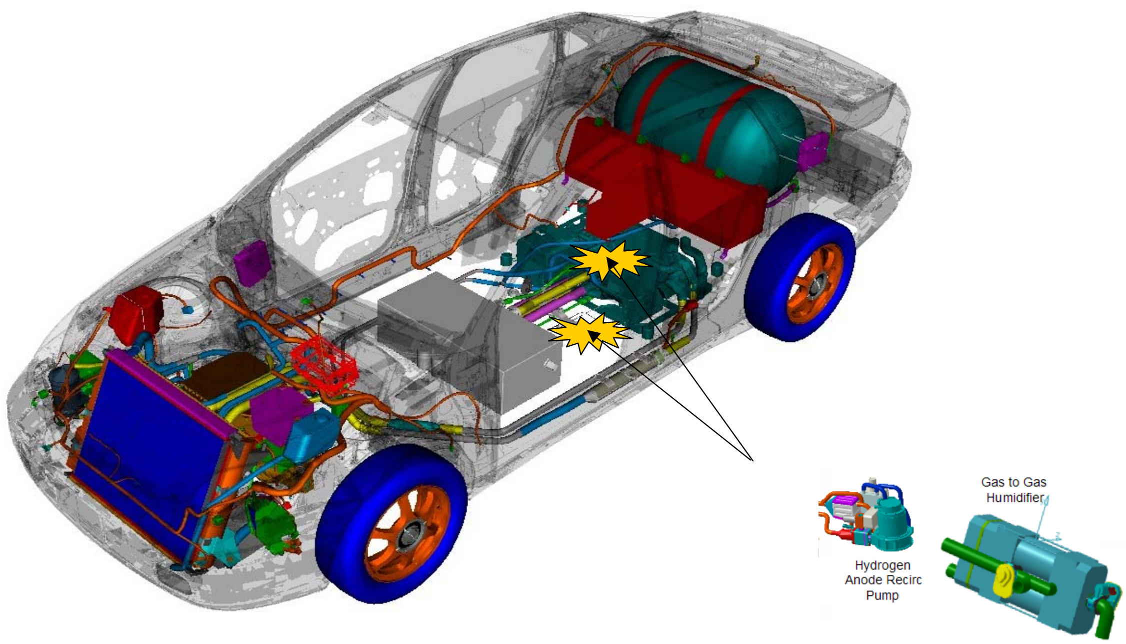


Fig. TDV1-3: TDV1 Physical Architecture

Fuel Cell & Battery Systems

TDV 1 used the Ballard Mark 902 system that was developed in the C264 vehicle, and the same Sanyo 216 volt, 1.2 kw-hr battery systems.

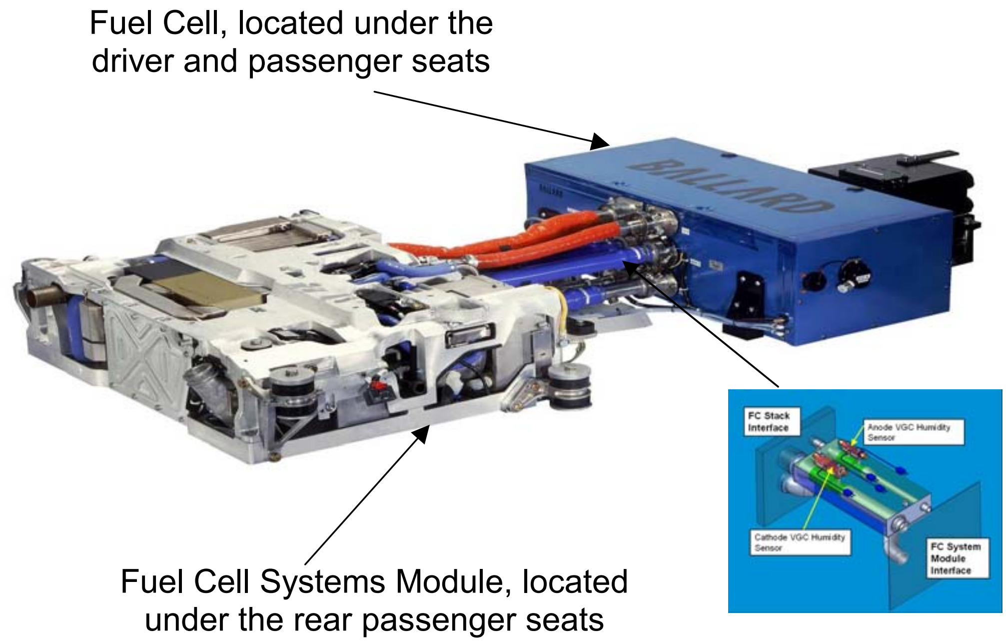


Fig. TDV1-4 TDV1 Fuel Cell System

Data

The following is a discussion of the testing and technical improvements in TDV1, and some of the pertinent data that characterizes those improvements

Durability Test

The following is a summary of the total dynamometer testing program for TDV1. It provides some understanding of the duty cycle used and its relation to real world driving conditions.

TDV1 Average Drive Time: ((90*219) + (120*152) + (44*255)) / 626 = **78.5 mins**
R-310 Test Duration: 90 minutes (219 cycles)
R-358 Test Duration: 120 minutes (152 cycles)
R-357 Test Duration: 44 minutes (255 cycles)
*Does not include vehicle driving during troubleshooting phases, which would (slightly) lower the average.

TDV1 Average Speed: ((63*219)) + (32.5*152) + (22.7*255)) / 626 = **39mph**
R-310 Avg Speed = 63mph, 219 cycles
R-358 Avg Speed = 32.5mph, 152 cycles
R-357 Avg Speed = 22.7mph, 255 cycles

TDV1 Time at Idle: **~60 hours**
Includes 219 R-310 cycles @ 15 min idle per cycle = 3,285 mins (54.75 hrs)
Plus ~30 sec idle to start each cycle (30s * 628 cycles) = 5.2 hrs
TDV1 Average Time Between Start = 3.48 hrs

TDV1 Average Number of Starts per Day: 783/201 = **3.9**

TDV1 Testing Overview

- Durability Test Duration = 2/23/06 – 9/11/06
- Total Miles Driven = **30,119**
- Total Fuel Cell Hours Accumulated = **737.2**
- Ran double MPG Equivalent Durability (C264 averaged 15,200 miles accumulated per vehicle at MPG)

The following plot provides the overall mile accumulation on TDV1 during the extended dynamometer test (Figure TDV1-5):

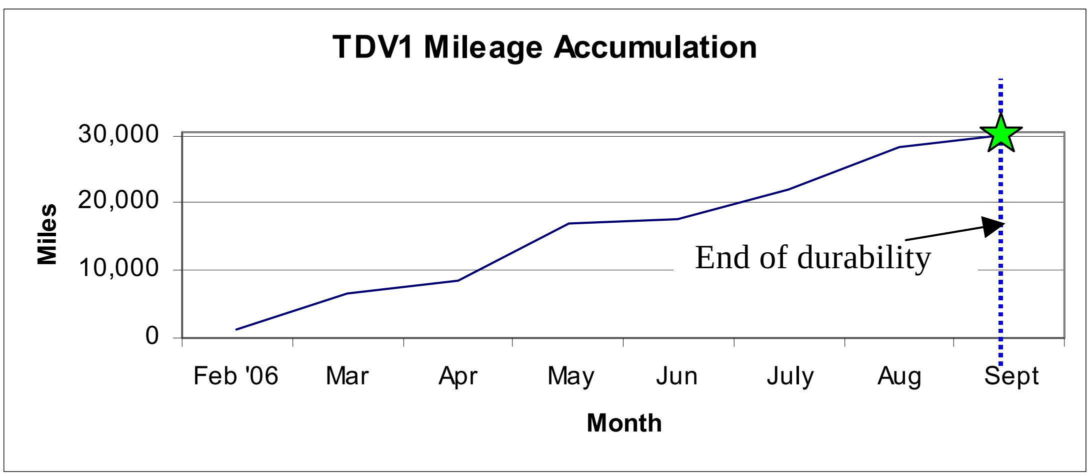


Fig. TDV1-5: TDV1 Durability Fuel Cell Miles Accumulation

Figure TDV1-6 summarizes the test cycles and durations for the 30,000 mile dynamometer run of TDV1. (Most of the emphasis is on R-358 and R-310. Passed all Transfer Leak Detection tests)

TDV1 Testing Order

Procedure	MPG Mileage Accumulated on Actual Durability	TDV1 Round 1	TDV1 Round 2
R-357	3196	3200	3100
R-358	7696	7700	7600
R-310	4275	4300	4100
	15,167	15,200	14,800
		TOTAL =	**30,000**

Figure TDV1-6: TDV1 Durability Test Cycle Durations

Figure TDV1-7: TDV1 Durability Test Configuration

The following plot (TDV1-8) details the stack polarization data during the 30,000 mile durability testing completed on TDV1. The polarization results show little stack degradation of maximum gross power output over the 30,000 mile testing. The plot also contains data from a vehicle labeled "P1" which is a field tested vehicle for which data had also been supplied to NREL. It helps to correlate the influence of real-world vehicle usage on stack degradation.

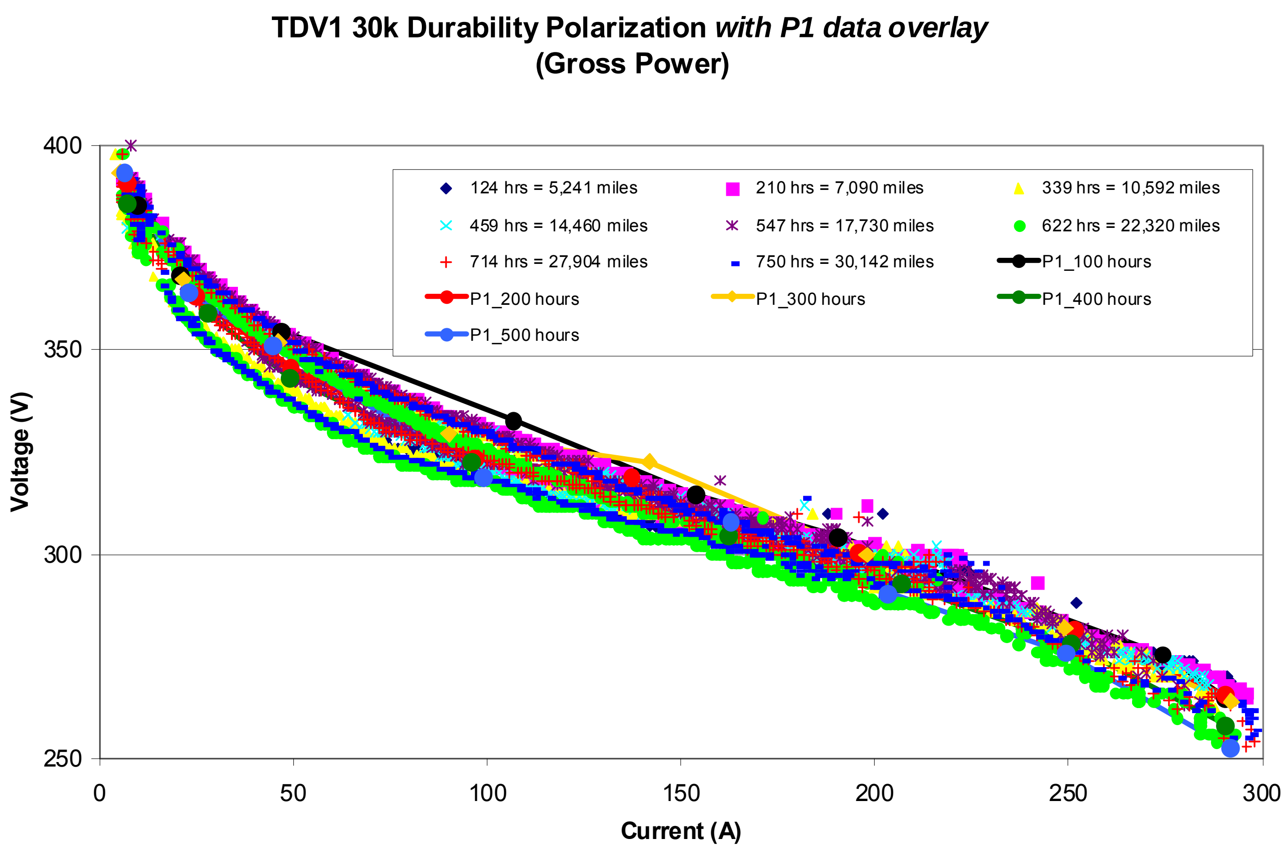


Figure TDV1-8: TDV1 Stack Polarization

TDV1 Improvements

Two principle improvement activities were made to improve the durability of the stack during the demonstration: Reactant Gas Conditioning and Hydrogen Recirculation. These were implemented with a succession of software improvements that controlled the upgraded components:

Reactant Gas Conditioner developed by Ford engineering
The objective of this development was to increases reactant gas temperatures, improve the stack dew point and control the relative humidity in the stack.

The device that was developed to accomplish these improvements is pictured here, and in the schematic.

In operation, the sensors located adjacent to the venturi (Figure TD1-9) identify the temperature and humidity of the gas flowing through the nozzle and transmit that state data to specially developed software in the control module. The module calculates the desired change in humidity to match the temperature of the incoming gas, and additional heat required to optimize stack operating conditions. The controller opens valves to inject DI water vapor when necessary, and heats the gas during cold air intake events. At power levels above 50 amps, DI water vapor is injected into the airstreams feeding the anode of the stack, adjusting the relative humidity toward the desired 60% target.

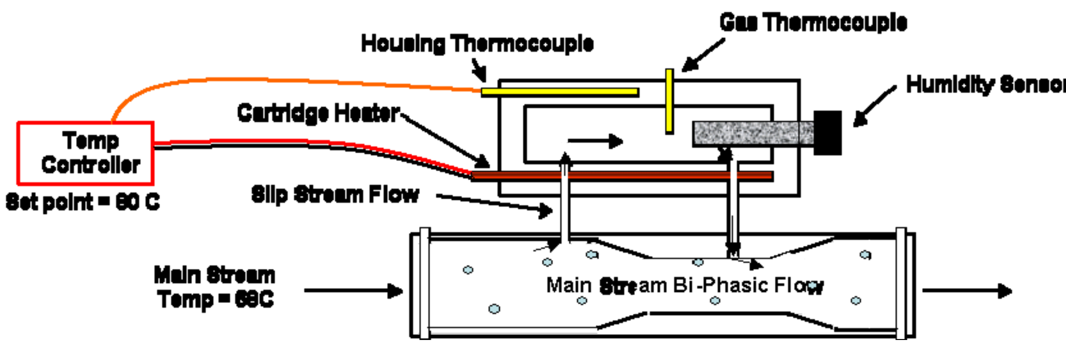


Fig. TDV1-9: TDV1 Humidity Sensor/Measurement Element

The results of the conditioning device can be seen in the following diagram. The results of this addition were to move the relative humidity in the stack closer to the target level for the system (Figure TDV1-10). The RH humidity target is determined for specific stack materials and configurations.

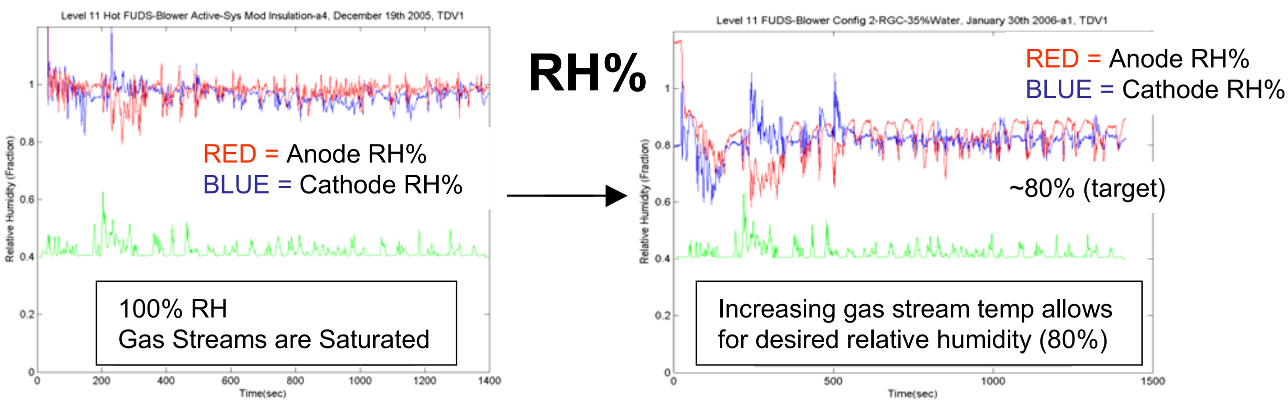


Fig. TDV1-10: TDV1 Stack Relative Humidity with and without Reactant Gas Conditioner

Hydrogen Recirculation Blower (next generation component)

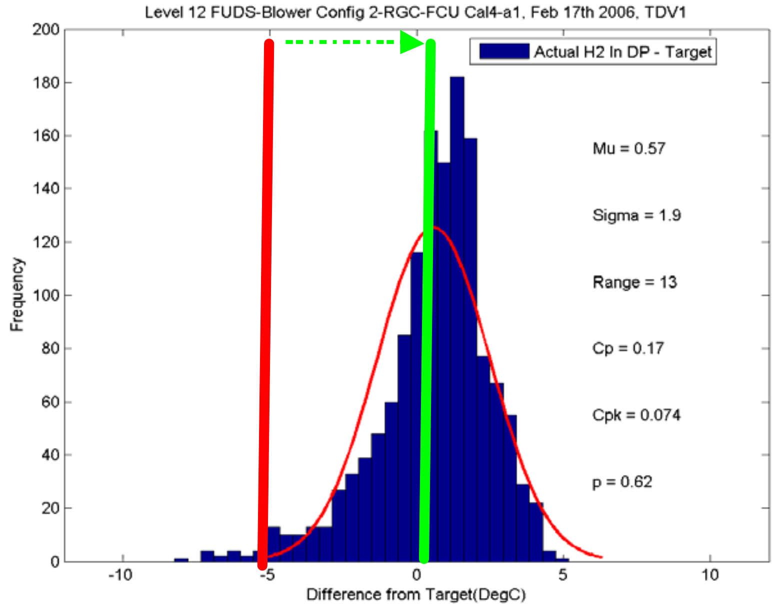
Planned for the generation 2 fuel cell systems, the hydrogen recirculation blower was added to the TDV1 system. The blower is designed to recirculate hydrogen gas that has already been conditioned for proper humidity levels but is in excess of that required to generate electricity. This excess gas is returned to the stack inlet, improving the incoming gas/water vapor mixture, and increasing the efficiency of the system.

The goal of this approach was to maintain stack pressure differential above 30mbar. The expected benefit can be seen at low power levels.

A secondary benefit of this device was improved water management. Stack dew point was increased by about 4° C and a measure of low cells protection was provided.

The following diagram (Figure TDV1-11) indicates the shift of average RH before the installation of the gas conditioner and recirculation blower, and the distribution of RH after.

Anode (H2)



*Recirc Blower and Gas Conditioner installed with increased water injection

Fig. TDV1-11: TDV1 Anode Dew Point change
With Hydrogen Recirculation Blower and Gas Conditioner

Accomplishments and Conclusions from TDV1

- Developed a novel humidity sensor
- Developed a novel gas conditioner
- Characterized FCS interface (RH, DP, P, T)
- Improved Humidification of Anode
- Applied next generation H2 recirculation blower
- Demonstrated improved stack lifetime and reliability
- Completed 30,000 mile dynamometer endurance test
- No stack performance or durability issues
- Stack polarization data shows no appreciable signs of deterioration
- First time dynamic humidity measurement were made in
- First time thermal characterization of anode and cathode gases in vehicle system
- 13 temp measurements during vehicle operation
- First-time characterization of a recirculation blower in parallel and series configurations (stack DP)
- First time next generation blower installed and operated on to vehicle
- Data driven prototype for solving known system temperature issue (RGC)

TDV2 Designed Around Hydrogen

Figure TDV2-1: Ford Fuel Cell Explorer; Designed Around Hydrogen

Demonstration Objective	TDV2
Next Generation Fuel Cell	
Over 300 Mile Range	X
700 bar Hydrogen Storage	
30,000 Mile STACK Life (miles)	
Unassisted Cold Start < 0°C	
Fuel Efficiency (mpg) (*normalized to Focus)	X
FCS Peak Noise (dBA)	X

Table TDV2-1: TDV2 Objectives

Goals:

TDV2 was the first "Designed Around Hydrogen" vehicle. The goal of this development was to:

- Demonstrate a "No compromise package" FCV with center mounted hydrogen tank for increased range
- Demonstrate Hydrogen Storage Architecture for 350 miles range
- Prove out an Under-hood Fuel Cell System packaging
- Demonstrate NVH that is better than the comparable internal combustion engine version of the Explorer vehicle.

Powertrain Architecture

TDV2 used the Ballard Mk902 system as its power source, but employed differently than in the Focus C264. TDV2 was built around a Ford Explorer frame and body, and incorporated all wheel drive (AWD) supported by two battery packs in a hybrid configuration (Figure TDV2-2).

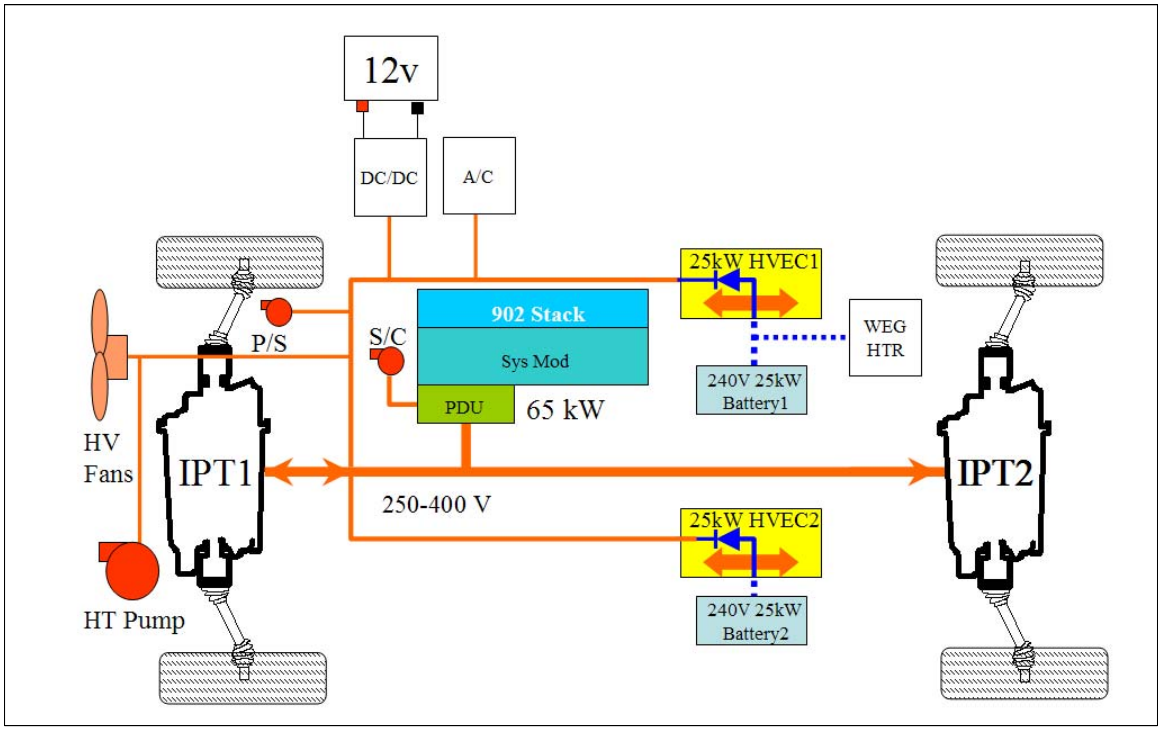


Fig. TDV2-2: TDV2 Physical Architecture

- HyWay 1 Stack/System
- Ford Explorer (SUV) Platform, 6 passenger
- 85 kW gross fuel cell
- All Wheel Drive,
- 2 X 25 kW Hybrid Batteries

How it Works

Like the Ford Focus (C264) the fuel cell provides both power to drive the vehicle, and to charge the batteries. The stack and systems module are mounted under-hood to minimize the intrusion of system element into the passenger compartment. All wheel drive is used to gain experience in systems architecture.

When the vehicle accelerates from a stop, the batteries provide power to the traction motors until the stack system begins to generate enough power to drive the vehicle. In drive mode, the stack propels the vehicle and charges the batteries.

Physical Architecture

TDV 2 is built around a Ford Explorer chassis. The large hydrogen fuel tank is positioned on the vehicle centerline between the frame rails. Passenger seats are positioned on either side of the tank. The fuel call and systems module are stacked under the hood (Figure TDV2-3) and the fuel tank is located along the vehicle centerline (Figure TDV2-4).

Fig. TDV2-3: TDV2 Physical Layout

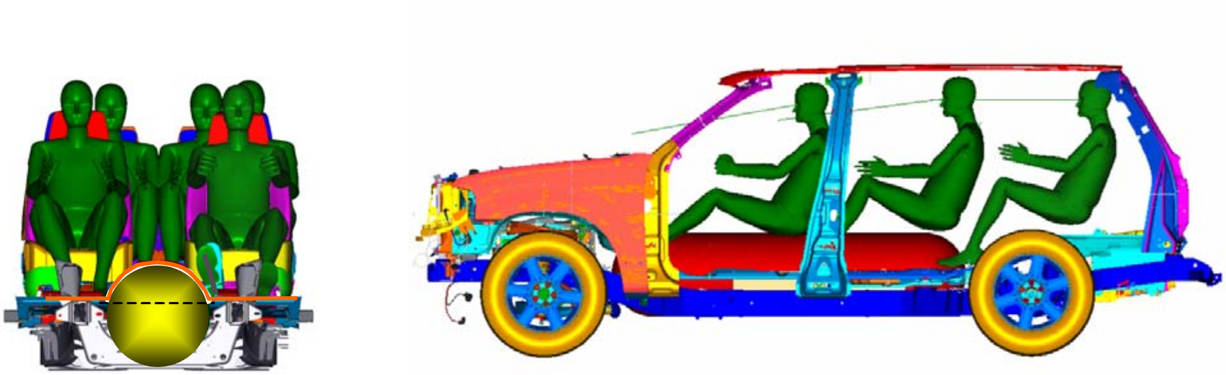


Figure TDV2-4: TDV2 Vehicle Layout

The actual vehicle was produced with a 350 bar fuel tank, while adequate space was allowed with the body and components for the installation of a 700 bar tank which was accomplished in another TDV.

Fig. TDV2-5: TDV2 Physical Layout

Fuel Cell & Battery System

The system used for this TDV is the Ballard Mk902. Batteries are 25 kw, 240 volt Sanyo packs.

Data

Operational data collected on this vehicle included second-by-second strobe data parameters (after 10/06), raw CAN messaging trigger logs during error events and basic information on fuel economy. Detailed data was provided to NREL to build consolidated data products and is not provided here.

TDV 2's hydrogen fuel system design optimizes the storage system density through mechanical packaging to maximize a single cylinder capacity. The result is a tank concept capable of holding nearly 10 kg of H_2 gas with a storage density over 5%. H_2 Storage Density can be improved 30% by packaging of the longer tank shape (Figure TDV2-6).

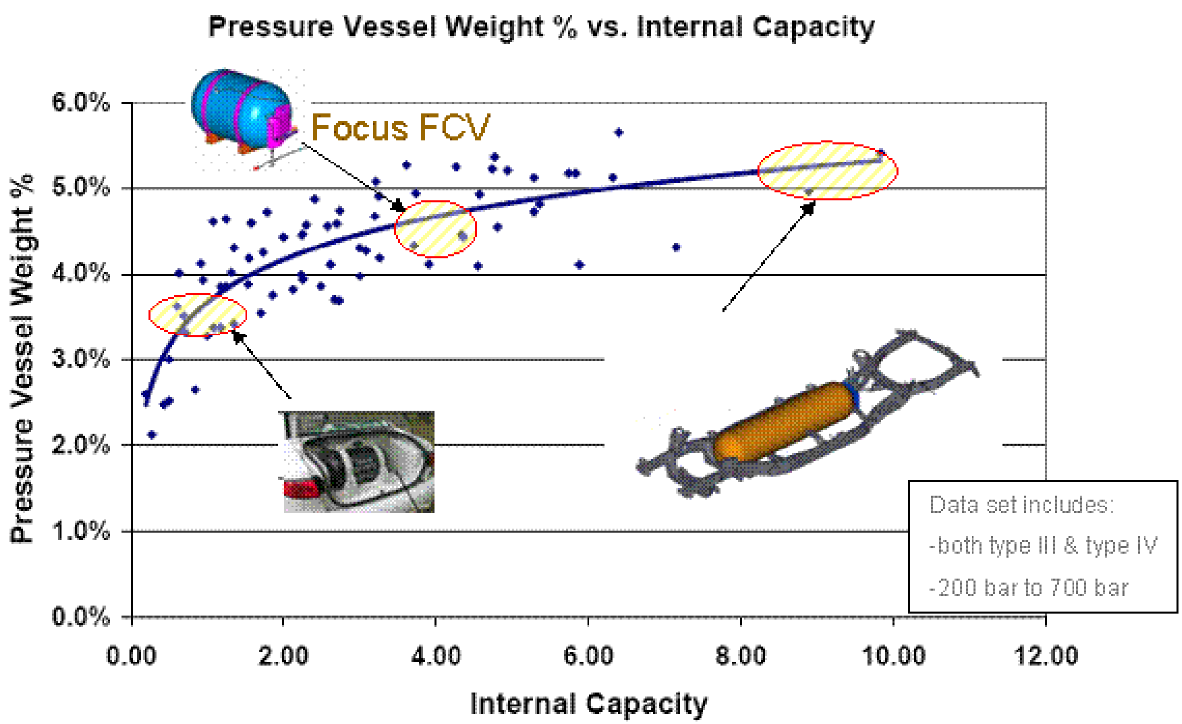


Fig. TDV2-6: TDV2 H2 Tank Capacity/ Weight

Fuel economy was demonstrated and measured on Ford's Dearborn proving grounds. The following plots (Figure TDV2-7 & 8) show the fuel economy at varied sustained speeds, and also during a standard drive cycle. Both are shown as a function of miles per equivalent gallon of gasoline (MPGe). ▲

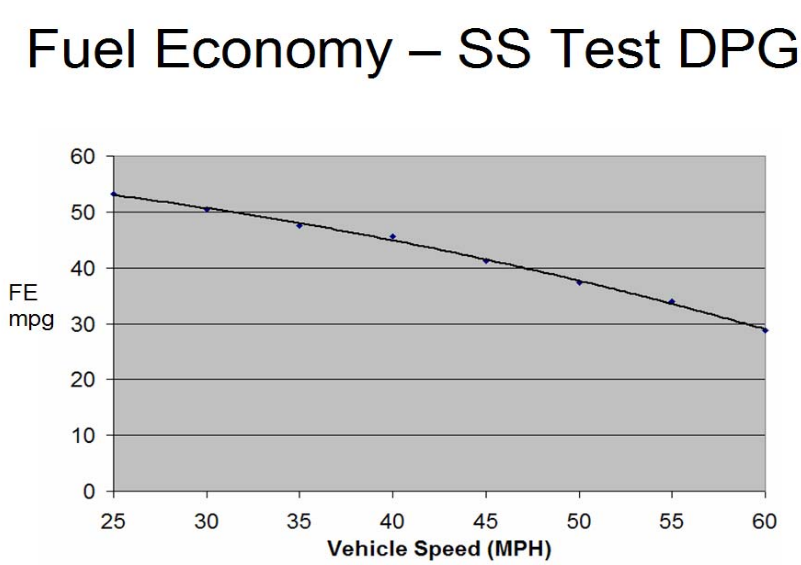


Fig. TDV2-7: TDV2 Fuel Economy at Sustained Speeds

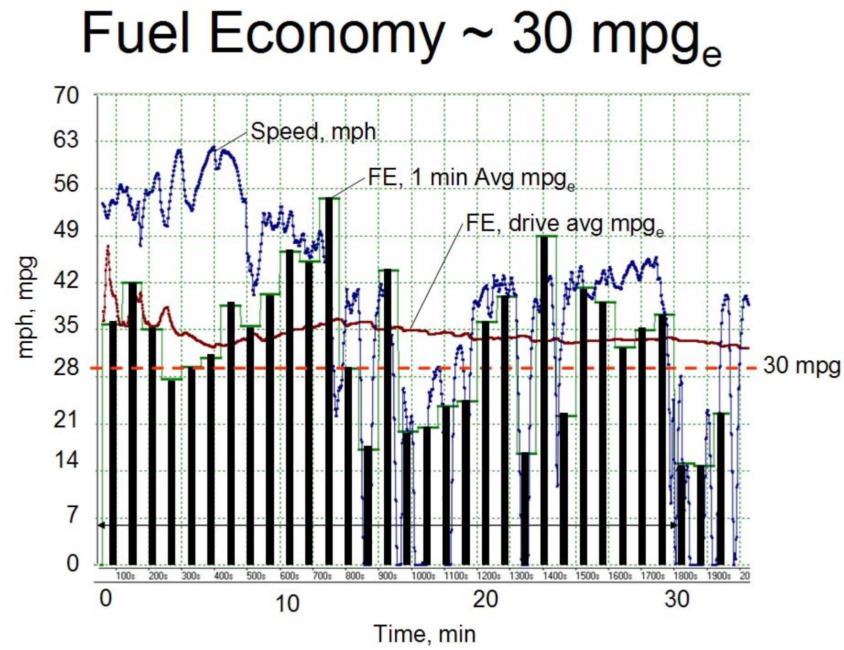


Fig. TDV2-8: TDV2 Drive Cycle Fuel Economy

Noise levels were measured for TDV2 and for standard Ford Explorer. Attention to noise controls in the compressor intake and exhaust, including the installation of muffling components, reduced noise levels rather dramatically as shown in the following figure (Figure TDV2-9).

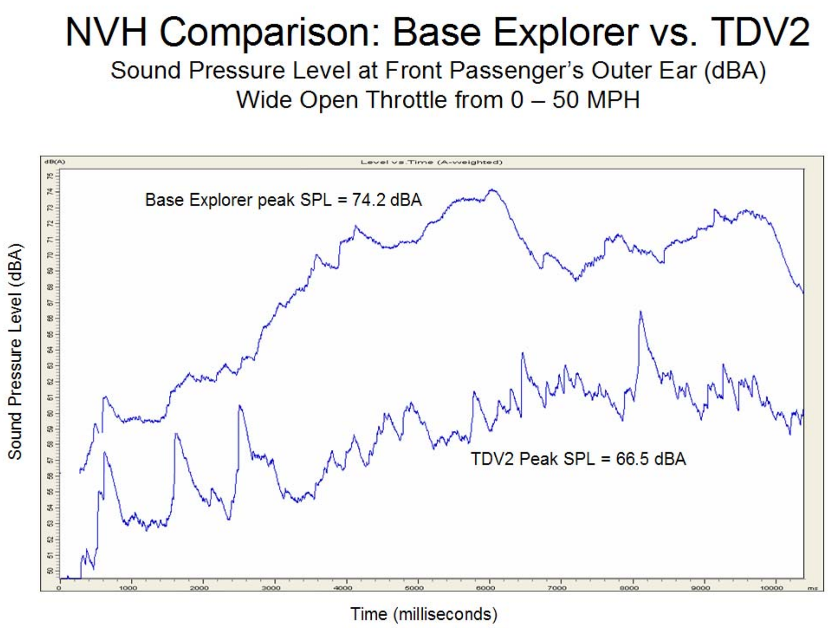


Fig. TDV2-9: TDV2 NVH Comparison

Accomplishments and Conclusions

The following is a summary listing of the accomplishments obtained from the development and operation of TDV2:

- Under hood packaged FC stack and system
- Full electric All Wheel Drive
- Improved vehicle current control
- Hydrogen Storage Architecture for an extended range
- NVH treatment for silent operation; NVH better than base ICE
- Demonstration of Hydra-boost Steering and Braking systems
- 1556 miles distance record for 24 hr run on test track
- Demonstrated Technology in hundreds of exposure drives for interested government and public officials
- Displayed at 2006 LA Auto Show
- TDV2 is still in operation in Iceland with in excess of 25,000 operating miles

TDV3 Hydrogen System Development Vehicle

Figure TDV3-1: TDV3 Designed Around Hydrogen System Development Vehicle

Demonstration Objective	TDV3
Next Generation Fuel Cell	▲
Over 300 Mile Range	
700 bar Hydrogen Storage	
STACK Life (30,000 miles)	
Unassisted Cold Start < 0°C	
Fuel Efficiency (mpg) (*normalized to Focus)	X
FCS Peak Noise (dBA)	

Table TDV3-1: TDV3 Objectives

▲ TDV3 was used to develop advanced cooling systems concepts for future versions of the Designed Around Hydrogen vehicle architecture. The fuel cell system was upgraded twice after the initial build, and the TDV3 platform was re-designated TDV3.1 and finally TDV3.2. TDV3 provided an important improvement activity in the program.

Goals:

- Engineering prototype for thermal system development.
- Test new thermal system design
- Further develop NVH strategy
- Gain experience with HyWay 2, Hyway 2/3 S1 and HyWay 2/3 S2.1 Fuel Cell Systems module designs.

Powertrain Architecture

TDV3 was built with the Mk902 Ballard stack and a second generation of systems module provided by NuCellSys. This was an early generation II system known as HyWay2 hardware. It included a Hydrogen recirculation blower, a gas-to-gas humidifier, an electronic H2 pressure control valve, no active anode humidification (cathode only), and an intercooler. A single 65kW IPT Motor provided the drive supported by a single NiMH battery as used in the C264 Focus.

After initial development, the systems module was replaced with a HyWay 2/3 S1 version for more development. Finally, a NuCellSys HyWay 2/3 S2.1systems module and Ballard Mk 1100 stack were installed as the vehicle was upgraded to the TDV3.2 configuration.

Physical Architecture

TDV3 was similar to TDV2 except that it employed a single IPT and a single high voltage battery pack (Figure TDV3-2).

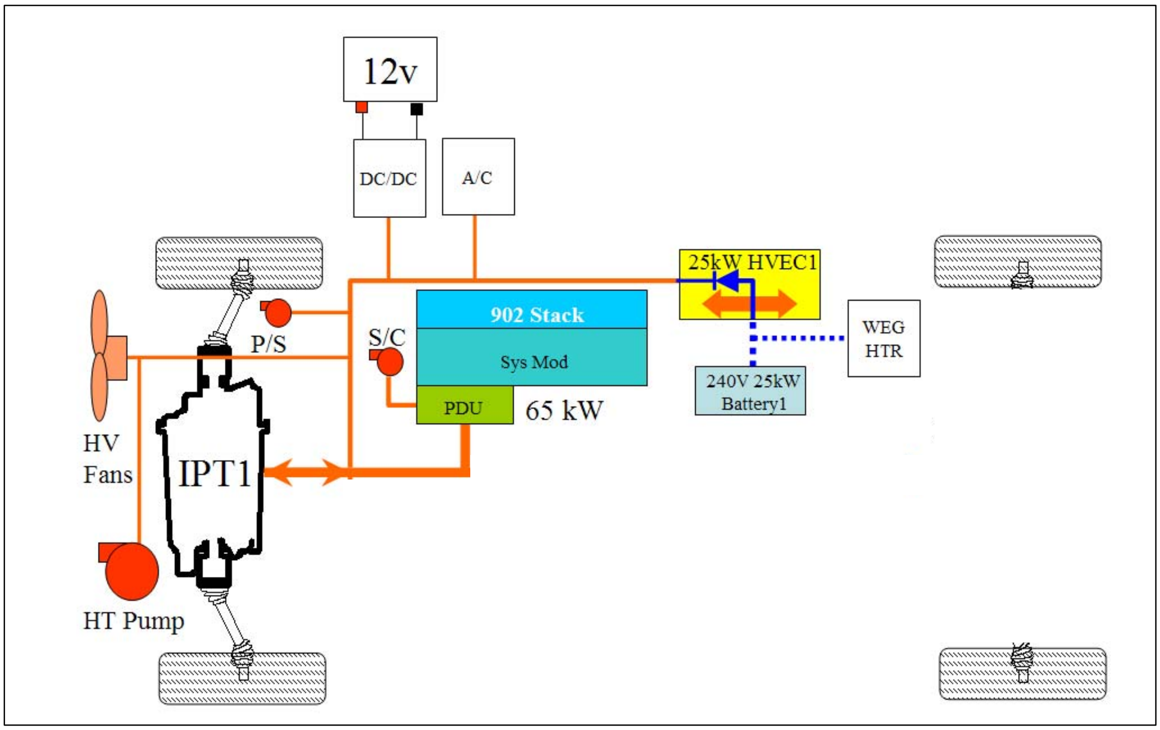


Figure TDV3-2: TVD3 Physical Architecture

How It Works

TDV 3 was not prepared to be a driving vehicle. It served primarily as a development platform for improved thermal systems that would be used in subsequent TDV versions. It was also used as the platform to check newer version of the systems module. This was done by attaching an improved HW 2/3 version of the stack and system. These improved systems became known as S1.1 and S1.2. (System connected with an umbilical, later becoming the gen II HW2/3 hardware, including the stack) Through most of TDV3's laboratory testing, umbilical cables connected the vehicle to the systems module test stands.

This illustration (Figure TDV3-3) provides some views of the analytical output from models developed with TDV3.

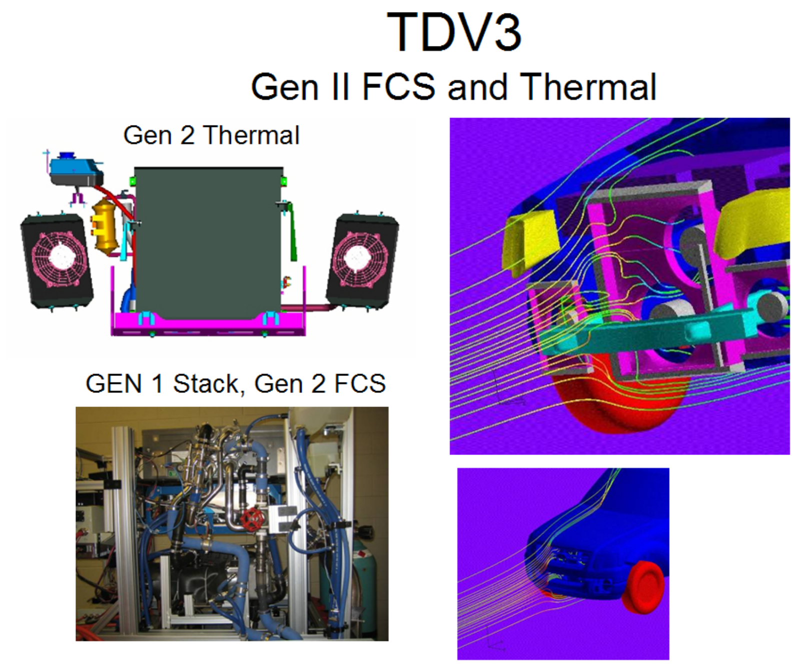


Figure TDV3-3: TVD3 Vehicle Components & Analytical Output

Physical Architecture

TDV3 has the same physical architecture as TDV2 previously described except that it is a two-wheel drive vehicle configured for four passengers. It has the following features:

- 2350kg fuel cell vehicle with electric thermostat
- Dual low temp radiators outside frame rails
- All new cooling hardware using “off the shelf” parts
- Single low voltage cooling fan
- Roll stability and traction control
- TRW low voltage pump for hydro-boost brakes and power steering
- Center mounted 350 bar fuel tank with a range of at least 140 miles based on an estimated fuel economy of 29/33 mpg.

Fuel Cell & Battery System

As described, this vehicle used the Ballard Mk902 stack with various versions of the systems module. The battery was the Sanyo pack used in the C264 vehicle.

Data

Data was not developed with this vehicle other than for design of subsequent TDVs. The HyWay2/3 MK1100 S1 level system was tested, only as an umbilical to the vehicle.

Accomplishments and Conclusions

TDV3 accomplished three important things:

1) Initial thermal development for next FCEV fleet
2) S1.1 and S1.2 FCS engine initial prove-outs
3) Freeze start testing

This vehicle was the development platform for the next iteration of the Explorer FCV, which was identified as TDV3.2 and is detailed in the next section.

Figure TDV3-4: TDV3 As Tested

TDV3.2 Next Generation Designed Around Hydrogen

Figure TDV3.2-1: TDV3.2 Next Generation Designed Around Hydrogen Vehicle

Demonstration Objective	TDV3.2
Next Generation Fuel Cell	X
Over 300 Mile Range	
700 bar Hydrogen Storage	
30,000 Mile STACK Life (miles)	
Unassisted Cold Start < 0°C	X
Fuel Efficiency (mpg) (*normalized to Focus)	
FCS Peak Noise (dBA)	

Table TDV3.2-1: TDV3.2 Objectives

TDV3 was redesigned and converted to a drivable development vehicle and renamed TDV 3.2. The successful implementation of the Highway 2/3 systems module into TDV3 was combined with the 65kw IPT preparing the improvements that were ultimately implemented in TDV4.

The second generation FCS (called HyWay2/3 MK1100 S2.1 system) was installed into the vehicle (TDV3.2).

Goals:

- Freeze start capability
- Efficiency (Key deliverable)
- FCS Lifetime 2000 hours based on bench testing
- Improved power output
  - 90 kW peak
  - 80 kW continuous
- Lower cost

Powertrain Architecture

Built into the TDV3 body and chassis, the powertrain architecture was the same but the fuel cell systems were updated. It contained the following elements:

- HyWay2/3 90kW fuel cell system
- 65kW Induction Motor
- 350-bar H_2 Type III Tank (4.6 kg)
- 50 kW (Peak) Cobasys NiMH Battery
- 50 kW HV DC/DC Buck-Boost
- 30 kW WEG Heater Controls
- Hydraulic Brakes, Parallel Regeneration
- TRW 12VDC EHPAS (EuCD)
- U251 EATC + C264 A/C & H_2 Vent
- TDV3.2 Thermal Components

Figure TDV3.2-2: TDV3.2 Under Hood

The results of this development were a vehicle that demonstrates improved efficiency and fuel economy. The smaller 4.6 kg H2 tank does not provide the range that could only be demonstrated with a larger, high-pressure tank. The four passenger configuration is not intended to represent a commercially viable vehicle.

The resultant performance of TDV3.2 is similar to TDV 4 in respect to the hydrogen systems of the vehicle and for this reason the overall performance is summarized as part of the discussion of TDV4 in the next section of this report. TDV3.2 is still in operation and has accumulated in excess of 3725 miles and 135 driving hours. It has been driven in excess of 4 months, experienced over 90 hours of sub-zero operational testing time and completed over 35 successful freeze startups (temperatures between –19 °C and –5 °C).

TDV4 Designed Around Hydrogen, 700 Bar Fuel, Cold Start Capable

Figure TDV4-1: TDV4 Designed Around Hydrogen, 700 Bar Fuel, Cold Start Capable

Demonstration Objective	TDV4
Next Generation Fuel Cell	X
Over 300 Mile Range	X
700 bar Hydrogen Storage	X
30,000 Mile STACK Life (miles)	
Unassisted Cold Start < 0°C	X
Fuel Efficiency (mpg) (*normalized to Focus)	X
FCS Peak Noise (dBA)	

Table TDV4-1: TDV4 Objectives

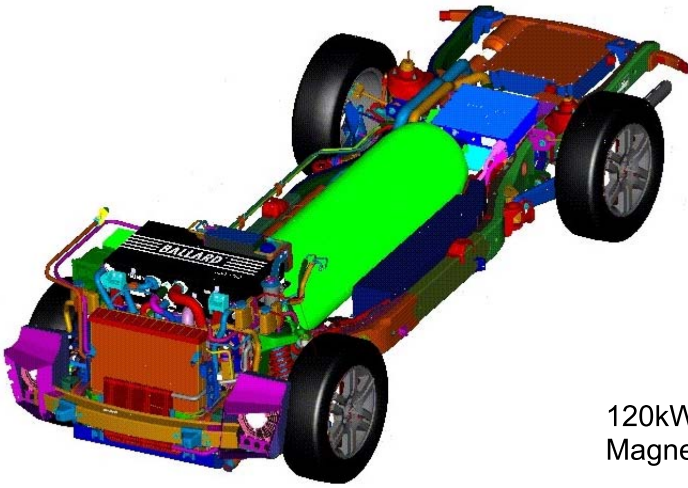
Goals

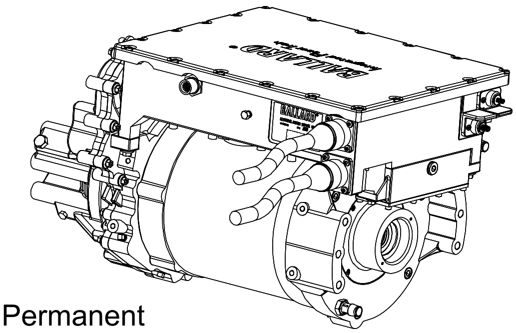
TDV4 is to incorporate all of the learning from prior developments and demonstrations. As such it is the most advanced version of hydrogen fuel cell vehicle using the "Designed Around Hydrogen" architecture. The following are the technology implementations contained in this demonstration vehicle:

- Freeze start capability
- Improved Efficiency
- Fuel cell system Lifetime of 2000 hours
- Improved power output
  - 90 kW peak
  - 80 kW continuous
- 700 bar fuel storage

An inherent part of accomplishing the goals of TDV4 development was significant effort associated with software development and control systems for the vehicle operating system.

Powertrain Architecture





120kW Permanent
Magnet Motor IPT

Figure TDV4-2: TDV4 Powertrain Architecture

Building on the powertrain architecture developed in TDV2 and TDV3, TDV4 was built on a Ford Explorer chassis modified to accept a single higher power IPT in a rear wheel drive form (Figure TDV4-2). The following are the principle elements of the powertrain:

- HyWay2/3 90kW fuel cell system
- Ballard MK1100 stack
- Air Module – A screw compressor with a maximum air output of 380 kg/Hour, used to supply air to the stack module. The compressor is driven by a 20kW high voltage electrical auxiliary drive motor.
- Anode Module (Hydrogen Module) – A hydrogen pressure control valve and ejector assembly with an active hydrogen recirculation pump, is used to supply hydrogen to the stack module and for recirculation of un-reacted hydrogen back to the stack module inlet.
- Humidifier Module – A Gas to Gas style humidifier is used to provide proper humidification of the air supplied to the stack module.
- 120kW Permanent Magnet Motor IPT
- 50kW HV DC/DC Buck-Boost
- 30 kW WEG Heater Controls
- Hydraulic Brakes, Parallel Regeneration
- TRW 12VDC EHPAS (EuCD)

How It Works

Improved Fuel Cell System

The FCS changes developed in TDV3.2 were incorporated in TDV4. The improvements were focused on shorter cold start-up times (Cold start-up is at ambient temperatures above freezing. When below freezing ambient temperatures, a start-up is referred to as a freeze start-up), fast re-starts and more efficient operation.

Cold starts up times, measured in a standardized test procedure, have been reported for all FCV configurations. The objective of TDV 4 (and TDV 3.2) development was to shorten real-world start times as would be demanded by consumers. In the established test procedure, after the vehicle is shut down and prior to beginning a cold start, the system is allowed to heat up for a period of time, and that permits evaporation of some residual water in the fuel cell system, having a beneficial effect in subsequent cold start up. In the real world, this warm up period is unlikely to happen.

Recognizing this, the system shut-down water management strategy was significantly changed. These changes focused on removal of more residual water from all of the key areas in the system. With a "dry" system, TDV 3.2 and TDV4 system was able to demonstrate system start up at temperatures as low as –19 °C (freeze start-up).

An additional benefit of this development was improved re-start time at all ambient temperatures above 0 °C (cold start-up). TDV 3.2 and TDV4 utilize revised controls logic and hardware that permit system re-start in less than four seconds.

Improved efficiency was attained with implementation of a fuel cell system start/stop strategy. In the fuel cell system, operational temperatures above 50 °C can cause the stack membranes to dry out. Dryness is undesirable for a number of reasons associated with efficiency of the chemical reaction, durability of the membranes, life of the cells and other operational concerns. In these TDVs, if the driver's current demand drops below a threshold level and the stack temperature rises to 50 °C, the stack output will be directed to charge the HV battery. But if the battery state of charge is at its maximum allowable level, the stack will be shut off, and the vehicle will operate on battery power alone until it discharges to a level that requires the stack to again begin generating required current at a lower temperature. Restart occurs in less than one second.

A secondary efficiency benefit that results from the start/stop strategy is reduced parasitic losses in the fuel cell system. Below a threshold current draw, the start stop strategy shuts down the air compressor, reducing parasitic current to around 1000 watts. In addition, future revisions have been identified that would reduce this idle current draw to near 200 watts, a very significant reduction from the approximate 2500 watts experienced in the Focus fleet demonstration vehicles.

A gas-to-gas humidifier is installed at the stack inlet. This device improves efficiency by allowing the system to idle at very low net current demand without the stack becoming flooded with excess water.

Altogether, these changes improve the efficiency, durability and start times for the system. Details of the resultant improvements is shown below in the data section of this TDV4 discussion.

Vehicle Systems Controller (VSC) Power Management

The VSC manages the balance of power between the fuel cell system and the battery. At drive-off, the battery supplies the motive power until the driver demand causes the fuel cell to start. The stack provides the motive power and recharges the battery to its optimal level. The power management strategy in TDV4 is designed to respond quickly to changes in driver demand while avoiding power generation in excess of what the battery can absorb. It targets "optimal" current draw from the stack.

TDV4 uses the battery as a current buffer. It acts as a sink for excess current from the stack, and supplements any current to the vehicle drivetrain when the stack is unable to meet driver demands.

The VCS must react quickly to use the battery buffer to avoid over or under estimating current demand. The result of over estimating current demand is unnecessary parasitic losses cause by such things as the compressor running when it could be shut off. Under-estimating current demand results in fuel starvation in the stack and subsequent slow response.

In previous systems, it was possible to have current generated in excess of what the propulsion system and the battery required. This power would then be dumped (consumed by another vehicle device), resulting in losses and an inefficient system.

Physical Architecture

TDV4 has an SUV platform as previously discussed in TDV2 and TDV3 with some specific differences shown here.

- 700-bar H_2 Type IV Tank (9.5 kg)
  - Center mounted fuel tank
  - 700bar H2 system
  - Range +300mi
- 2500kg, 6 passenger configuration

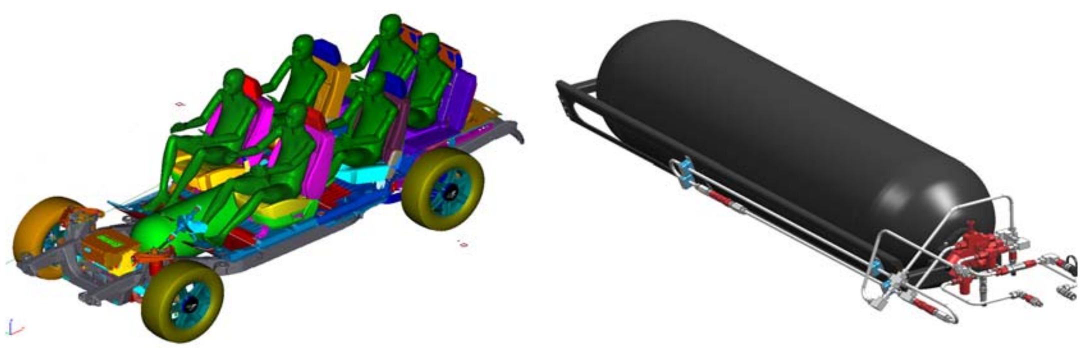


Figure TDV4-3: TDV4 Physical Architecture

Fuel Cell & Battery System

Stack Module (STM)– TDV uses a 408 cell stack module generating a maximum voltage of 430V, maximum current of 400A, continuous output power of 80kW and a peak output power of 90kW with MK1100 stack (Figure TDV4-4).

The BoP system was the Highway 2/3 design developed through a series of technology improvements targeted to meet the overall performance objectives. The battery is a Cobasys 50 kW (Peak) NiMH Battery

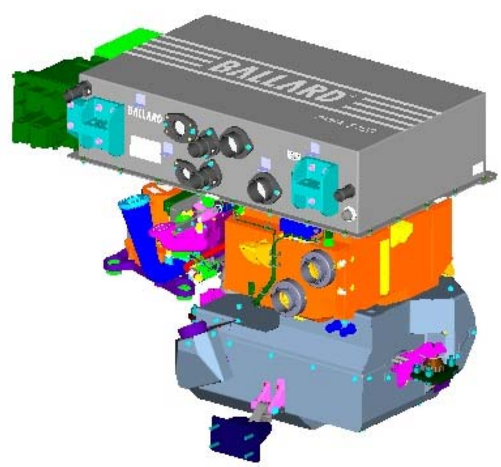


Fig. TDV4-4: Highway 2/3 FCS

700 bar Fuel System

The implementation of the 700 bar fuel system was hindered by multiple problems related to leaks, damage during component installation and early component failure. Due to these issues, the Type IV 70 MPa project used revised assumptions for balance of plant taken from those components used in the Type III 70 MPa project. The resulting accomplishments are:

- Successfully completed ambient fill with pre-cooling
- Successfully completed de-fuel test
- System installed in TDV 4 (Fuel Cell Explorer)

700 bar Fuel System

The results of the fueling studies performed on the 700 bar system are shown in the following plots. The first (Figure TDV4-5) depicts the full fill of 9.5 kg in 7 minutes with operating temperatures maintained within acceptable limits. This fill operation required pre-cooling to keep within acceptable operating temperatures.

The second plot (Figure TDV4-6) shows a successful de-fuel operation in which the entire system was drained. This process takes a considerable amount of time to complete but demonstrates the capability of being performed successfully.

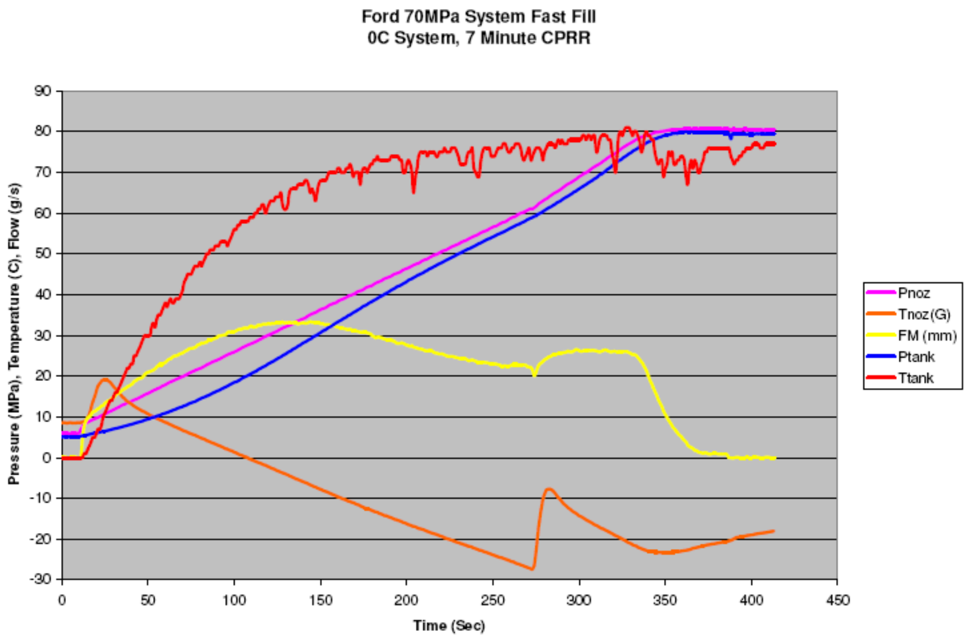


Figure TDV4-5: TDV4 700 bar Fast Fill Test Results

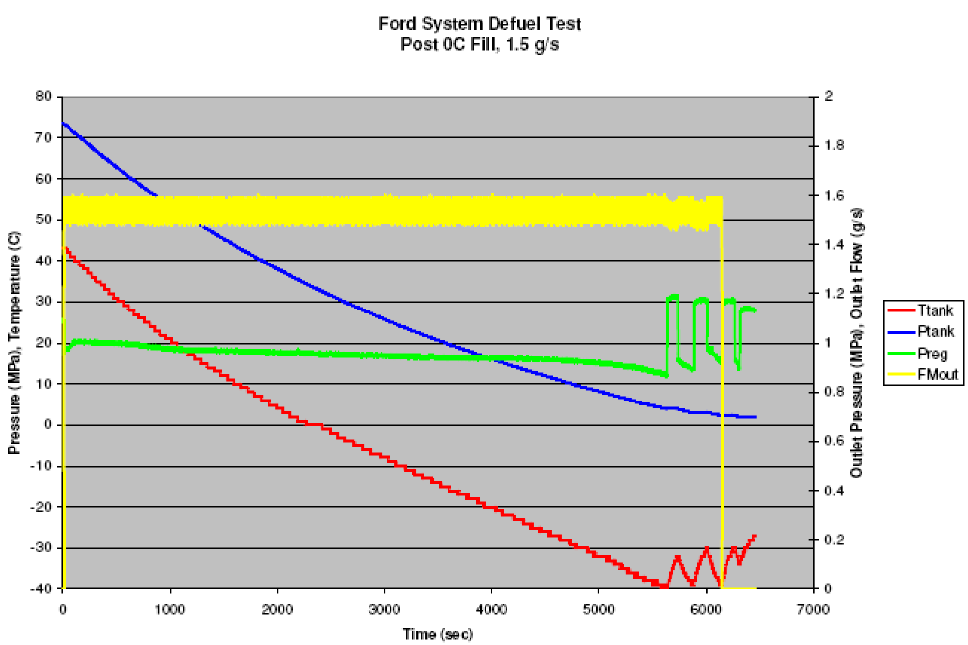


Figure TDV4-6: TDV4 700 bar De-Fuel Test Results

Accomplishments and Conclusions

Each of the goals set for TDV4 were met as demonstrated in the data summary above. Specifically these were:

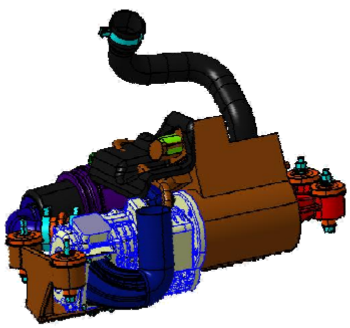
- Freeze start capability at -19ºC
- Cold start time less than 4 seconds for temperatures above 0 ºC
- Improved Efficiency of 55% at 40 kw and a combine drive cycle fuel efficiency of nearly 40 miles/kg in an SUV configuration.
- Fuel cell system Lifetime of 2200 hours
- Improved power output
  - 90 kW peak
  - 74.9 kW continuous at 40ºC
- 700 bar fuel storage of 8kg H2 for a feasible range over 300 miles
  - Successfully completed ambient fill with pre-cooling
  - Successfully completed de-fuel test

Freeze start testing was very challenging. Initial tests took 350 seconds to begin the fuel cell system startup. By the end of freeze start development; a typical -15ºC freeze start required just 45 seconds. Fully conditioned -5ºC starts also improved markedly (<20 seconds). This was possible by optimizing the thermal and water management in the anode sub-system. Removing water during shut down eliminated the need to heat the anode at re-start, shortening the start cycle. The hydrogen recirculation blower was moved to the high-temp cooling loop, eliminating the potential for freezing at low temperatures and improving cold start up.

Although Ford was able to perform better than the initial freeze start time target by a significant margin, it is believed that several improvements can still be made within the existing vehicle and FCS architecture.

In addition to meeting the establish goals, other improvements were made that provide significant improvement of the overall fuel cell vehicle concept. These feature changes and the resultant benefits are summarized in the table below (Table TDV4-3):

Feature Changes	Benefit
Removal of DI Water System	Freezability & Reliability
Gas to Gas Humidifier	Freezability & Reliability
Active H2 Recirculation (replaces ejector)	Reliability & Lifetime
Active H2 Pressure Control	Reliability & Efficiency
Compressor Redesign (no water injection)	Reliability (similar NVH)
After-cooler (no water injection)	Reliability
Lower Operating Pressure	Efficiency
Removal of Cell Voltage Monitoring (CVM)	Efficiency

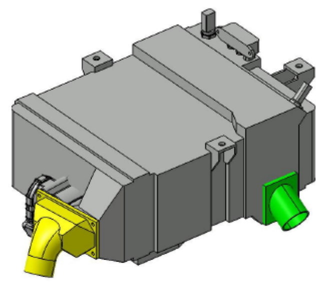


Air Compressor

The air compressor consumes the most power in the systems module. By disabling it during stop mode, energy is saved and no air mass is moved. H_2 purging & anode drainage are also disabled.

H_2 Blower

The H2 Recirculation Blower can be run at minimum speed during stop mode to prevent fuel starvation. The Anode Pressure Control remains active and the Anode Isolation Valve is opened to protect the stack.



Gas to Gas Humidifier

Replaces DI water loop used in the Focus fleet vehicles, improving efficiency by permitting no minimum net current demand at Idle.

TDV4-3: TDV4 System Changes and Benefits

TDV7 APU Configuration

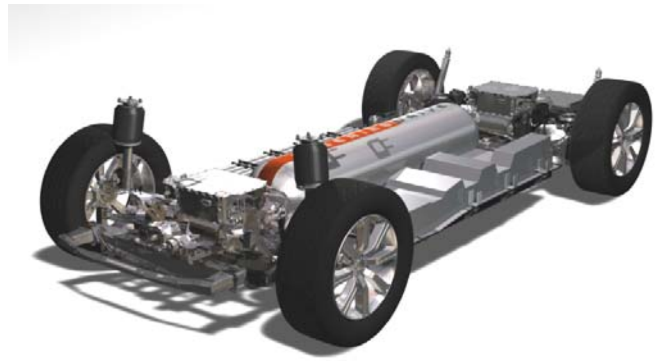


Figure TDV7-1: TDV7 Auxiliary Power Unit Configuration

Demonstration Objective	TDV7
Next Generation Fuel Cell	▲
Over 300 Mile Range	▲
700 bar Hydrogen Storage	
30,000 Mile STACK Life (miles)	▲
Unassisted Cold Start < 0°C	
Fuel Efficiency (mpg) (*normalized to Focus)	**X**
FCS Peak Noise (dBA)	**X**

Table TDV7-1: TDV7 Objectives

▲ TDV 7 utilized a specially designed, smaller fuel cell stack based on the Mk902 stack technology that was used to generate power at two fixed levels during operation. This concept is expected to reduce cost of the stack and increase life of the stack because of the steady state operation.

▲Using the plug-in feature daily, the average range before refueling with hydrogen can be extended to over 400 miles using 25 miles per day from home recharging.

TDV7 Goals:

- Lifetime
- Range
- Reliability
- In house FCS and Stack Development
- APU Powertrain Architecture

TDV7 demonstrates a "series hybrid" architecture in which the fuel cell acts as an on-board fixed-point charger to a Lithium-Ion traction battery. The approach reduces the size, weight, cost, and complexity of the Fuel Cell System while also promising to increase the lifetime of the stack. This architecture may provide an alternative commercialization approach to the current "load following" fuel cell systems.

Powertrain System Architecture

TDV7 is packaged using a “designed around hydrogen” approach. A series architecture places a 336 Volt Lithium Ion Battery as the primary power source for the vehicle. The on-board charger (110/220 VAC) charges the battery overnight using a standard home outlet (Plug-in Hybrid feature, Figure TDV7-2).

Fig. TDV7-2: 110/220 VAC Charge Port

The auxiliary systems (Fuel Cell Air Compressor, Power Steering pump, A/C Compressor, cooling pump, etc.) are placed on this same high voltage bus. The Fuel Cell Auxiliary Power Unit (APU) is connected to the battery through a High Voltage Energy Converter (HVEC) that converts the 150 volt bus to 336 volts at a peak power of 35 kW. The vehicle has three cooling loops to cool the fuel cell system, the dual IPT electric motors and electronics and the battery system. The vehicle is fitted with a 350 bar hydrogen tank that supplies 4.5 kg of useable hydrogen (Figure TDV7-3).

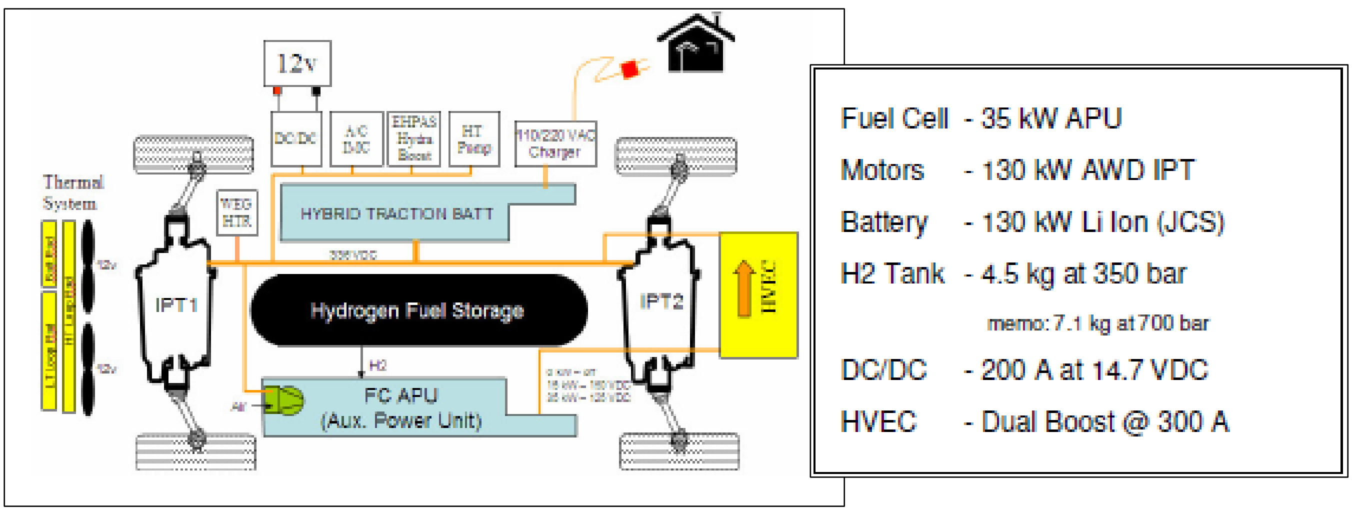


Figure TDV7-3: TDV7 Powertrain Architecture

How it Works

TDV7 is a battery-powered plug in hybrid with a fuel cell that operates as an on-board charger. The vehicle operates in "battery only" mode for the first 25 miles at speeds up to 85 mph. When the battery is depleted to approximately 40% the Fuel Cell Aux. Power Unit (APU) automatically starts and recharges the battery giving the vehicle an additional 200 miles of range. The overall FE equivalent using 420 Wh/mile is 41 mpg_e.

Physical Architecture

The hydrogen tank is located in the center of the vehicle with the fuel cell and battery on either side. The AWD dual electric motors are placed between the wheels. In order to accommodate the 440 kg additional load in the mid-ship of the unibody structure a design concept called "unitized body on frame" is utilized (Figure TDV7-4).

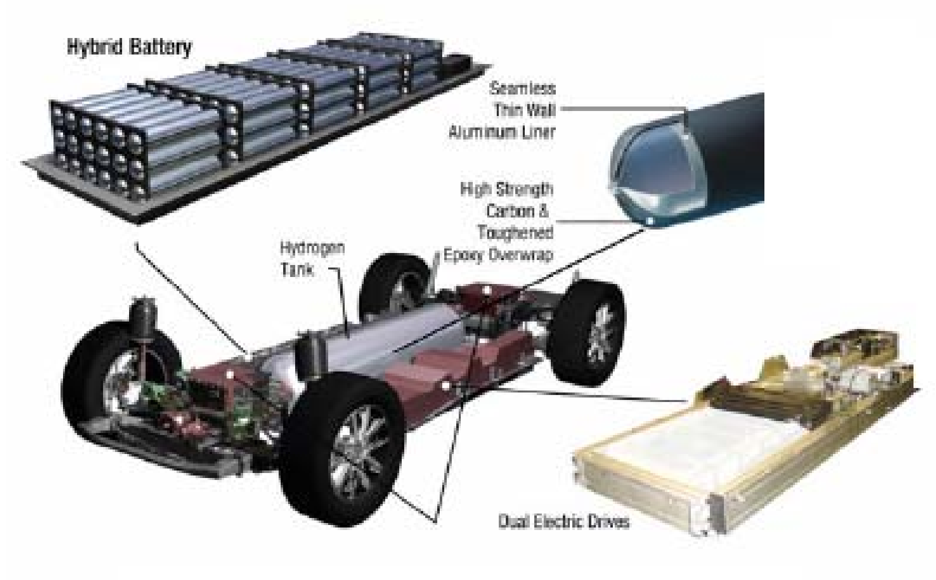


Fig. TDV7-4: TDV7 Physical Architecture

Flexibility

The TDV7 was designed to demonstrate a flexible physical architecture. While the platform is designed to accommodate a Fuel Cell APU, it can also be retrofitted with a combustion engine (3 Cyl Diesel, Gasoline, Micro-Turbine, etc) APU.

Another variant is to replace the APU and the H2 Tank with a Lithium battery large enough for 150 miles range. The engine compartment has 120 L of empty volume allowing top hat flexibility.

Fuel Cell System

The Fuel Cell system operates in three modes: Off, 15 kW, and 35 kW. The idle mode is eliminated which reduces high OCV plate corrosion (life issue) and eliminates negative water balance operation. The 15 kW mode is near peak efficiency (48%) and maintains battery voltage in city driving modes. The 35 kW mode is peak power and used to sustain highway speeds.

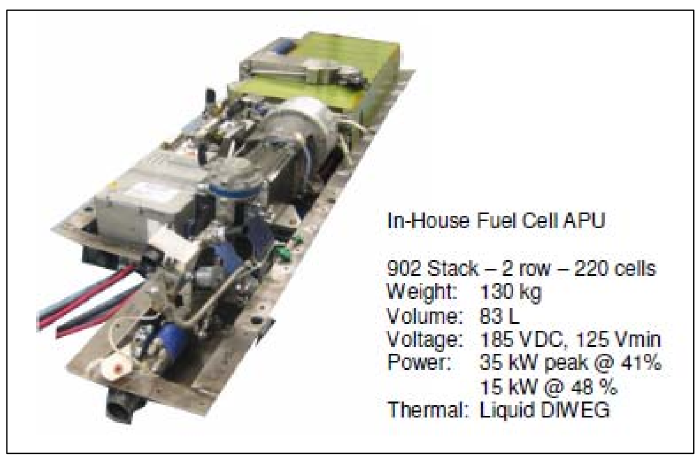


Fig. TDV7-5: TDV7 APU

By operating the fuel cell at 15 and 35 kW the fuel cell self humidifies thus reducing the need for complex humidification systems. However, it has a humidifier on the cathode (a combination of water injection into compressor and the honeycomb substrate), but no humidifier on the anode. It uses ejectors and does not have an HRB for recirculation

The TDV7 APU (Figure TDV7-5) is a simplified derivative of the Focus Fuel Cell. Approximately 115 kg (60%) of weight was eliminated by deleting the cathode and anode contact humidifier, the Power Distribution Unit, 2 cell rows, the 902 Stack – 2 row – 220 cells manifold, the frame, the expander, and piping. By integrating the fuel cell system into a unique "quiet steel" box a significant noise reduction was achieved. Heat integration of the entire FCS in one box also improves freeze start issues and hydrogen leak management strategies.

Battery System

Three battery packs were developed to support the TDV7 project: 1) JCS SAFT Lithium Ion, 2) GAIA (Lithium Technologies) Lithium Ion, and 3) COBASYS NiMH as a back up. The specifications for Lithium packs are as follows:

Type:	Lithium Ion	Lithium Ion
Mfr:	JCS SAFT	GAIA (Lithium Tech.)
Model:	VL45E	HP-602050
Number of Cells:	100 cells	90 cells
Voltage(max/nom/min)	400 / 360 / 230	400 / 360 / 240
Energy (C/3)	15.9 kW-hrs	14.6 kW-hrs
Peak Pwr (20s)	130 kW	130 kW
Cell Weight	107 kg	140 kg
Pack Weight	139 kg	182 kg
Thermal	Liquid Cooled	Air to liquid Hx
Cell Dia X H	54.3 OD X 222 mm	60 OD X 232 mm

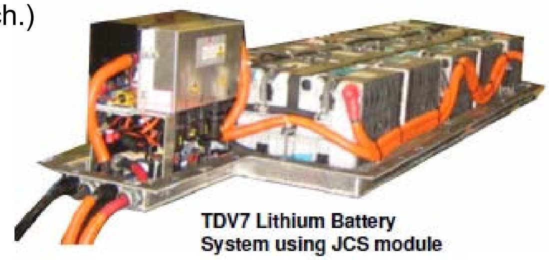

TDV7 Lithium Battery System using JCS module

Figure TDV7-6: TDV7 Battery Pack Specifications

System Sizing

The APU is sized with two basic parameters in mind. The first is having power for a sufficient grade and top speed capability and the second is to optimize for efficiency when using it in stop and go commute cycles. The curve below (Figure TDV7-7) sets 40 kW as a minimum threshold using a base vehicle model of an EDGE with the understanding that in order to better support a vehicle with this system architecture, future improvements in weight and CdA will be required.

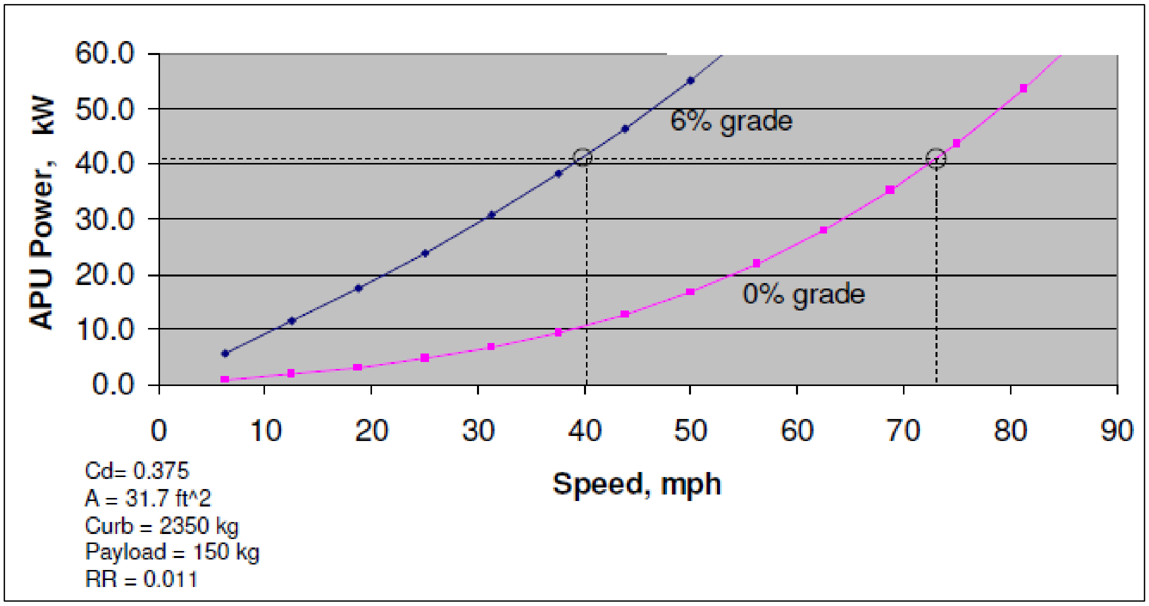


Figure TDV7-7: TDV7 Gradeability

Conclusion

TDV7 explores the benefits of operating a fuel cell system at a fixed point to achieve a 60% reduction in cost and a significant improvement in life. Additional benefits are:

Technology

- Increase Stack Life (>100,000 mi)
- NVH & Freeze Start –one insulated box
- Eliminate Cathode/Anode Humidifier, 2 cell rows, PDU, h/w
- 115 kg reduction in FCS weight
- Modular FC APU design (upgrades)

Business / Commercialization

- Reduce FCS cost >60%
- Less reliance on H2 Infrastructure
- Reduce System complexity
- Flexible Vehicle Design

Customer

- Reduce Fuel Cost (plug in) by 60-70%
- 25 mi BEV Range
- Increased FE (41 mpg SUV)
- Range per fill (400-500 mi)
- NVH (silent)
- Environmentally friendly

TDV7 offers a flexible platform for powertrain development including other APU energy converters and other fuels. A commercialization path can be more readily identified with this approach and should be investigated in parallel with vehicle development and testing. TDV7 is still in operation and has accumulated nearly 13,000 miles and 275 hours of service.

TDV8 Critically Efficient Design

Some discussion of a partial development referred to as TDV8 is provided here to present an overview of a technological vision, built from the TDV7 concept, that may forecast future hydrogen vehicle design elements based on the technical restriction imposed by the state of the art in hydrogen storage and emerging battery technologies.

The advanced design teams looked for a vehicle design that would demonstrate a “proof of concept” that forms the basis for commercially viable hydrogen powered vehicles. Following the TDV7 HySERIES architecture, this Plug-in hybrid fuel cell vehicle would target a significant powertrain cost reduction and have the flexibility to replace the fuel cell generator with other power sources to permit multiple configurations leading to higher volumes and improved vehicle cost. This cost reduction approach was predicated on radically improved vehicle efficiencies.

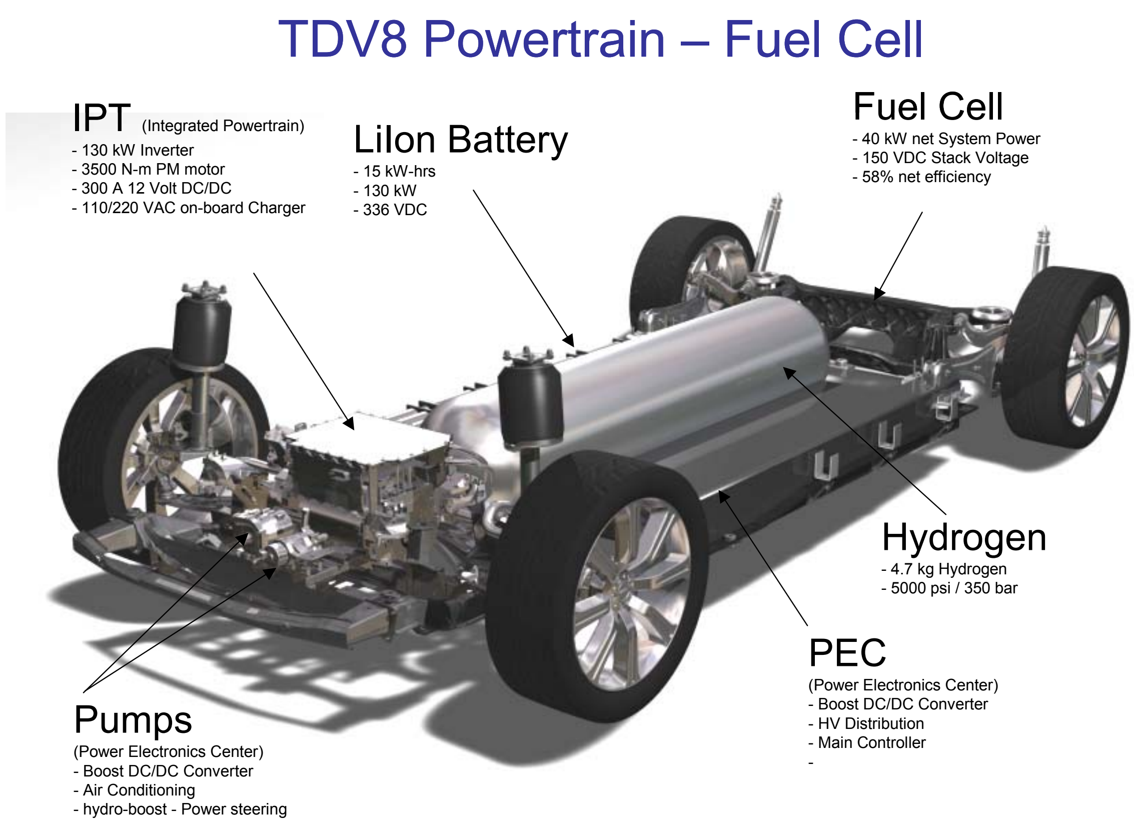


Figure TDV8-1: TDV8 Powertrain Architecture

The vehicle was referred to as the “Critically Efficient Design” as the team recognized the need for optimizing all aspects of the design to provide both performance and cost that would meet customer expectations. Attention was focused on the appearance of the car for both low drag coefficient for required fuel economy, and customer appeal. It was conceived in a manner that permitted the use of an existing “donor platform” in order to leverage the use of high volume parts. And finally, the concept provided for alternative power sources.

The work on this concept was stopped due to cost and manpower constraints. Subsequently, the project was reviewed with the DOE for its key concepts as a means of sharing alternative visions with the program experts.

TDV9 700 Bar Demonstrator

Figure TDV9-1: TDV9 700 bar Fuel System Demonstrator

Demonstration Objective	TDV9
Next Generation Fuel Cell	
Over 300 Mile Range	▲
700 bar Hydrogen Storage	X
30,000 Mile STACK Life (miles)	
Unassisted Cold Start < 0°C	
Fuel Efficiency (mpg) (*normalized to Focus)	X
FCS Peak Noise (dBA)	

▲ TDV9 demonstrated progress toward this objective, extending range in the same vehicle packaging allowance.

Table TDV9-1: TDV9 Objectives

TDV9 Goals

- Upgrade a Focus (C264) to 700 bar fuel storage system
- Provide on-road testing and development

Powertrain Architecture

The powertrain is identical to the C264 Focus vehicles that were part of the fleet demonstration in phase 1 of this demonstration.

How It Works (Fuel System as compared to 350 bar)

	350 bar System	700 bar System
Hydrogen Capacity	**4.2 kg**	**5.2 kg**
Weight (grav. %)	**104 kg (4%)**	**135 kg (3.9%)**
Package Volume (g/liter)	**234 liters (17.9)**	**201 liters (25.8)**

Table TDV9-2: 350 bar and 700 bar Fuel System Comparison

Fuel Storage System

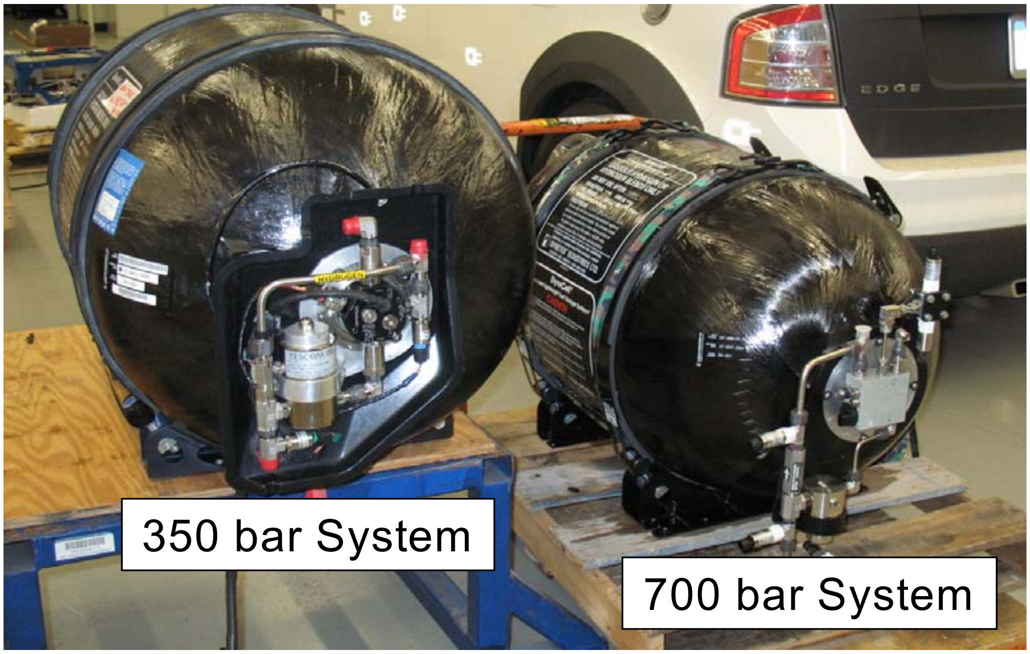


Figure TDV9-2: TDV9 700 Bar Tank Compared to 350 bar Tank

Upgrades include:

- Current tank size upgraded to 700 bar (Ø600mm X 965 mm)
- System weight increase ~ 50 kg
- Revised inline components for increased pressure
- Packaged and integrated components
- System Certification to:
    - ANSI/CSA NGV-2-2000
    - ANSI/CSA NGV-3.1-95
    - ANSI/IAS PRD 1-1998/PRD1a-1999
    - FMVSS 304
    - EIHP Rev. 12 and TUV (under consideration)

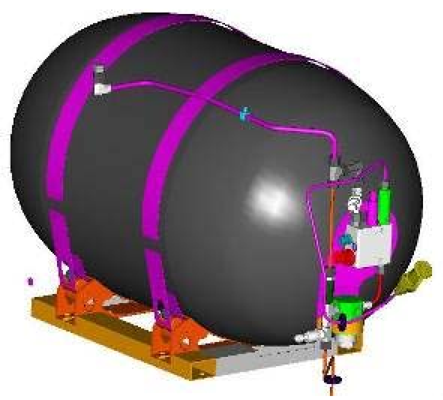


Fig. TDV9-3: 700 bar Fuel Tank

Data

Data from the driving and development testing has been supplied to NREL for use in the composite data products.

Accomplishments

Demonstrated new 700 bar technology through durability and real-world customer cycles: 350 bar vs. 700 bar drive cycle performance data was collected and used to demonstrate statistical equivalence of regulated delivery pressure and transient response to the fuel cell.

Durability mileage accumulation of over 5600 miles on the 700-bar system has been experienced with few issues. When filling stations have greater than –20 C cooling constraints, and components are manufactured properly no operational problems or leaks have been experienced. The system showed the same level of fueling and safety experience for the vehicle operators. Software can be modified to ensure components function as required for effective operation.

Positive vehicle experience gained with 700-bar in real world drive cycles in both urban and highway drive cycles.

Provided the capacity improvement pathway to the 300-mile driving range goal.
TDV9 driving range with 350-bar storage is 200 miles, and with the smaller 700 bar storage range is extended to 250 miles. This demonstrates that larger high-pressure tanks could meet the 300 mile range target.

The high-pressure system improves volumetric density by about 1.5x while maintaining the same weight ratio.

Successful fueling trials have been conducted providing experience that is similar to the experience of the C264 fleet with 350 bar systems.

H2 fuel station fill cycle characteristics data and model have been developed for 700 bar fills providing key input to the design process for future systems developments.

Tank valve control using PWM valve control strategy was confirmed both in test stands and on the vehicle, and controls have been validated.

Achieved the Ford implementation ready milestone, which indicates that the system technology developed in this project meets Ford's internal requirements for use In commercial applications on future vehicles

At the end of 2009, the TDV9 700 bar fuel system had accumulated 5600 miles of test and service drive miles.

Conclusions and Recommendations

In this final report the lessons learned and experience gained from operating Ford Focus vehicles powered by fuel cell powertrains for four years under the DOE program have been presented. During this program the DOE vehicle fleet accumulated over 760,000 miles and the larger 30 vehicle fleet drove over 1.3 million miles. This provided ample opportunity to exercise different hydrogen fueling station technology, perform maintenance and repair service on fuel cell vehicle powertrains, and learn about driver reaction to the vehicle technology in real-world applications.

The data accumulated from the Ford Focus FCV fleet operation, and the testing of Technology Demonstration Vehicles has all been provided to the NREL data center in Golden, Colorado for this project. The work has demonstrated that fuel cell technology is a viable powertrain option for vehicle propulsion from a functional, performance perspective. It was shown to be capable of meeting performance requirements across a wide range of vehicle platforms and automotive duty-cycle stresses (within the known limits of the design, e.g. freezability). The remaining hurdles for fuel cell technology involve the need for significant cost reduction while improving performance, robust operation over a wide range of conditions and improved lifetime.

Based on the experience gained in this program, and through internal research efforts, Ford has concluded that additional demonstration fleets are not required at this time to further the cost reduction work and durability improvements needed to commercialize the technology. Work in cost reduction and lifetime improvement, which will require technological breakthroughs not just incremental improvement, is best pursued in laboratory investigations where lower research and development costs permit novel improvements , prior to returning to high cost vehicle demonstration programs.

Therefore Ford's near term research and development efforts will concentrate on investigating fuel cell stack innovations and fuel cell balance of plant simplification in a laboratory environment. Once laboratory results warrant, then a return to vehicle demonstration of the next generation of affordable, zero-emission powertrains can be undertaken with the goal of reaching a commercially viable implementation.

Fueling Infrastructure

Ford's fuel provider in this demonstration project was BP America. At the outset, BP provided a plan for the development and construction of a number of fueling stations. In the original concept, the following activities are some that were specifically relevant to the Ford demonstration project:

- BP to install a network of refueling stations in Sacramento, Southeast Michigan and Orlando to demonstrate various hydrogen infrastructure technologies. BP to install several hydrogen stations at BP retail sites with additional refueling stations at maintenance facilities and customer locations. These stations will be sited to provide vehicle operators with the greatest access to hydrogen fuel.

- BP to select station locations to allow for significant public visibility and fuelling convenience.

- BP to utilize, in general, a retail compatible hydrogen site layout format. However because BP will use diverse technologies and suppliers, each station will have unique features.

- An economic analysis of the hydrogen infrastructure designs developed will be performed, as well as conduct of additional "forward looking" economic analysis to examine the potential for cost reductions in major system components.

- Documentation and Analysis of the stations that are placed in each region will be performed, once the stations begin operation. Hydrogen cost will be evaluated on the basis of specific technology options at each site.

- The infrastructure data collection system will comprise of two main elements:
    - Online data acquisition (e.g. refueling rate, energy usage, hydrogen quantities)
    - Manual logs (e.g. maintenance, safety incidents)

The actual implementation varied from the original plan for a number of reasons. Significant challenges related to site approvals, building inspections, code compliance and equipment suppliers hindered the ability to meet the original objectives. BP revised the number and location of installed stations and ultimately supported the Ford demonstration with three fleet stations (one each in Taylor Michigan, Jamestown Florida and Sacramento California) and upgraded the Ford Dearborn station.

In the final project report submitted to the DOE, BP ultimately identified two primary objectives of this learning demonstration. These are to:

- Evaluate the operational performance and economic feasibility of distributed hydrogen sites, including the safety of these systems.

- Glean key lessons and knowledge on such operations so that future efforts could build on this knowledge base for scale-up purposes should hydrogen become more competitive.

In spite of the changes, the infrastructure effort provided some key learning to be applied to future efforts. This learning is supplied in the BP report. From that report, there are four areas that have some direct effect on fuel cell vehicle designs for the future and are highlighted here.

Eliminate 700 bar fuel dispensing. BP reports that 700 bar fuel involves high cost and complexity. They observe that current station designs maintain three discrete pressure levels and therefore three sets of pressurized tubes. Future efforts could incorporate a "cascade fill" in which compressors raise the hydrogen's pressure from a relatively low value up to 350 bar. (using a single storage pressure and inter-stage compressor cooling). This type of approach would require future designs of FCVs and refueling sites to be "co-designed" by the OEMs and hydrogen producers to ensure an optimum design and most efficient use of capital in both the vehicles and at the hydrogen refueling sites.

Ford does not agree with this observation by BP. 700 bar fuel is being widely adopted and developed by a broad range of automotive OEM's and it is likely that this technology will assist in defining potential solutions for fuel carrying capabilities to enhance operating range of FCVs.

Hydrogen Purity: There is a need for mutual agreement between the automotive OEM's and the hydrogen station developers on purity specifications. Opinion about what level of purity is required varies between fuel cell manufacturers. This complicates the fuel supplier's ability to plan and installed fuel stations that will be approved by all vehicle OEMs. Ford agrees with BP's observations.
.
Hydrogen Testing Standards: There is a need to finalize development of test procedures and standards applied to hydrogen purity analysis. This needs to be done in concert with the automotive OEMs to permit industry wide understanding of how these assessments are made and reported. Ford agrees with BP's observations.

Fueling Component Designs: Future projects should incorporate innovative technological approaches to refuel fuel cell vehicles. This will require future FCVs and refueling sites to be "co-designed" by the OEMs and hydrogen producers to ensure an optimum design and the most efficient use of capital in both the vehicles and at the hydrogen refueling sites. The needed technological innovations in new designs will provide improved refueling site processes when jointly developed by the OEMs and hydrogen site providers. BP views the current efforts to be focused on the vehicle designs and fuel cell components.

Overall, the economic learning from the project as viewed from the vehicle side indicates that the cost of hydrogen, near-term, presents significant challenge to broadly dispersed adoption of hydrogen as a vehicle fuel. Focus should be made on "return-to-base" refueling operations for fleets of vehicles, rather than using single-driver vehicles. Such operations will ensure high site and vehicle utilizations; otherwise, hydrogen costs will not be competitive.

Appendix

1) Iceland Vehicle Assignment
2) Program Safety Audit Form
3) FMEA Overview
4) Topical Report Abstract
5) Service Procedures
6) Technical Service Bulletins
7) Data Collection Overview

Appendix 1 Vehicle Assignment to Iceland

February 12, 2008

Doug Hooker
US Department of Energy
Golden Field Office
1617 Cole Blvd
Golden, CO 80401-3393

Re: Proposal for Re-Assigning a Ford Hydrogen FCV to Iceland

This letter presents, for your consideration, a request to reassign one of the eighteen Ford Fuel Cell Vehicles currently operating as a part of our Cooperative Agreement DE-FC36-04GO14287. The opportunity that has been presented to Ford Motor Company would provide continued learning in support of the DOE's objectives while offering new learning in a cooperative international effort.

Ford Motor Company has been asked by Jon Bjorn Skulason, General Manager of Icelandic New Energy Ltd. (INE) In Reykjavik, Iceland to consider placing a hydrogen fuel cell vehicle in Reykjavik in support of their national efforts in assessing and developing a hydrogen based economy. Here is what he has provided from their "Icelandic New Energy Initiative":

> Since the early days of this new millennium, Icelandic New Energy (INE) has focused its attention on the testing of hydrogen as fuel. Iceland's abundance of renewable energy resources is chief among the factors that make it a perfect location for this significant fuel transformation: to develop hydrogen into fuel that can sharply reduce Iceland's remaining reliance on fossil fuels.
>
> From March 2001 to autumn of 2005, Icelandic New Energy has managed the Ecological City Transport System project, or ECTOS. This has been the first real-scale demonstration project in Iceland to use hydrogen as a fuel.
>
> During the ECTOS project, the first hydrogen production, storage and filling station has opened in Iceland and hydrogen-fueled buses have driven tens of thousands of kilometers in Reykjavik, saving great amounts of carbon dioxide emissions. Public response has indicated a widespread enthusiasm for the project and acceptance of hydrogen as a fuel.
>
> *Plans for the future include the application of hydrogen as a fuel for passenger cars*, as well as for Iceland's fishing fleet. Iceland is becoming a centre for research and international discourse on the use of hydrogen fuel, a living laboratory for an experiment that could have

global implications. INE's goal of Iceland's conversion from fossil fuels to hydrogen by 2050 is ambitious, but feasible.

New undertakings of INE include a vehicle initiative as described below:

Passenger vehicle RD&D
The goal of INE is to follow the current activities with demonstration of hydrogen passenger vehicles. Already contacts have been established to several car manufacturers with the goal to get a small fleet of hydrogen vehicles for a follow up RD&D project. It is very important to expand the learning by comparing findings from a bus project with passenger vehicles. In Iceland's case ICE-H_2 vehicles could be a perfect bridging strategy to the future fuel cell vehicles.

These efforts, combined with INE's involvement a number of public awareness and educational programs, conferences and learning projects, make Iceland a very attractive place to learn about how a fuel cell vehicle fits into their vision, and perform in their environment.

In our original FCV Demo program plan, Ford had agreed with the DOE to operate eighteen cars for thirty-six months in three distinct environments with the intention of gaining vehicle operational data:

- to direct and augment future design efforts, and
- to provide input to industry-government efforts to define a future hydrogen economy.

With the DOE's support, we are meeting these original objectives. With the steadily accumulating operational experience with the vehicles, we find ourselves better positioned to identify the truly important aspects of the fuel cell vehicle concept. We trust that you agree that this has been a mutually beneficial program, giving the DOE the data and learning to make an objective assessment of this emerging, environmentally beneficial transportation concept.

Because our learning is accelerating, we are confident that important understanding of the technologies will come from the eighteen vehicle fleet during the extension of the demonstration through the end of 2009 as we have discussed. Most of our partner fleets will continue to use assigned vehicles for more that a year beyond the original thirty-six month plans. However, our assessment is that more value can be added to this program if Ford were to re-assign one of the eighteen cars in response to the request from INE. Here is what we think are the benefits to the DOE if a reassignment is permitted:

- Continued supply of meaningful data
- Operation in a completely different environment (grades, humidity and temperatures)
- Faster accumulation of miles/hours of operation is a more operationally aggressive placement
- International cooperation in the assessment of hydrogen as an energy source
- Goodwill demonstration with the people of Iceland.

These benefits would flow from a continuation of the practices that have been established in the current demonstration program. In the attached proposal document, we have detailed our vision of how a joint DOE/INE/Ford vehicle assignment would could be conducted and managed.

We hope that this background and our proposal meet with your approval. Of course we are very open to discussing this in detail, and are willing to consider ideas that the DOE may have in regard to optimizing the effort. With your concurrence, Ford would like to take action to move this vehicle to Iceland in time to be displayed and demonstrated at the *Conference on Hydrogen in the North Atlantic Area* this coming April.

We look forward to hearing from you and we hope you will approve our request.

Greg Frenette
ZEV Programs Chief Engineer
Ford Motor Company

Appendix 1 Vehicle Assignment to Iceland

Proposal to Place a Ford C264 Focus in Iceland As Part of the DOE Controlled Hydrogen Fleet & Infrastructure Demonstration Project Cooperative Agreement DE-FC36-04GO14287

The following are the specific proposals that Ford makes to create an optimized re-assignment of a vehicle to Icelandic New Energy (INE):

Reassignment of a Current Program Vehicle

There is a vehicle assigned to the Florida Department of Environmental protection that has not been used at a level that will approach the goals of the program. This vehicle, P22, has only accumulated 17,300 miles against our target of around 32,000, and operating hours are 637, about 50% of our target 1180. This represents the least use of any of the eighteen program vehicles.

Ford would propose to reassign this vehicle to Iceland. The removal of one vehicle from Florida should not present a technical or programmatic hardship since our original plan called for five vehicles to operate in Florida, but since the closing of the Ann Arbor EPA Hydrogen Fueling Station, a sixth car has been located there.

We have not yet communicated a possible change in placements to the users in Florida.

Vehicle Maintenance

INE has pledged to provide technician manpower to maintain and repair the vehicle in the same approach that has been employed with all other DOE fleet placements. Their technicians have previous training on the Ballard Fuel Cell System because of the current placement of some Daimler FCVs in Iceland.

Technician Training

Iceland will send personnel to Dearborn, MI for required training to service the Ford vehicle. The cost of training will be born by INE and Ford and will not be a part of the DOE sharing agreement.

Ford will use the technical training material that has been developed for all service personnel involved with the Focus FCV fleet in all locations.

Emergency Responder Training

Ford will provide emergency Responder training to local personnel in training classes to be held in Iceland. Safety in operation and management of the vehicle will continue to be stressed as it has in the current fleet placements. Cost of training will be borne by INE.

Appendix 1 Vehicle Assignment to Iceland

Vehicle Maintenance & Repair Parts

This vehicle would be maintained in accordance with the established schedules, and repairs would be conducted with parts supplied from Ford. These parts are part of the original purchases of service parts and spares for the DOE demonstration program. Ford does not propose to re-allocate these early program costs, but rather would supply them to INE as part of the DOE demonstration program.

Possible re-core of the fuel cell stack or component replacements in the systems module would be treated differently. Ford proposes to have INE cover such cost if they occur.

Data Gathering

When P22 is operated in Iceland, data would be collected from the vehicle network gateway (VNG) and transmitted to the Ford data server on a regular schedule. Ford proposes to continue to report this data to NREL as a part of the quarterly data summaries and detailed second-by-second data files.

Use of the vehicle data in Iceland would be constrained. No data reporting or analysis would be permitted with prior Ford approval.

Product Engineering and Service Engineering Support

Ford would propose to supply technical assistance for diagnosis, repair and data collection as well as the use of Ford's third party data collection systems as a part of the DOE program. Man-hours required and the cost of the ongoing purchase services of the third party data collection company would continue to be shared with the DOE as a part of the demonstration project. INE would not share in this program cost. This provides the ability to support the objectives of the DOE in this demonstration, and supports the efforts of INE in their national endeavors.

Logistics

Ford proposes that INE would cover all costs associated with transportation of the vehicle to and from Iceland, as well as shipping of parts and components. Fueling, storage and tool purchases will be INE's responsibility and these costs will not be shared.

Vehicle Marking

Ford proposes to require that the vehicle contain suitable graphics to identify both the DOE and Ford as participants in their use of the vehicle. This tangible evidence of joint participation should help to serve the communications and outreach messages of all involved parties. Vehicle marking will be an INE responsibility, but will have pre-approval from both Ford and the DOE.

Appendix 2 Program Safety Audit Form

PROGRAM SAFETY AUDIT CHECK LIST

Facility: ____

Date: _______________   Audit team: ________________________________

NO.	ITEM	✓
	Communications	
1	Current Program Communications Structure Chart available at all sites	
2	Latest positions and incumbent's names, with specific contact information available at all sites	
3	Incident Reports on file (central location)	
4	14D Reports on file (central location)	
5	Technician Repair Order System (TROS) in use and up to date at all service sites	
6	E-Tracker System in use and up to date at all service sites	
7	Current FCV Operators List available at all service sites	
8	FCV Field Service Action Follow-up Audit Sheets on file (central location)	
9	Up to date FMEA on file (central location)	
	Safety Training Plans	
10	Training materials have been prepared for: • Vehicle Operators/Drivers • Vehicle Fleet Managers • Vehicle Service Technicians • Vehicle fueling training (developed and delivered by BP) • Emergency Responders	
11	Proficiency testing conducted and on record for all training sessions	
12	All personnel trained before delivery of vehicles at each location	
13	All personnel provided with copies of training information, and with access to updates	
14	All personnel trained in both common procedures and procedures specific to their local site	
	Safety Management Procedures	
15	Safety Management Team (SMT) in place and meeting at least bi-monthly	
16	Safety Audits conducted at least annually at each facility	
17	Detailed safety targets in place and being met for each of the facilities	
18	At least 3 Evacuation Drills conducted per year at each facility	
19	Training records available for all personnel (vehicle operators, fleet managers, service technicians, fueling technicians, and emergency responders) at each	

Appendix 2 Program Safety Audit Form

NO.	ITEM	✓
	facility	
20	Safety information posted in all work areas, printed material delivered to all involved personnel and posted on the Program Document Web-site at www.fcevdataviewer.net "Documents".	
21	All hydrogen gas and fire detectors checked monthly at each facility	
22	The up-to-date version of the Operational Safety Plan and referenced documents is available to all personnel at each facility	
	Facility Procedures	
23	Proper permits obtained from city, state and federal levels based on state and local guidelines, for each facility	
24	All refueling sites are selected and designed to provide the required distance between storage tanks and other buildings, property lines, public sidewalks, parked vehicles and places of assembly	
25	Applicable regulations permits, codes, standards and practices are identified. The resultant operating requirements are documented and communicated to the workforce	
26	Emergency information posted throughout each facility to define emergency communications, actions and evacuation routes.	
27	For all fueling facilities, clearly defined start-up, operating, maintenance and shutdown procedures are in place with designated authorities identified (e.g. permit to work, hand-over, equipment and process isolation, etc). These procedures define key operational parameters which are established and regularly monitored. The workforce must understand their roles and responsibilities to maintain operations within these parameters	
28	All refueling stations safely meet standards for required pressure relief valves and hydrogen compatible components	
29	Pertinent records are maintained, available and retained as necessary. Obsolete documentation is identified and removed from circulation	
30	Any location where hydrogen gas may be present as the result of a vehicle service procedure, fueling procedure, defueling procedure, storage or venting is marked with a Hydrogen Hazard Sign.	
31	The up-to-date FCV service manual is to be located in a place that is readily accessible to the service technicians at each service facility	
32	Evacuation sketch prepared and posted at key locations in each facility	
33	Warning signs in all facilities prohibiting smoking, welding and other sources of combustion	
34	Other safety requirements for vehicle hoists, fork lift trucks, cranes, etc. in place and clearly posted in service facilities	
35	Hydrogen refueling stations are keycard activated ensuring that only properly trained and authorized drivers and personnel have access to pump hydrogen	
36	Local procedure in place for operations at each site during rain and lightning	
37	Local procedures in place at each facility for disasters such as tornados, hurricanes, earthquakes, bomb threats, etc.	
38	Local procedures in place at each facility for response to power failures	
39	Local procedure in place at each facility for access control	
40	Local procedure in place at each facility for contacting emergency response personnel	
41	Local procedure in place at each facility for maintenance and calibration of safety	

Appendix 2 Program Safety Audit Form

NO.	ITEM	✓
	equipment	
42	Local procedures in place at each facility for limiting maximum allowed hydrogen charge of vehicles inside building	
43	Local procedures in place at each facility for operation of vehicles inside building	
44	Local procedures in place at each fueling facility for operation of local equipment	
45	Local procedures in place at each facility for admittance of non-fuel cell vehicles	
46	Local procedures in place at each facility for defueling and purging vehicles	
47	Local procedures in place at each facility for response to and reporting of safety incidents	
48	Local procedures in place at each facility for vehicle traffic and parking control on site	
49	Local procedures in place at each facility for handling compressed gas cylinders and other hazardous materials	
50	Local procedures in place at each service facility for fueling, defueling or purging hydrogen vehicles inside the building	
	Safety Equipment at each facility	
51	Portable hydrogen gas detectors available at all facilities	
52	Continuous hydrogen gas detection system installed at all service facilities	
53	High level ventilation system installed at all service facilities	
54	Fire detection and warning system installed at all service facilities	
55	Hydrogen fire sensing and warning system installed at all fueling facilities	
56	Emergency hydrogen shut-off installed at all hydrogen fuel dispensers	
57	Remote hydrogen shut-off installed at all hydrogen fueling facilities	
58	Safety glasses available, with usage requirements posted	
59	Face shields suitable for protection from electric arcs available in service facilities	
60	High voltage rubber insulating gloves available, with usage requirements posted	
61	Fire blankets available at all facilities	
62	Means for grounding vehicles available at all servicing and fueling stations	
63	Orange cones available for marking off safety perimeter around vehicle during service or fueling from a mobile fueling facility	
64	Approved fire extinguishers available at all service and fueling facilities	
65	Non-conductive safety hook for shock victim rescue available at all service facilities	
66	Straw brooms for hydrogen fire detection readily available at all facilities	
67	Unobstructed access paths to straw brooms, fire extinguishers, safety hooks, fire alarms, emergency shut-down buttons, and emergency exits at all facilities	
68	All dispensing stations equipped with special hoses and appropriate shut-off valves that automatically cut the flow of hydrogen if the hose is disconnected.	
69	First aid kit readily available at all facilities	

Appendix 3 FMEA Overview

December 7, 2005

Keith Wipke
Senior Project Leader
Electric & Hydrogen Technologies & Systems Center
1617 Cole Blvd
Golden, CO 80401-3393

Dear Keith,

Please find enclosed two documents addressing the Fuel Cell Vehicle Demonstration project requirement for an FMEA submission.

The first document is a presentation file that provides a description of the Ford Motor Company approach to planning and assuring vehicle safety in the FCV demonstration program. It presents the current practices, approach to leak detection, our limited operating strategy, fueling features, modeling and testing. This overview summarizes our efforts to plan for foreseeable safety related issues during vehicle design and development.

The second document is a matrix that identifies Key Safety Failure Modes, Effects, Causes and Actions taken to ensure safety. This matrix represents an extraction from Ford Motor Company FMEA reviews of the unique vehicle systems in the Fuel Cell Vehicle. The unique fuel cell vehicle systems covered are:

1. Fueling Interface
2. Fuel Storage
3. Fuel Cell
4. Vehicle Hydrogen System Leaks

Our matrix represents the review of 1723 individual failure modes for these systems. Our engineers identified 181 high priority issues from that total. Finally, 76 key safety related failure modes were selected for this report.

As previously agreed with the DOE, the inclusion of failure modes was made based on the assignment of numerical ratings, by teams of expert vehicle engineers, for Severity, Occurrence and Detection of a failure mode, and represent, in their opinions, those items that present the most significant safety related issues for this vehicle design. As also agreed, our matrix does not include those rating factors, since they address some of our company's most confidential vehicle development information.

Appendix 3 FMEA Overview

Submission of this information to the controlled data center at NREL is the methodology agreed to by the DOE and Ford Motor Company as the most appropriate method for protecting the level of information we have provided.

With these two documents, we believe we have met the program requirements for the submission of a high level FMEA review and we trust that this submission meets with your approval. If there are questions that you would like us to address as a result of your review, we would be pleased to provide input that clarifies the information presented.

Thank you for your guidance in the preparation of an acceptable format for this deliverable.

Greg Frenette
Chief Engineer
Fuel Cell Programs, R&A SMT
Ford Motor Company

Appendix 4 Topical Report Abstract, October 2007

Appendix 4 Topical Report Abstract, October 2007

This report provides a summary of the most critical of the currently identified challenges to moving the Fuel Cell Vehicle (FCV) to economic viability, and a projection of those factors that will dictate transition to commercial viability. It is assumed that commercially viable sources of high quality, affordable hydrogen are in place to make private ownership a conceivable reality, without which commercial viability of the FCV concept cannot be achieved.

The FCV will become both economically and commercially viable when technology breakthroughs are made, cost, performance and service meets customer expectations, and return on investment (ROI) for Original Equipment Manufacturers (OEMs) becomes realistic. Due to the uncertainties in these areas, it is impossible to make an accurate forecast of the timeframe in which viability will be achieved. Ford Motor Company internal consensus points to at least a 30-year evolution of technology (that began in 1995), vehicle and infrastructure before the concept approaches economic and commercial viability.

Commercial viability of the FCV can be foreseen with products that meet consumer expectations for performance and cost. Application in at least three commercially viable vehicle platforms will be required to attain the 500K volume directed by the DOE and to drive cost reductions. The replication of vehicle development and manufacturing costs for multiple platforms increases the challenge of commercial viability. Many billion dollars in industry wide investments will be required without the prospect of near term return on investment - exposing automakers to potentially stranded investments in the event of alternative technologies becoming commercially viable and accepted by consumers.

Increasing FCV production levels can be accomplished with cooperative government and targeted fleet sales as a means to set the stage for more traditional retail consumer purchases. Each phase of commercial development is challenging, owing to the extensive and complex nature of the hydrogen technology being deployed. Sufficient numbers of government fleet placements to support multiple automobile manufacturers, economics of central fueling for fleet operators, and a very large projected cost penalty for vehicles purchased by early-adopters make it especially challenging to paint a picture of the commercialization pathway.

A substantial societal payback of the price premium for fuel cell technology over internal combustion technology can be attributed to its zero emission capability from the vehicles and the potential for ending the nation's fossil fuel dependency. However, these significant benefits are difficult to estimate and have not been quantified. These societal benefits have to be calculated and factored into the FC commercialization analysis and are likely to manifest in the future as incentives, mandates and taxation on polluting technologies. How society can pay for the benefits provided by these technologies also needs to be addressed.

Forecasting future system costs from experience to date and using current technology components and systems is very difficult. Predicting the economic viability of FCVs in high volume requires an understanding of current and upcoming research breakthroughs that will migrate to products and eventually reduce design cost and improve performance. Another identifiable need is better definition of the cost models for fuel cell stack, systems module, hydrogen storage, traction motor and high voltage battery to adequately forecast the individual system cost, the cost reductions from the scale effect, other manufacturing efficiencies and material supply issues.

Appendix 5 Service Procedures

Appendix 5 Service Procedures

1.	2005 Towing Manual-Final-signoff.pdf
2.	AirProducts safetygram_4.pdf
3.	Alignment Specs.pdf
4.	Ballard P&ID Diagram SCH5100330_Rev_0C_PID_HyWayI.pdf
5.	C264 FCEV Flatbed_Towing_Hydrogen 2-29-08.pdf
6.	C264 MaintenanceCare_Schedule_TROS ver 2-15-06.pdf
7.	C264 PDA Installation Manual 1-9-06 rev_mjo.pdf
8.	C264 Service Data Collection Procedure - BCM - 20050310.pdf
9.	CaFCP_Map.pdf
10.	Debubbling Process HT_LT 9-13-04.pdf
11.	Decoding DTCs 4 to 5 digit format.pdf
12.	di_pump_outlet_pressure_sensor_work_instruction_040227.pdf
13.	di_tank_level_switch_work_instruction_040226.pdf
14.	di_tank_temp_sensor_work_instruction_040227.pdf
15.	di_water_pump_work_instruction_040226.pdf
16.	EHB - Hydraulic Schematic Diagram.pdf
17.	FC Stack Bracket Thread Repair Helicoil.pdf
18.	FCEV C264 Alignment Specs.pdf
19.	FCEV Module Network.pdf
20.	FCEV PRE-DELIVERY3.pdf
21.	FCS process fluid flow.pdf
22.	FGD2998 Replacement process.pdf
23.	Fuelcells course AirProducts.pdf
24.	H2 High Pressure Leak Test 092105.pdf
25.	H2 Refueling valve installation_replacement.pdf
26.	H2 WDS SMTLIFuelPad-WDS FUELING Procedure.pdf
27.	HT_LT Diagram C264.pdf
28.	HV Battery R_Mode Reconditioning 90 day procedure 5-19-05.pdf
29.	HV Leakage Diagnostic Procedure Updated 6-10-04.pdf
30.	IPT CrossSectionGearBox.pdf
31.	Keyless FOB Programming FCV 2002 MY.pdf
32.	LT-Coolant_TexacoMSDS-fromWeb-SimilarNumberNotSame 3-18-04_P.pdf
33.	No Start.pdf
34.	Nyogel installation Procedure.pdf
35.	PDA FCV Users Guide 1-9-06.pdf
36.	PDA Powerpoint Schematic - Rev B.pdf

Appendix 5 Service Procedures

37. PDU high voltage discharge proceedure rev 5.pdf
38. PDU leak test proceedure rev 6.pdf
39. PDU RandR proceedure rev 4.pdf
40. Power Steering Bleed Procedure.pdf
41. RCM Reprogramming with NGS 10-27-04.pdf
42. Refueling valve installation_replacement.pdf
43. Remote Keyless FOB Programming FCV 2002 MY.pdf
44. Response to H2 Leak 092105.pdf
45. R-Mode Process Diagram.pdf
46. SM di_pump_outlet_pressure_sensor_work_instruction_040227.pdf
47. SM di_water_pump_work_instruction_040226.pdf
48. SM FC Stack Bracket Thread Repair Helicoil.pdf
49. SM stack_inlet_outlet_coolant_temp_sensor_work_instruction_0.pdf
50. SM stack_module_leak_tests.PDF
51. SM SYS Module_lower_frame_removal.pdf
52. SM WRK5100403 AIR MODULE OIL SVCE.pdf
53. SM WRK5100570_0C DI tank drain and fill.PDF
54. SM WRK5100573_F3000_filter_SERVICE.PDF
55. SM WRK5100574_ION_CARTRIDGE_REPLACEMENT.pdf
56. SM WRK5100695_0D system module replace.pdf
57. SM WRK5100696_0E stack module replace.pdf
58. SM WRK5100699_0C DI tank lvl sw replace.pdf
59. SM WRK5100700_0B DI tank temp sensor replace.pdf
60. SM WRK5100701_0B STM temp sensor replace.pdf
61. SM WRK5100842_0A STM vent filter replacement.pdf
62. SM WRK5100970_FCS fluid port protection.pdf
63. TROS Tips rev mjo 11-17-05 .pdf
64. VSC Outline of functions Summary.pdf
65. WDS H2 Tank Purging Procedure 092105.pdf
66. WDS PID List All Modules 4-5-05. pdf.pdf
67. WDS PTU battery pack replacement procedure.pdf
68. WDS SMTLIFuelPad-WDS Defueling Procedure 092605.pdf
69. WDS SMTLIFuelPad-WDS FUELING Procedure.pdf
70. WDS SMTLTank Presure Procedure.pdf
71. WDS Updating OPERATING System CD method.pdf
72. WDS Updating VEHICLE MODULE Software CD method.pdf
73. WDS Updating with new Vehicle Software CD method.pdf
74. Welding Precautions FCV.pdf

Appendix 6 Technical Service Bulletins

Alphabetic TSB List

TSB Number

08-07-01	3 Way Valve connector Reseal
05-04-05	AC O-ring Information (All orings used on this vehicle)
06-08-01	Aux Drive - System Module - Stack Module Serial Numbers
07-12-01	Axle Shaft Joint Noise - Boot, Joint and clamp replacement.
06-01-03	Brake Lights ON - Brake Pedal Switch Adjustment Procedure
05-08-02	Brake System ACU replacement
05-04-01	Carpet Contact to Steering Shaft
05-04-02	Carpet Detachment (Side step well area)
05-11-03	Condensation - Front Lower lights Park/Turn
05-07--02	Connector C51 Check and retorque attachement bolt
05-08-07	Defueling Valve Noise Oring Mod
07-06-02	DI Water Line Stack (Check and Clean)
08-05-01	Di Water tank plug replacement
05-07-05	DI WEG Water Filter expiration date
06-08-03	EHB- High Pressure Accumulator Connector
05-04-04	EMM Time Out No Refueling
07-03-01	FCEV Update Battery Control Module (BCM) Software Level 12A
06-01-01	FCEV Update to Job 2 Software Levels (Version 12)
07-01-02	FCEV WDS Maintenance (Information Only)
05-08-05	Front Creaking Noise - Springs
05-09-01	Front Seat Adjuster Cross Link Wires
05-06-01	FSC HV Battery SoC Vancouver Vehicles FSC
05-10-01	Gear Shifter Lever Transitional Fault code
05-11-01	Handle - Pass Assist Grab Handle
05-03-23	High Voltage Battery Air Handling System Filter Orientation
05-08-04	HT 3 Way valve Reseal Process
06-08-02	Hydrogen Storage Vessel - (Dynetek)
05-08-06	IPT 3 Phase Cover Oring leaking MOD 1
05-04-07	IPT Oil level Check Procedure
05-04-03	Low SLI Battery Guidelines
05-05-03	LT pump protective Sleeve repositioning
05-05-02	LT Valve Screening Process
05-05-0_02	LT Valve Service Part Testing Process
06-02-01	Maintenance Care Schedule Revised (Date 2-15-06)
05-06-02	New NVH Cover R&R Instructions
05-03-26	New PDU Procedures UPDATED
06-09-01	PDA System Removal
05-03-28	PDU Assy Procedure Update
05-08-01	Rear Seat Cushion Arm Rest Staples
05-07--01	Rear View Mirror Pivot Joint (Sticky/Binding)
05-07-04	Replace Air Module mounting bolts and washers
05-05-01	R-Mode HV Battery Reconditioning Tips Info
05-12-01	Serial Numbers - Major Components List

Alphabetic TSB List

07-06-01	Service Monitor Version 52 Available for use in the field
06-01-02	SLI Low Voltage Battery Conversion
07-07-01	Software Level 12B Module Updates
07-09-01	Stack Module Enclosure Damage LV Connector
05-08-06_02	Supplement IPT 3 Phase cover terminals inspections MOD 2
05-06-01_02	Supplemental FSC Hv Battery SoC ALL Vehicles
05-07--03_02	Supplemental VNG Compact Flash Card Memory
05-04-06	Thread Repair
07-01-01	Transfer Leak Detection Procedure
05-11-02	TROS tips for smoother operation
05-03-27	Updated H2 Pressure Test Procedures
05-03-24	Vehicle Confirmation Relay Fueling
09-06-01	VNG Battery Replacement
05-07--03	VNG Compact Flash Card Memory Update
08-11-01	VNG Download - Hardware Method
05-03-25	WDS Lost Comms Defueling
05-04-08	Wheel Alignment Specs

TSB Summary by Bulletin Number

TSB Number

05-03-23	High Voltage Battery Air Handling System Filter Orientation
05-03-24	Vehicle Confirmation Relay Fueling
05-03-25	WDS Lost Comms Defueling
05-03-26	New PDU Procedures UPDATED
05-03-27	Updated H2 Pressure Test Procedures
05-03-28	PDU Assy Procedure Update
05-04-01	Carpet Contact to Steering Shaft
05-04-02	Carpet Detachment (Side step well area)
05-04-03	Low SLI Battery Guidelines
05-04-04	EMM Time Out No Refueling
05-04-05	AC O-ring Information (All orings used on this vehicle)
05-04-06	Thread Repair
05-04-07	IPT Oil level Check Procedure
05-04-08	Wheel Alignment Specs
05-05-01	R-Mode HV Battery Reconditioning Tips Info
05-05-02	LT Valve Screening Process
05-05-0_02	LT Valve Service Part Testing Process
05-05-03	LT pump protective Sleeve repositioning
05-06-01	FSC HV Battery SoC Vancouver Vehicles FSC
05-06-01_02	Supplemental FSC Hv Battery SoC ALL Vehicles
05-06-02	New NVH Cover R&R Instructions
05-07--01	Rear View Mirror Pivot Joint (Sticky/Binding)
05-07--02	Connector C51 Check and retorque attachement bolt
05-07--03	VNG Compact Flash Card Memory Update
05-07--03_02	Supplemental VNG Compact Flash Card Memory
05-07-04	Replace Air Module mounting bolts and washers

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TSB Summary by Bulletin Number

05-07-05	DI WEG Water Filter expiration date
05-08-01	Rear Seat Cushion Arm Rest Staples
05-08-02	Brake System ACU replacement
05-08-04	HT 3 Way valve Reseal Process
05-08-05	Front Creaking Noise - Springs
05-08-06	IPT 3 Phase Cover Oring leaking MOD 1
05-08-06_02	Supplement IPT 3 Phase cover terminals inspections MOD 2
05-08-07	Defueling Valve Noise Oring Mod
05-09-01	Front Seat Adjuster Cross Link Wires
05-10-01	Gear Shifter Lever Transitional Fault code
05-11-01	Handle - Pass Assist Grab Handle
05-11-02	TROS tips for smoother operation
05-11-03	Condensation - Front Lower lights Park/Turn
05-12-01	Serial Numbers - Major Components List
06-01-01	FCEV Update to Job 2 Software Levels (Version 12)
06-01-02	SLI Low Voltage Battery Conversion
06-01-03	Brake Lights ON - Brake Pedal Switch Adjustment Procedure
06-02-01	Maintenance Care Schedule Revised (Date 2-15-06)
06-08-01	Aux Drive - System Module - Stack Module Serial Numbers
06-08-02	Hydrogen Storage Vessel - (Dynetek)
06-08-03	EHB- High Pressure Accumulator Connector
06-09-01	PDA System Removal
07-01-01	Transfer Leak Detection Procedure
07-01-02	FCEV WDS Maintenance (Information Only)
07-03-01	FCEV Update Battery Control Module (BCM) Software Level 12A
07-06-01	Service Monitor Version 52 Available for use in the field
07-06-02	DI Water Line Stack (Check and Clean)
07-07-01	Software Level 12B Module Updates
07-09-01	Stack Module Enclosure Damage LV Connector
07-12-01	Axle Shaft Joint Noise - Boot, Joint and clamp replacement.
08-05-01	Di Water tank plug replacement
08-07-01	3 Way Valve connector Reseal
08-11-01	VNG Download - Hardware Method
09-06-01	VNG Battery Replacement

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Appendix 7 Data Collection Overview

Table D1 Performance Summary
(One vehicle per geographic region every six months)

Performance Summary[1]	Source of Data
Fuel Economy (dynamometer testing)	DYNO
Range	DYNO
Refueling Time	DYNO
Max Rated FC System Power (Net)	DYNO
Fuel Cell System Efficiency vs. net FC System Power	DYNO
@ Idle	DYNO
@ 10% Rated Power	DYNO
@ 25% Rated Power	DYNO
@ 100% Power	DYNO
Vehicle Fuel Cell System Efficiency (per SAE J2572)	DYNO
Top Speed	DYNO
Acceleration (0-60 mph)	DYNO
Gradeability	DYNO
Max. Continuous Power at 40C	DYNO
Time at Max. Rated Power	DYNO
Cold Start-up Time: -20C to Max Power	DYNO
12-hour soak	DYNO
Equilibrium Soak	DYNO
Cold Start-up Time: -20C to "Drive-away"	DYNO
12-hour soak	DYNO
Equilibrium Soak	DYNO
Cold Start-up Energy: -20C to Max. Power	DYNO
12-hour soak	DYNO
Equilibrium Soak	DYNO
Emissions (does not apply for FCV)	Not Applicable
Comments	DYNO

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Appendix 6 Technical Service Bulletins

Table D2* Fleet Summary *(All Vehicles)

Fleet Summary[1]	**Source of Data**
Unique Vehicle Identifier	EOL/TROS
Vehicle Model	Other
Powerplant Model (e.g. Gen 1, Gen 2, etc.)	Other
Fuel Cell Stack Identifier(s)	TROS/Other
Starting Date of Vehicle Operation	Other (Service Team)
Final Date of Vehicle Operation (if no longer in service)	Other (Service Team)
Primary Location of Operation (City, State)	Other (Service Team)
Primary Refueling Location (Unique Station Identifier)	Other (Service Team)
H2 Tank Pressure (psig)	Ref Data
Still in Operation (Y, N)	Other (Service Team)
Miles Traveled	VNG
Operating Hours	VNG
Average Fuel Economy (mi/kg H2)	VNG/ Vehicle Log
Scheduled Labor Hours	TROS
Un-Scheduled Labor Hours	TROS
Maximum Ambient Temp. During Operation (deg. C)	VNG
Minimum Ambient Temp. During Operation (deg. C)	VNG
Significant Comments	TROS/Service (Other)

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Table D3 Stack Durability Summary (All Vehicles)

Stack Durability Summary[1]	**Source of Data**
Unique Fuel Cell Stack Identifier	TROS/EOL
Unique Vehicle Identifier	EOL
Operating Hours During Reporting Period	VNG
Total Operating Hours	VNG
# Start/Stop Cycles During Reporting Period	VNG
Total # of Start/Stop Cycles	VNG
Still in Operation? (Y, N)	Service (Other)
Operating Hours at End of Life (if applicable)	VNG
# Start/Stop Cycles at End of Life (if applicable)	VNG
End of Life Cause/Comments	TROS/Service (Other)

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Table D4 Maintenance Summary (All Vehicles)

Maintenance Summary[1]	**Source of Data**
Component Name	TROS
Vehicle, Fuel Cell System, or Powertrain	TROS
Fuel Cell Subsystem	TROS
Component Category	TROS
Power Plant Model	TROS
Unique Vehicle Identifier	TROS
Maintenance Type	TROS
Associated with an on-road vehicle failure, shutdown?	TROS
Scheduled, Un-Scheduled	TROS
Direct Labor Hours	TROS
Date of Repair, Replacement	TROS
Vehicle Miles Traveled (with component) at Repair, Replacement	TROS
Vehicle Operating Hours (with this component installed) at Repair, Replacement	TROS
Comments, Description of Maintenance	TROS
Fuel Cell Subsystem Pick List (consistent with DRAFT SAEJ2615)	TROS
Component Pick List	TROS

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Table D5 Safety Summary (All Vehicles)

Safety Summary[1]	**Source of Data**
Event Type (HV leak, H2 leak, Vehicle Accident & other FMVSS Safety concerns)	VNG/TROS
Power Plant Model	Other
Unique Vehicle Identifier	EOL/TROS
Associated with an on-road vehicle failure, shutdown?	VNG/TROS
Date of Event	Serious Incident Reporting Procedure (SIRS) / TROS
Detailed Event Description/Result	Serious Incident Reporting Procedure (SIRS) / TROS
Event Type Pick List	TROS/SIRS

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Table D6 On-Road Fuel Economy (All Vehicles)

On-Road Fuel Economy[1]	**Source of Data**
Date	VNG/ Vehicle Log
Fill-up Number	VNG/ Vehicle Log
Odometer at Fill (miles)	VNG/ Vehicle Log
Kg H2 filled	VNG/ Vehicle Log
Miles/kg H2	VNG/ Vehicle Log
Comments	TROS/Service (Other)

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Table D7 Dynamometer Test data
(One vehicle per geographic region every six months)

Dyno Test Data[1]		**Source of Data**
N/A	Time	DYNO
Vehicle	Vehicle Speed	DYNO
	H_2 mass flow rate	DYNO
Traction Motor/Generator	Voltage	DYNO
	Current	DYNO
Energy Storage	Voltage	DYNO
	Current	DYNO
Fuel Cell Stack	Voltage	DYNO
	Current Out	DYNO
Air Compressor/Blower	Voltage In	DYNO
	Current In	DYNO
Cooling Fan(s)	Voltage In	DYNO
	Current In	DYNO
H2 Recycle	Voltage In	Not Applicable
	Current In	Not Applicable
Coolant Pump(s)	Voltage In	DYNO
	Current In	DYNO
A/C Compressor	Voltage In	DYNO
	Current In	DYNO

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Table D8 On Road Data
(One vehicle per geographic region, continuous)

On Road Data[1]		**Source of Data**
N/A	Time	DAE (ON-BOARD LAPTOP COMPUTER)
Vehicle	Vehicle Speed	DAE (ON-BOARD LAPTOP COMPUTER)
	Cumulative Operating Hours	DAE (ON-BOARD LAPTOP COMPUTER)
	Start/Stop Events	DAE (ON-BOARD LAPTOP COMPUTER)
N/A	Ambient Temperature	DAE (ON-BOARD LAPTOP COMPUTER)
Traction Motor (Motoring & Regen)	Voltage	DAE (ON-BOARD LAPTOP COMPUTER)
	Current	DAE (ON-BOARD LAPTOP COMPUTER)
Energy Storage	Voltage	DAE (ON-BOARD LAPTOP COMPUTER)
	Current	DAE (ON-BOARD LAPTOP COMPUTER)
Fuel Cell Stack	Voltage	DAE (ON-BOARD LAPTOP COMPUTER)
	Current Out	DAE (ON-BOARD LAPTOP COMPUTER)

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Table D9 Vehicle Parameters
(One time submission)

Vehicle Parameters[1]	**Source of Data**
Vehicle CD	SPEC DATA
Vehicle FA	SPEC DATA
Vehicle Mass	SPEC DATA
Vehicle front wt frac	SPEC DATA
Vehicle cg height	SPEC DATA
Vehicle wheelbase	SPEC DATA
Hybrid Vehicle	SPEC DATA
Tire Type	SPEC DATA
Fuel Tank	SPEC DATA
a. Manufacturer	SPEC DATA
b. Type	SPEC DATA
c. Usable Fuel Amount	SPEC DATA
d. Total Tank Volume (internal)	SPEC DATA
e. Total Tank Volume (external)	SPEC DATA
f. Mass Rated Pressure	SPEC DATA
g. Tank mass	SPEC DATA
h. Calculated Weight % Hydrogen	SPEC DATA
i. Calculated Mass of Hydrogen per Liter	SPEC DATA
j. Cycle Life	SPEC DATA
Fuel Cell System	SPEC DATA
a. Manufacturer	SPEC DATA
b. Type	SPEC DATA
c. Power Rating (net)	SPEC DATA
d. Fuel Cell Power Plant Mass	SPEC DATA
e. Fuel Cell Power Plant Volume	SPEC DATA
f. Calculated Specific Power	SPEC DATA
g. Calculated Power Density	SPEC DATA
Propulsion Battery or Capacitor	SPEC DATA
a. Manufacturer	SPEC DATA
b. Type	SPEC DATA
c. Maximum Rated Ampere-Hour Capacity	SPEC DATA
Electric Propulsion Motor	SPEC DATA
a. Type	SPEC DATA
b. Peak Power Rating	SPEC DATA

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Table D10 Consolidated NREL Data Reports generated using DOE Program Participant data (Quarterly)

Report	Performance Measure
1	Fuel Cell Durability
2	Vehicle Ranges
3	Reliability
4	Start Times
5	Fuel Economy (Dynamometer and On-Road)
6	Normalized vehicle fuel efficiency
7	Fuel Cell System Efficiency
8	Safety Incidents
9	Vehicle Hydrogen Tank Cycle Life
10	Combined Heat and Power Efficiencies
11	Refueling Rate Histogram
12	Average Maintenance Hours- Scheduled and Unscheduled
13	Range of Actual Ambient Temperatures During Vehicle Operation
14	Number of Vehicles vs. Operating Hours
15	Number of Vehicles vs. Miles Traveled
16	Cumulative Vehicle Miles Traveled
17	Progression of Low to High Pressure On-board Storage