2006 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Review

Controlled Hydrogen Fleet and Infrastructure Analysis

Keith Wipke, Senior Engineer II
NREL

May 19, 2006

Project ID# TV-12

This presentation does not contain any proprietary or confidential information

NREL/PR-560-39783
Presented at the 2006 DOE Hydrogen, Fuel Cells & Infrastructure Technologies Program Annual Merit Review in Washington, D.C., May 16-19, 2006.

Disclaimer and Government License

Project Objectives and Targets

- Objectives
  - Validate H_2 FC Vehicles and Infrastructure in Parallel
  - Identify Current Status of Technology and its Evolution
  - Re-Focus H_2 Research and Development
  - Support Industry Commercialization Decision by 2015

Hydrogen refueling station, Chino, CA Photo: NREL

Key Targets

Performance Measure	2009*	2015**
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	$3/gge	$2-3/gge

* To verify progress toward 2015 targets
** Subsequent projects to validate 2015 targets

Project Overview

Timeline

- Project start: FY03
- Project end: FY09
- ~33% of Task III complete (see timeline slide)

Budget

- NREL FY04 funding: $630K
- NREL FY05 funding: $750K
- NREL FY06 funding: $812K
- Context: Overall DOE project is ~$170M project over 5 years
  - Equal investment by industry

Partners

- See partner slide

Tech. Val. Barriers

A. **Vehicles** – lack of controlled & on-road H_2 vehicle and FC system data

B. **Storage** – technology does not yet provide necessary 300+ mile range

C. **Hydrogen Refueling Infrastructure** – cost and availability

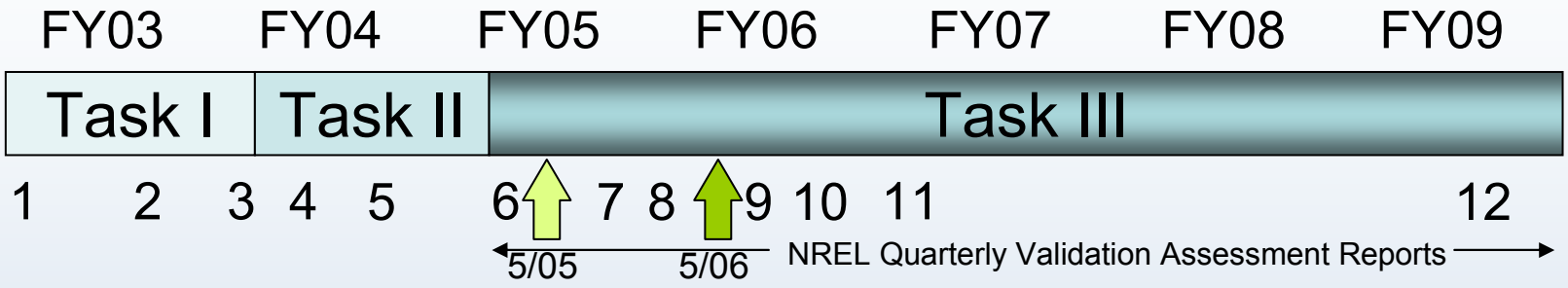
D. **Maintenance and Training Facilities** – lack of facilities and trained personnel

E. **Codes and Standards** – lack of adoption/validation

H. **Hydrogen Production from Renewables** – need for cost, durability, efficiency data for vehicular application

I. **H_2 and Electricity Co-Production** – cost and durability

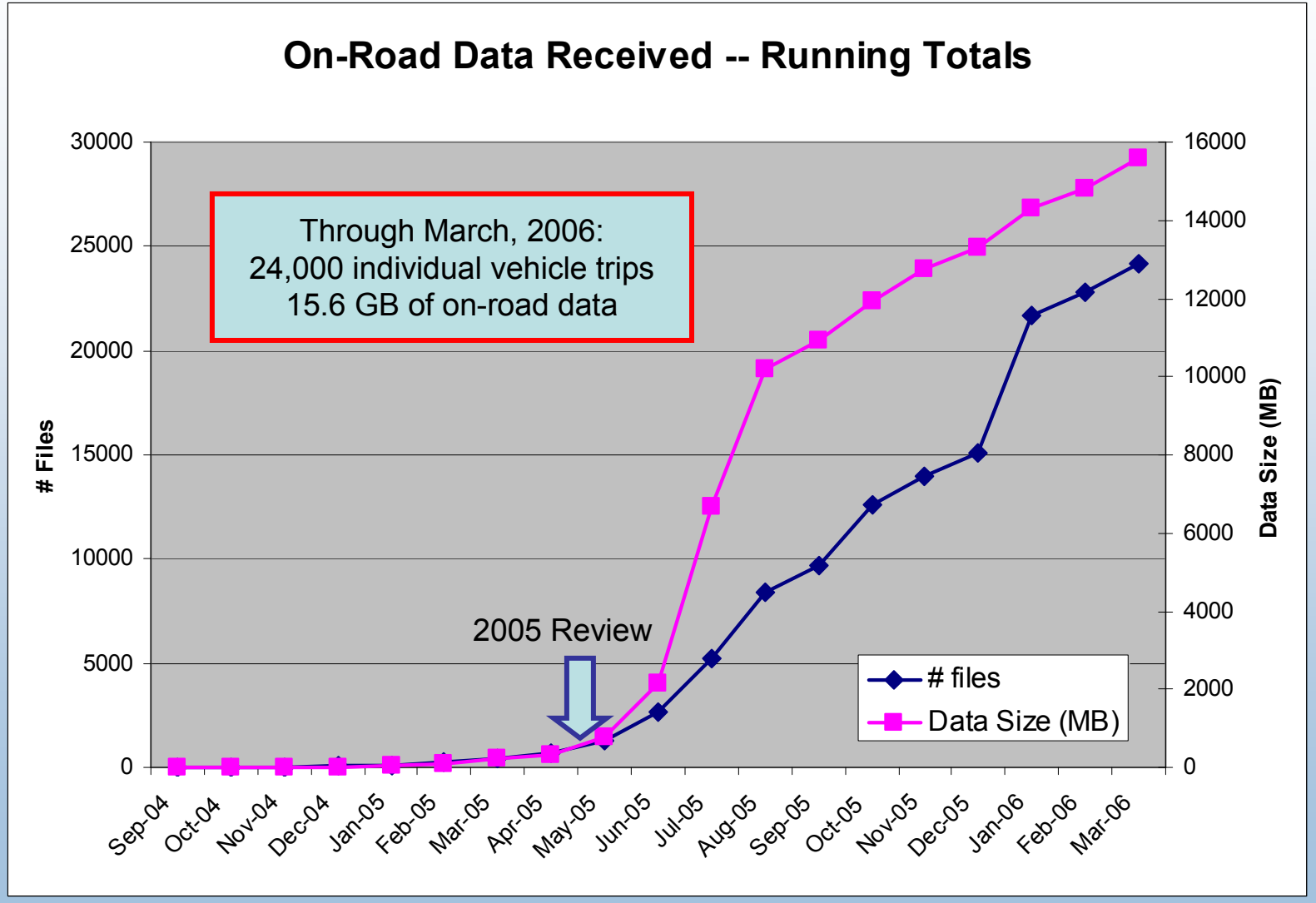
Project Timeline



- **Task I – Project Preparation [100% Complete]**
  - 1 Support development of RFP, statement of objectives (Appendix C)
  - 2 Bidder's meeting in Detroit – launch of RFP
  - 3 Create data analysis plan and presentation for discussion with industry
- **Task II – Project Launch [100% Complete]**
  - 4 Announcement of successful bidders (4/04)
  - 5 Kick-off meetings and cooperative agreement awards
- **Task III – Data Analysis and Feedback to R&D activities (partial list) [33% Complete]**
  - 6 Preliminary data collection, analysis, and first quarterly assessment report
  - 7 Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles
  - 8 Publication of first "composite data products"
  - 9 Validate demonstration FCV 1000-hour durability
  - 10 Go/No-Go: Decision for purchase of additional vehicles based on perf., durability, cost
  - 11 Introduction of 2nd Generation FC systems into vehicles
  - 12 Validate FCVs with 250-mile range, 2,000 hour durability, and $3.00/gge (based on volume production)

Project Now Well Underway: 1st Year of Data Analyzed

Current Status of Data Reporting to the Hydrogen Secure Data Center at NREL



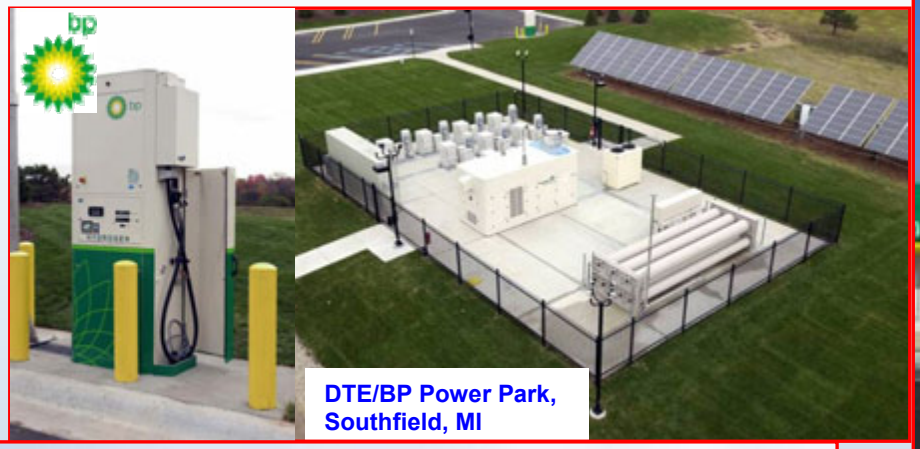
Industry Partners: Actively Working with 4 Teams with Signed DOE Cooperative Agreements

(1) Fuel cells supplied by Ballard

Teams are Fielding Four Main Types of Vehicles

Validation also includes FCV Sprinter vans

Representative Hydrogen Refueling Infrastructure Supporting Vehicles



DTE/BP Power Park, Southfield, MI

LAX refueling station

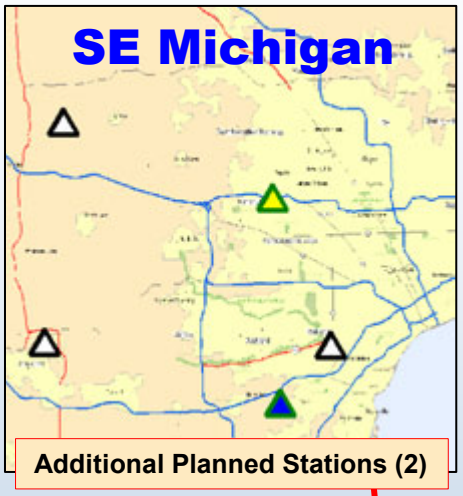
Hydrogen and gasoline station, WA DC

Photo:Shell Hydrogen

Chino, CA

Photo: H2CarsBiz

Refueling Stations from All Four Teams Test Vehicle/Infrastructure Performance in Various Climates



Legend
- Chevron & Hyundai/Kia
- DaimlerChrysler & BP
- Ford & BP
- General Motors & Shell
- Other

Project Approach

- Provide facility and staff for securing and analyzing industry sensitive data
  - NREL Hydrogen Secure Data Center (HSDC)
- Perform analysis and simulation using detailed data in HSDC to:
  - Evaluate current status and progress toward DOE vehicle and infrastructure targets
  - Feedback current technical challenges and opportunities into DOE H_2 R&D program
  - Provide analytical feedback to originating companies on their own data (detailed data products)
- Publish/present progress of project to public and stakeholders (composite data products)

Approach: Providing Data Analysis and Results for Both the Public and for the Industry Project Teams

Raw Data, Reports

Hydrogen Secure Data Center (HSDC)

- Located at NREL: Strictly Controlled Access
- Detailed Analyses, Data Products, Internal Reports

Composite Data Products

- Pre-agreed upon aggregate data results for public
- No confidential information

Detailed Data Products

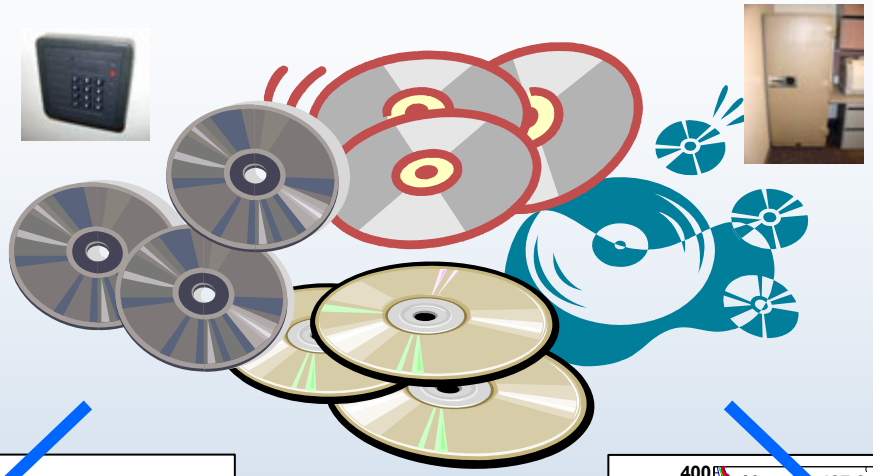
- Only shared with company which originated the data

Approach: Collect Detailed Vehicle and Infrastructure Data for Analysis

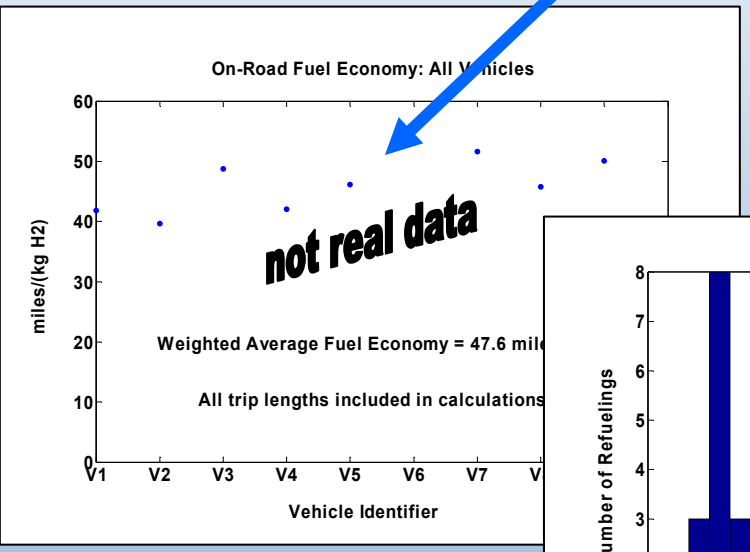
Key Vehicle Data	Key Infrastructure Data
Stack Durability	Conversion Method
Fuel Economy (Dyno & On-Road) and Vehicle Range	Production Emissions
Fuel Cell System Efficiency	Maintenance, Safety Events
Maintenance, Safety Events	Hydrogen Purity/Impurities
Top Speed, Accel., Grade	Refueling Events, Rates
Max Pwr & Time at 40C	H_2 Production Cost
Freeze Start Ability (Time, Energy)	Conversion, Compression, Storage, and Dispensing Efficiency
Continuous Voltage and Current (or Power) from Fuel Cell Stack, Motor/Generator, Battery & Key Auxiliaries: (Dyno & On-Road)	

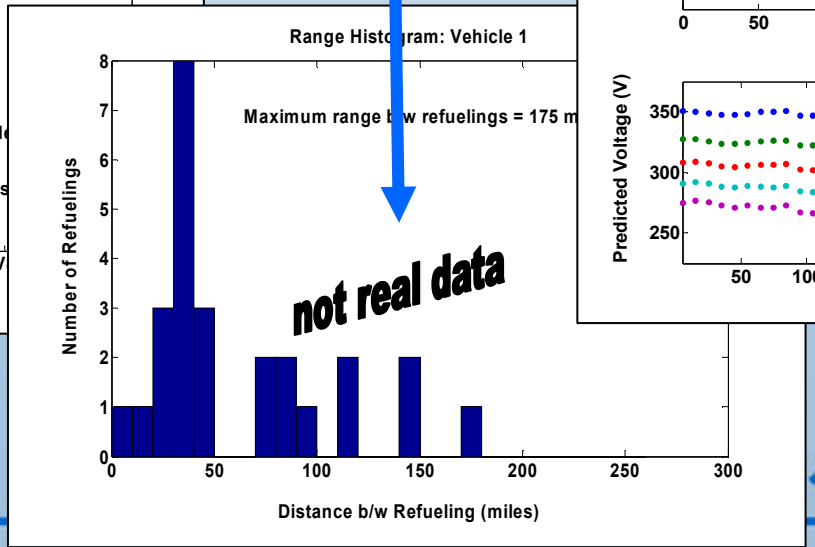
Approach for Vehicle Data Analysis: Automated Process from CD/DVD Delivery to Results

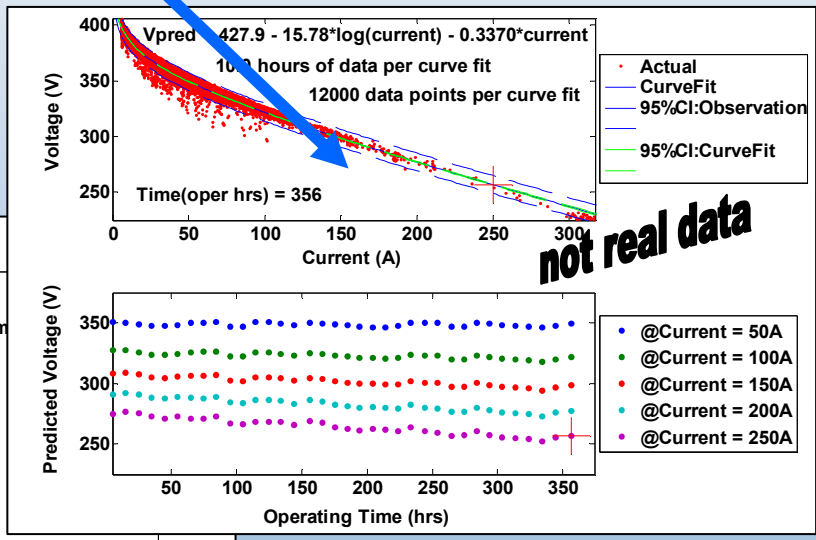
Data is delivered to NREL's Hydrogen Secure Data Center (HSDC) on CD/DVDs



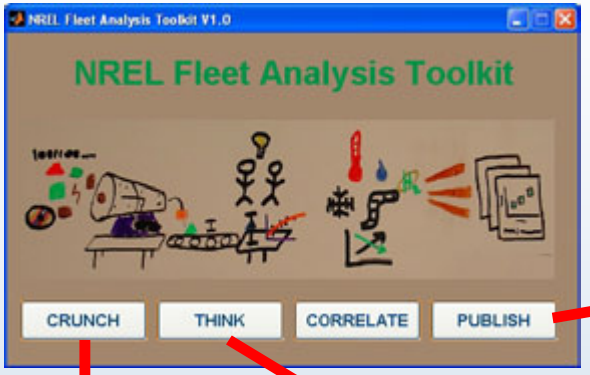
Data protected in HSDC for 5 years after data is developed under EPACT 2005, Sec. 810

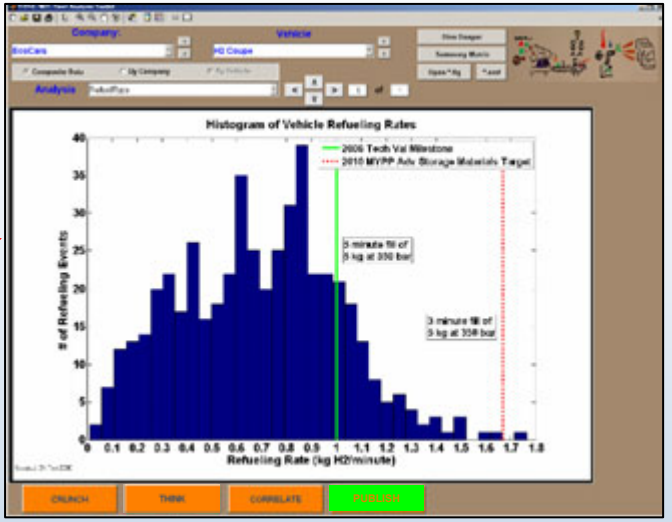


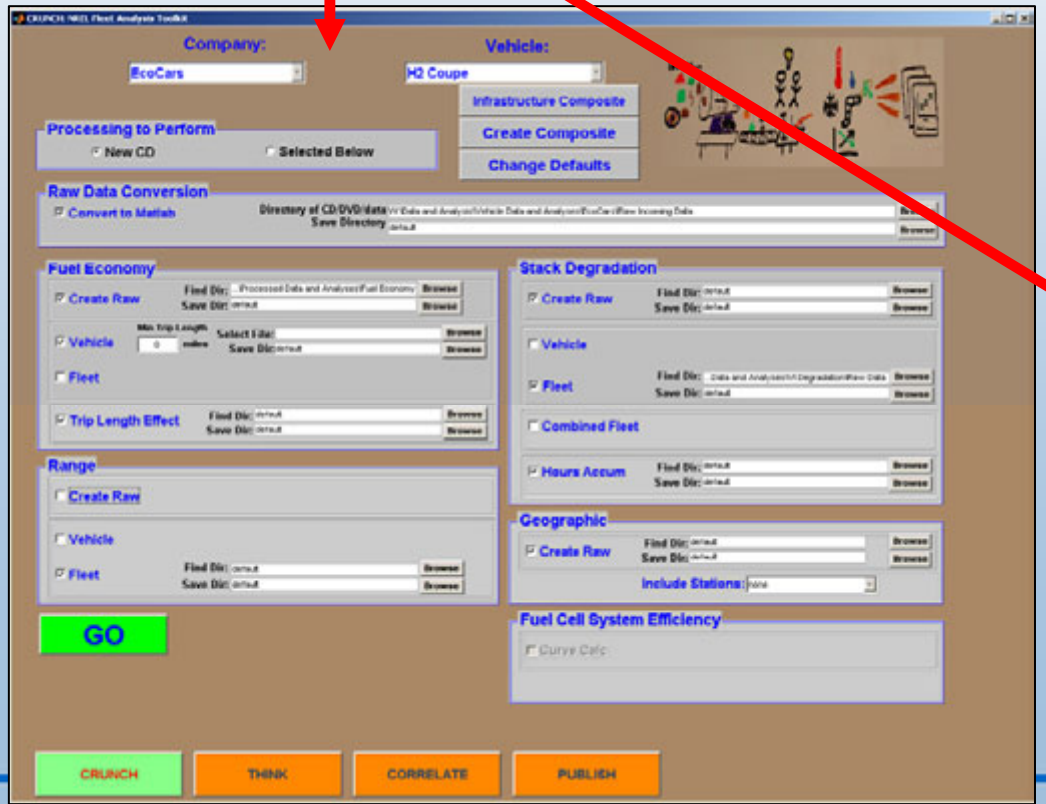


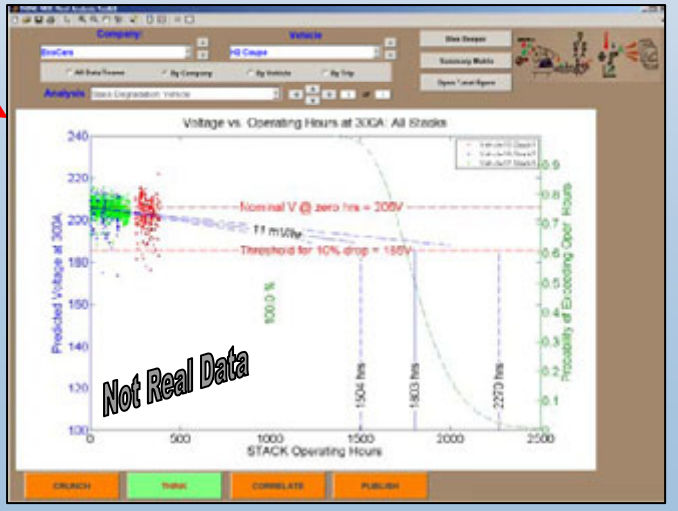


Accomplishment: Analysis Controlled by New NREL-Developed GUI – Fleet Analysis Toolkit (FAT)

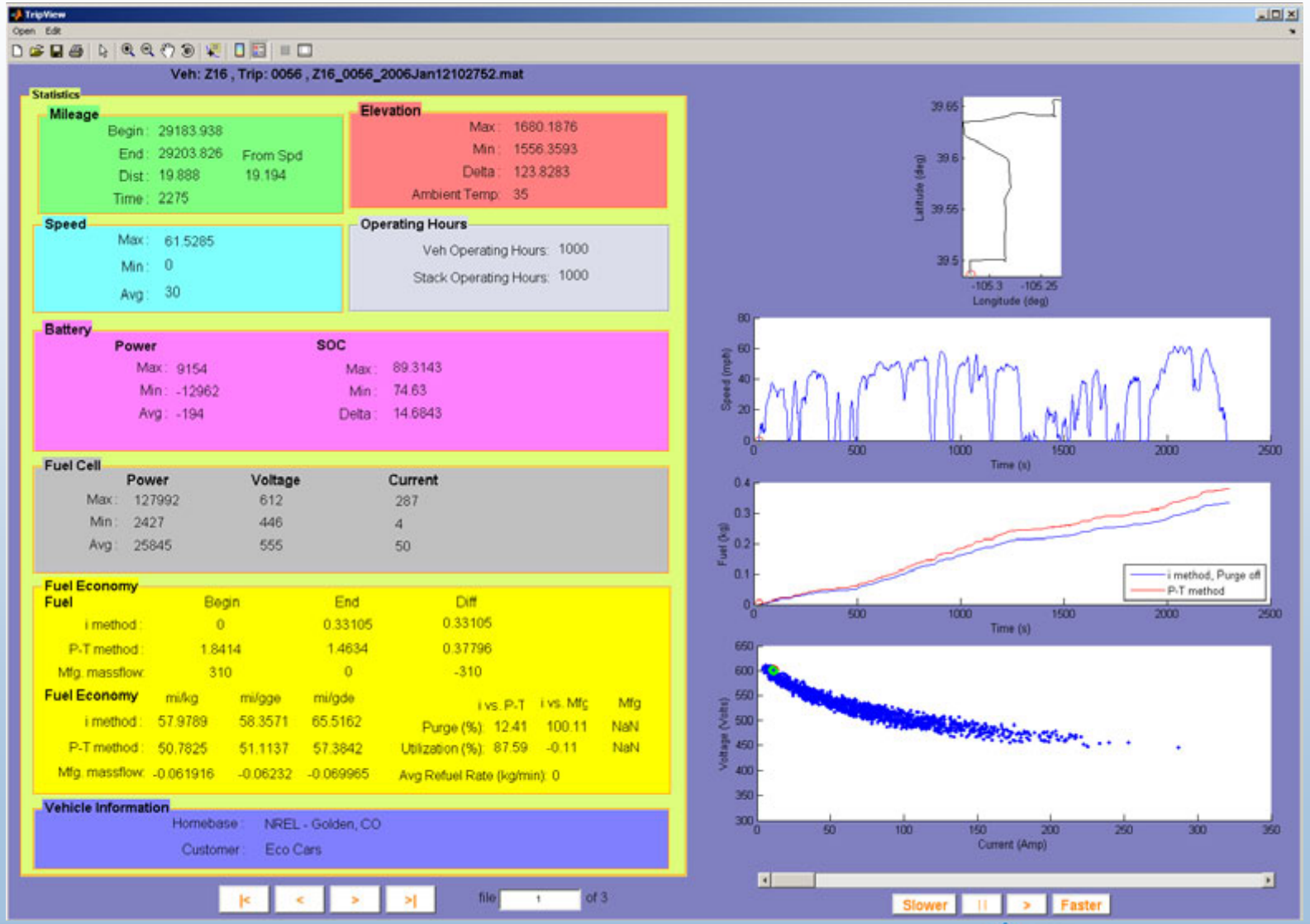




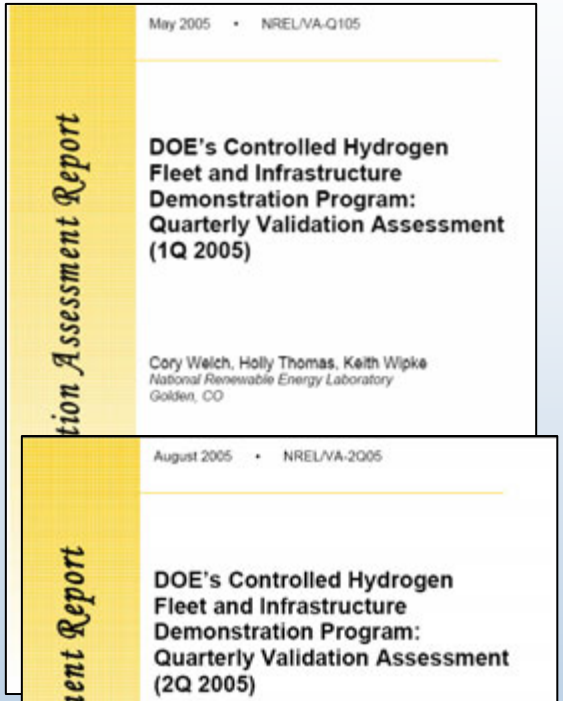


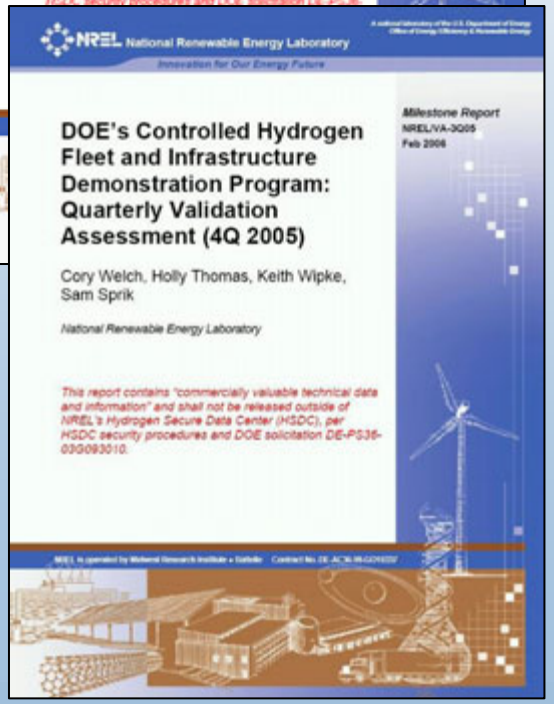


Accomplishment: FAT GUI Includes TripView to Further Investigate Individual Trips and Refuelings



Accomplishment: Completion of Four New Quarterly Technology Validation Assessment Reports





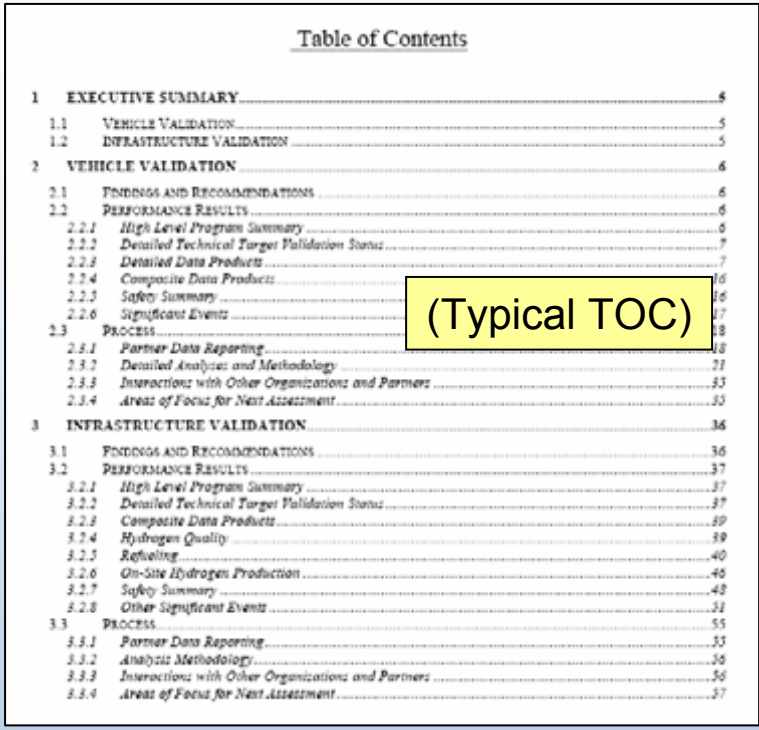


Table of Contents

(Typical TOC)

- Internal reports document detailed methodology and results (detailed data products)
- Used to help guide DOE H_2 R&D

Accomplishment: Baseline Vehicle Chassis Dynamometer Testing Completed by All Four Teams

- One vehicle per team per geographic region
- 11 vehicles tested using SAE J2572
- Some teams may elect to use test results for EPA certification

Chevron/Hyundai-KIA

DaimlerChrysler/BP

GM/Shell

Ford/BP

Accomplishment: Created First 16 of 26 Composite Data Products

A. Critical Program Metrics:

1. Fuel Cell Durability, Actual vs. DOE Targets, All OEM's
2. Vehicle Ranges, Actual vs. DOE Targets, All OEM's
3. H2 Production Cost. Actuals/Projections vs. DOE Targets

B. Composite Performance Tracking:

Vehicles

4. Reliability (FC System & Powertrain, MTBF)
5. Start Times vs. DOE Target
6. Fuel Economy: Dyno, On-Road
7. Normalized Vehicle Fuel Economy
8. Fuel Cell System Efficiency
9. Safety Incidents - Vehicle Operation
10. Weight % Hydrogen
11. Energy Density of Hydrogen Storage
12. Vehicle Hydrogen Tank Cycle Life

Hydrogen Infrastructure

13. H2 Production Efficiency vs. Process
14. Combined Heat and Power (CHP) Efficiencies
15. H2 Production Cost vs. Process
16. H2 Purity vs. Production Process
17. Hydrogen Impurities - Range for Production Process A
18. Histogram: Refueling Rate
19. Average Maintenance Hours - Scheduled and Unscheduled
20. Safety Incidents - Infrastructure

Highlighted CDPs Have Been Completed and Will Be Presented

C. High Level Program Progress:

Vehicles

21. Range of Actual Ambient Temperatures During Vehicle Operation – All Vehicle Teams
22. Histogram: # Vehicles vs. Operating Hours to Date
23. Histogram: # Vehicles vs. Miles Traveled to Date
24. Cumulative Vehicle Miles Traveled - All Teams
25. Progression of Low to High Pressure On-board H2 Storage

Hydrogen Infrastructure

26. Cumulative Hydrogen Production – All Teams

Composite Data Products are Main Output to Public and Hydrogen Community

Accomplishment: Published Composite Data Products in NHA 2006 Paper and Presentation

CONTROLLED HYDROGEN FLEET AND INFRASTRUCTURE DEMONSTRATION AND VALIDATION PROJECT: PROGRESS UPDATE[1]

K. Wipke[2], C. Welch[2], H. Thomas[2], S. Sprik[2], S. Gronich[3], J. Garbak[3], D. Hooker[4]

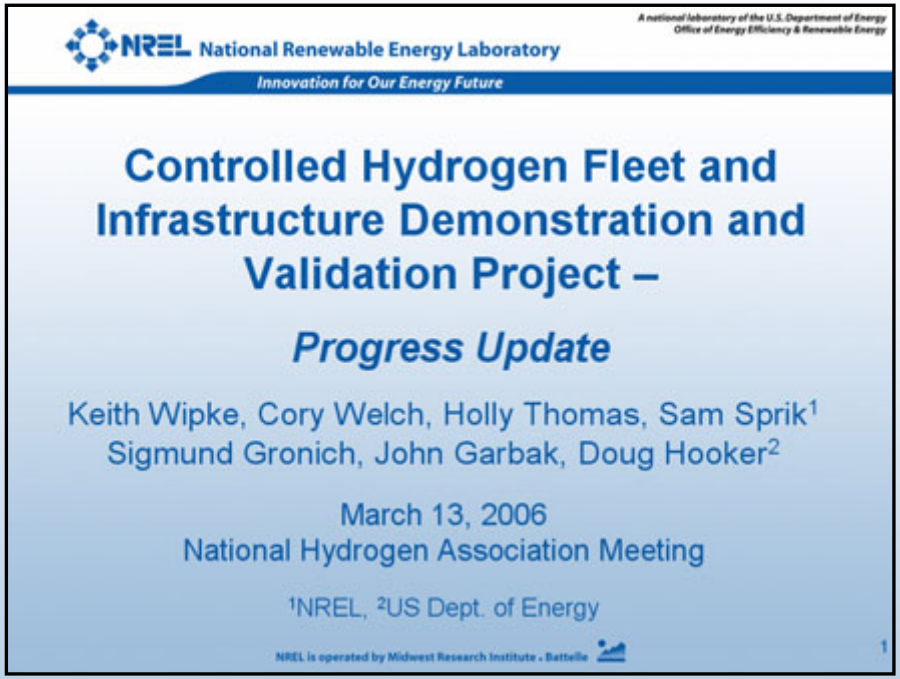
Abstract

The U.S. Department of Energy (DOE) initiated the "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" through a competitive solicitation process in 2003. The purpose of this project is to conduct an integrated field validation that simultaneously examines the performance of fuel cell vehicles and the supporting hydrogen infrastructure. Insights from the vehicles and infrastructure study will be fed back into DOE's research and development program to guide and refocus future research, making this project a "learning demonstration." Five teams were selected and four cooperative agreements between DOE and industry partners have been awarded and commenced. These four cooperative agreements will ultimately support more than 130 fuel cell vehicles, which will be validated on-road, as well as more than 25 hydrogen refueling stations. Fifty-nine first-generation vehicles have already entered into service with customers, and several new hydrogen refueling stations have opened, with more vehicles and stations planned. Lessons learned from this project on the interrelationship between the vehicles and the infrastructure will influence ongoing development of codes and standards. The auto industry and the energy companies are strongly committed to this project, and the government's investment in this project is matched by each industry team.

This DOE/industry collaborative project will continue for a total of 5 years, during which multiple generations of technology will be tested. Technical performance of vehicles and infrastructure will be compared against DOE targets at intermediate stages and at project completion. Examples of 2009 DOE validation targets include a 250-mile vehicle range, 2,000-hour durability of vehicle fuel cell stacks, and a hydrogen production cost of $3/gge untaxed, when produced in quantity. This paper provides a status update covering the progress of the demonstration and validation project over the last year. This includes the first composite data products to be released from the project, along with a summary of the data inputs and analysis methodology. The composite data products aggregate

[1] This work has been authored by an employee of the Midwest Research Institute under Contract No. DE-AC36-99GO10337 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

[2] National Renewable Energy Laboratory, Golden, CO.
[3] U.S. Department of Energy – Washington, DC.
[4] U.S. Department of Energy – Golden Field Office, Golden, CO.



NREL National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project –

Progress Update

Keith Wipke, Cory Welch, Holly Thomas, Sam Sprik[1]
Sigmund Gronich, John Garbak, Doug Hooker[2]

March 13, 2006
National Hydrogen Association Meeting

[1]NREL, [2]US Dept. of Energy

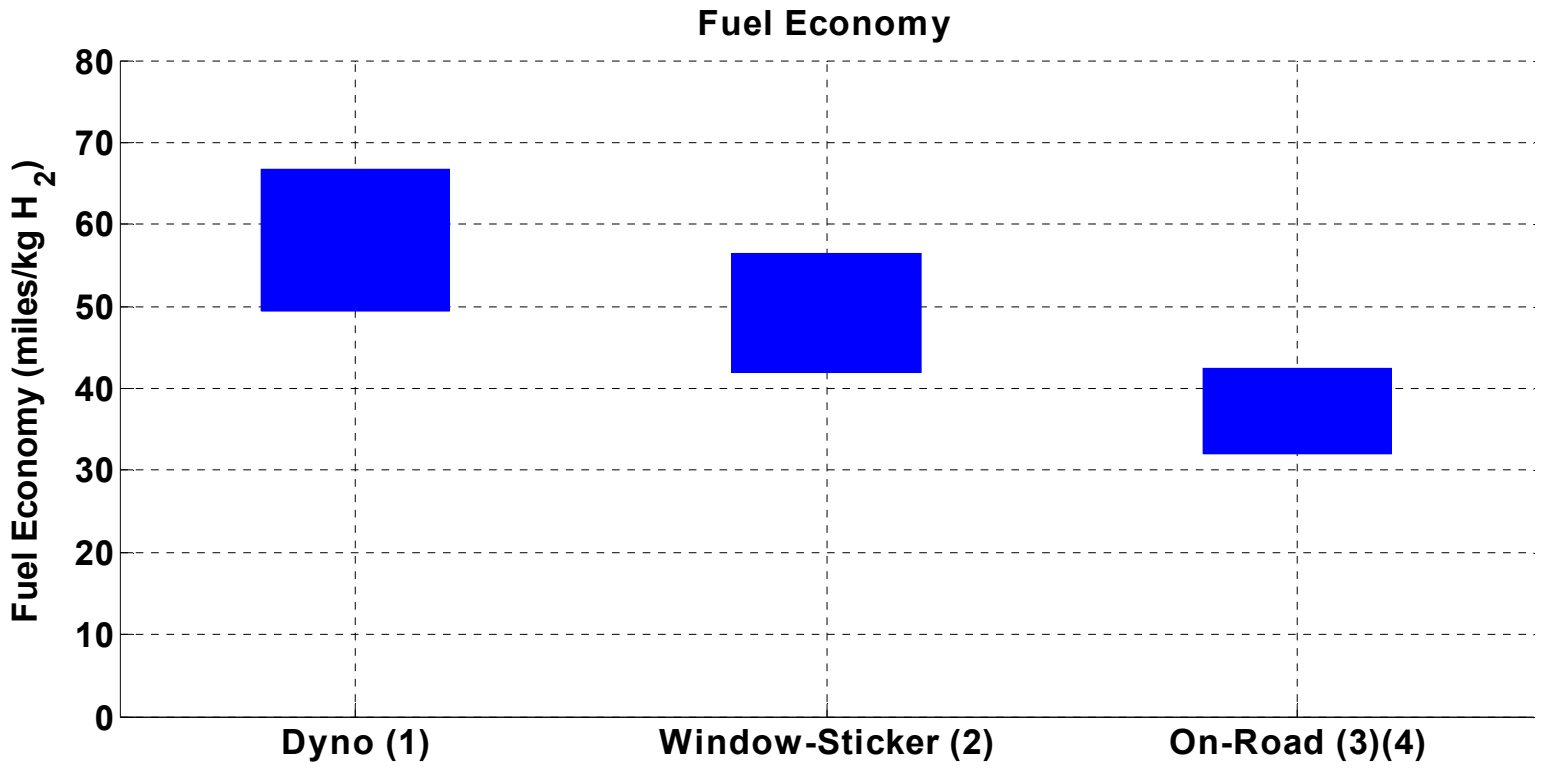
NREL is operated by Midwest Research Institute - Battelle

1

Paper and presentation available online at http://www.nrel.gov/hydrogen/proj_tech_validation.html

The Following 12 Slides are the Public Technical Results: Composite Data Products

Dynamometer and On-Road Fuel Economy



(1) One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAEJ2572.

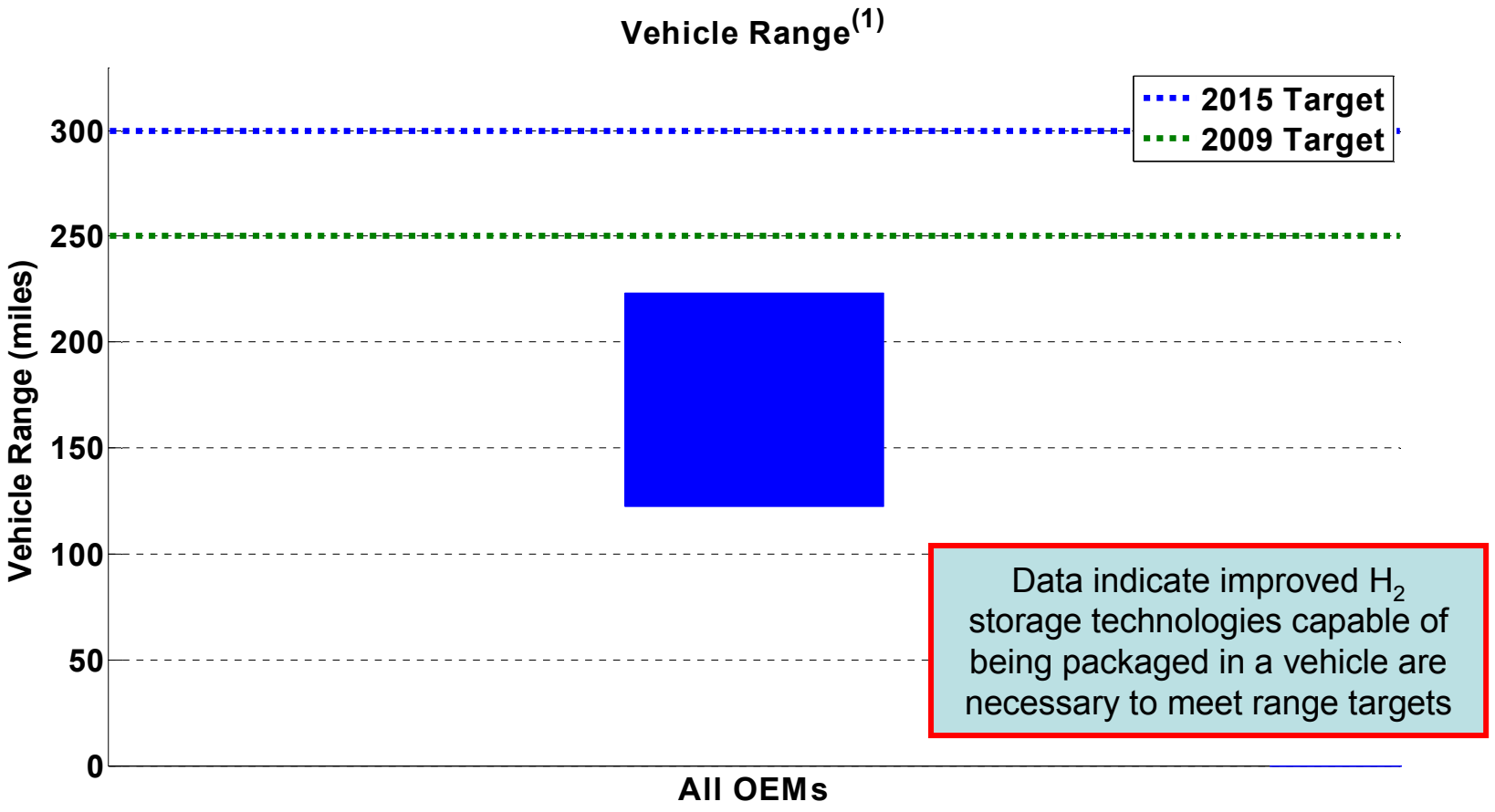
(2) Adjusted combined City/Hwy fuel economy (0.78 x Hwy, 0.9 x City).

(3) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.

(4) Calculated from on-road fuel cell stack current or mass flow readings.

Created: 16-Feb-2006

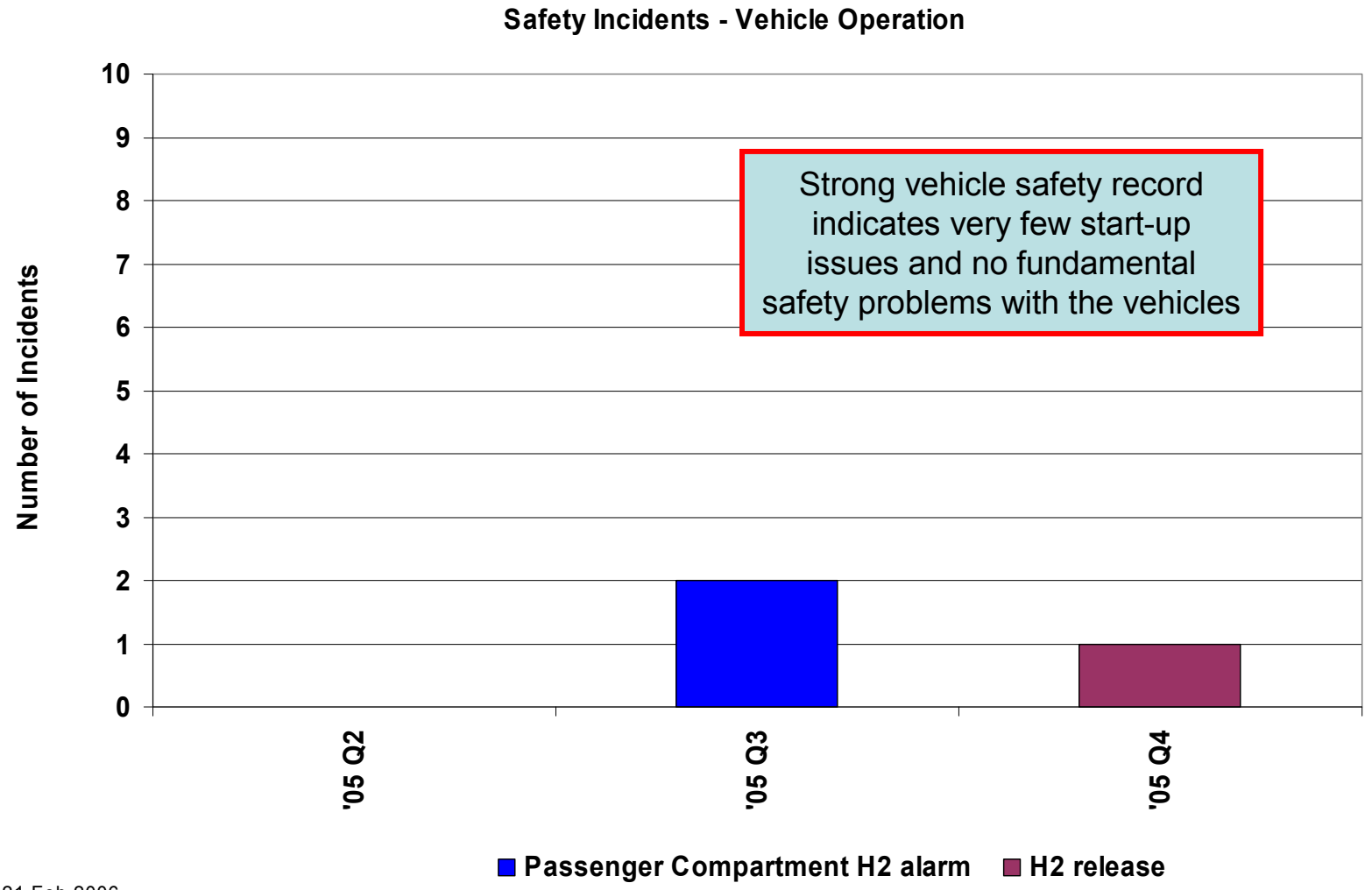
Vehicle Range Based on Dyno Results and Usable H_2 Fuel Stored On-Board



Created: 21-Feb-2006

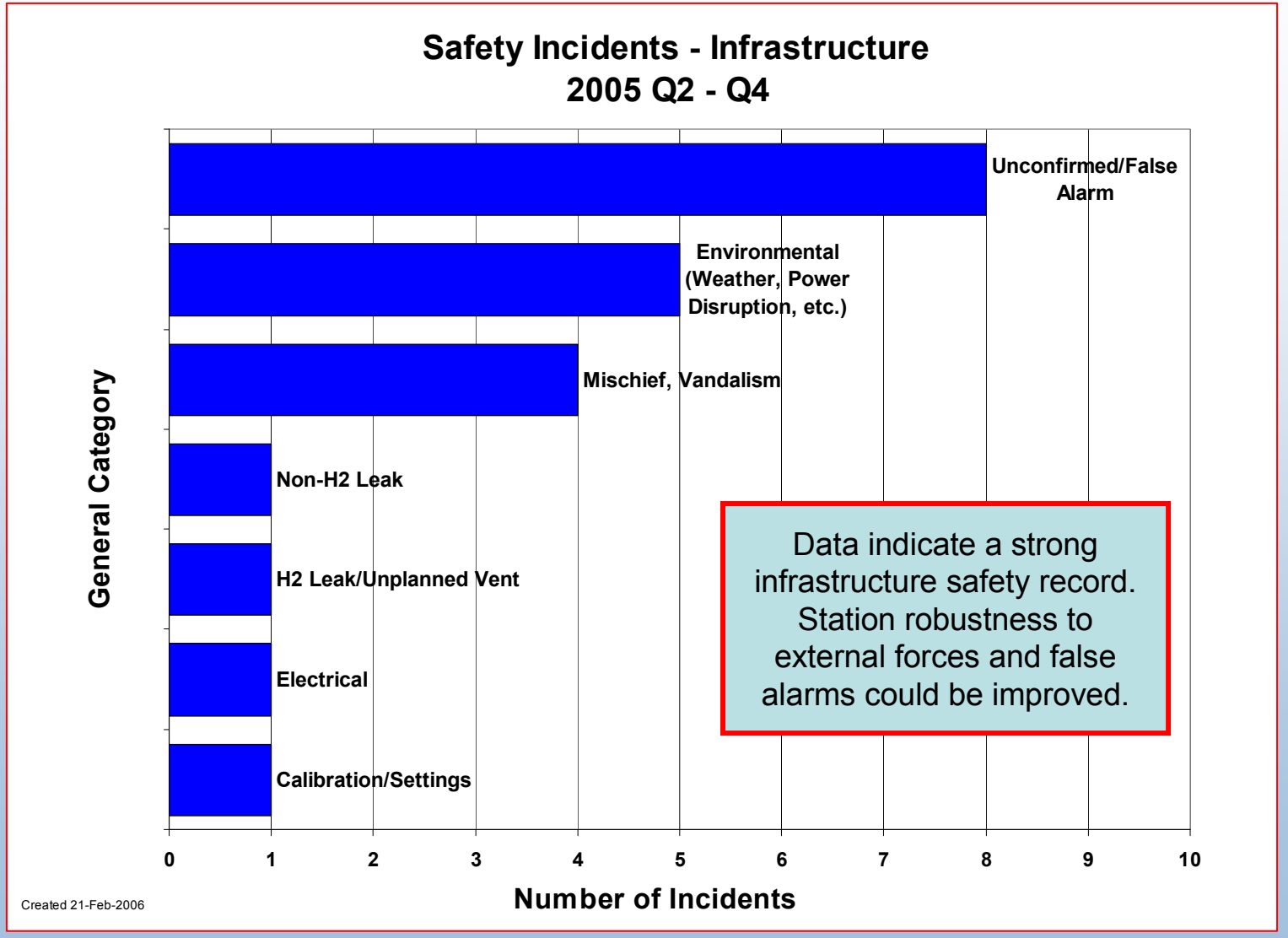
(1) Calculated from combined City/Hwy fuel economy (dyno test) per DRAFT SAE J2572 and usable fuel on board.

Safety Incidents – Vehicles

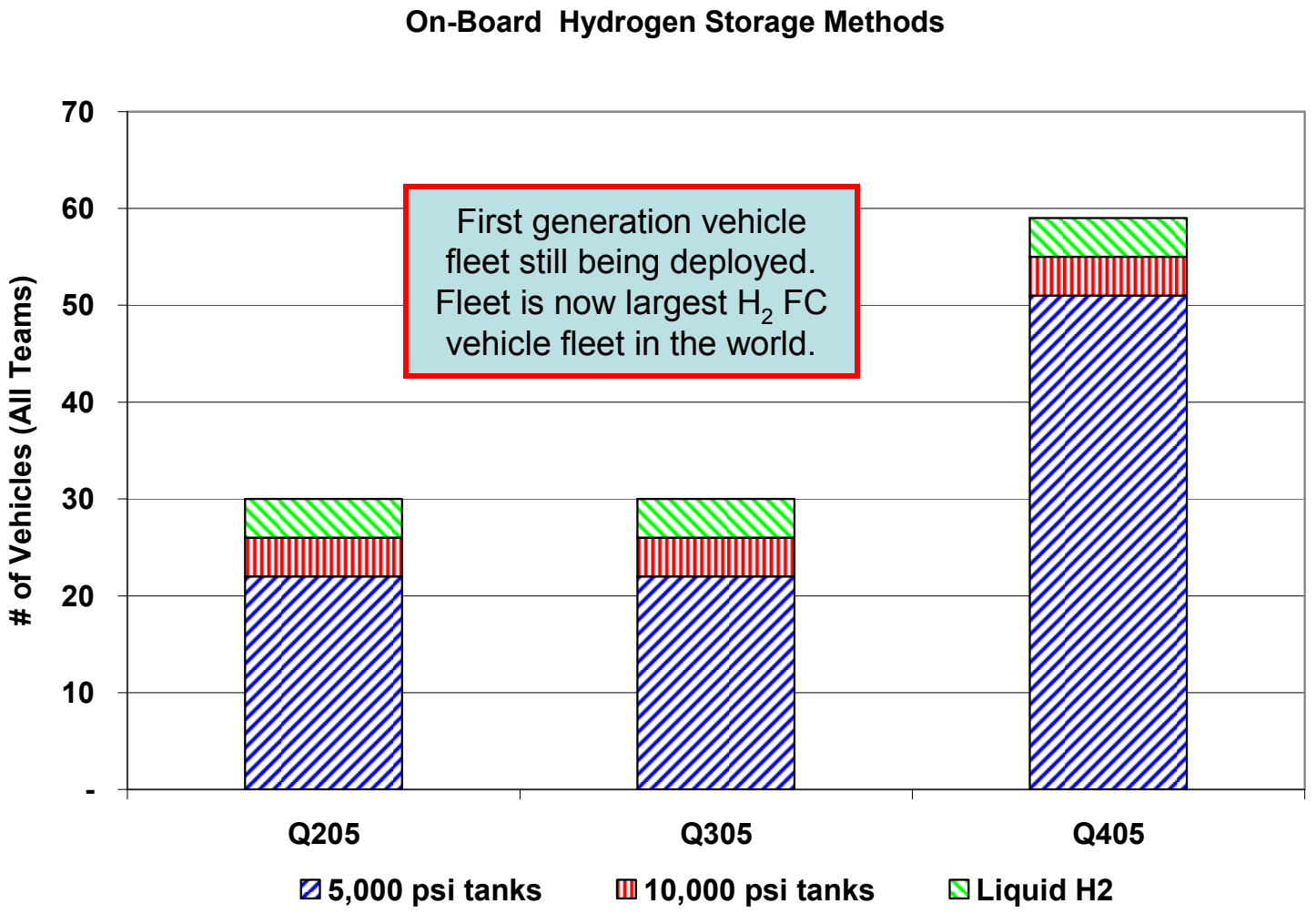


Created 21-Feb-2006

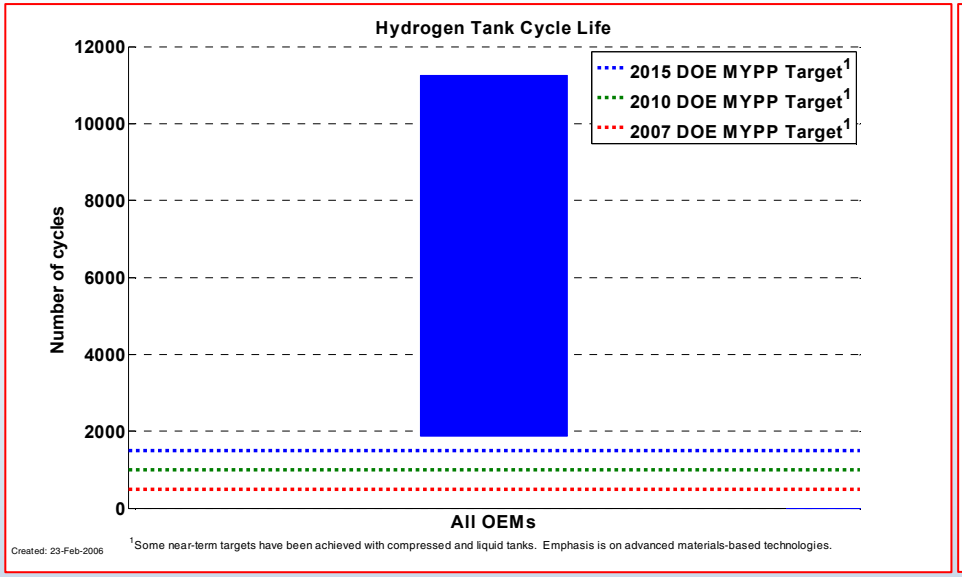
Safety Incidents – Infrastructure

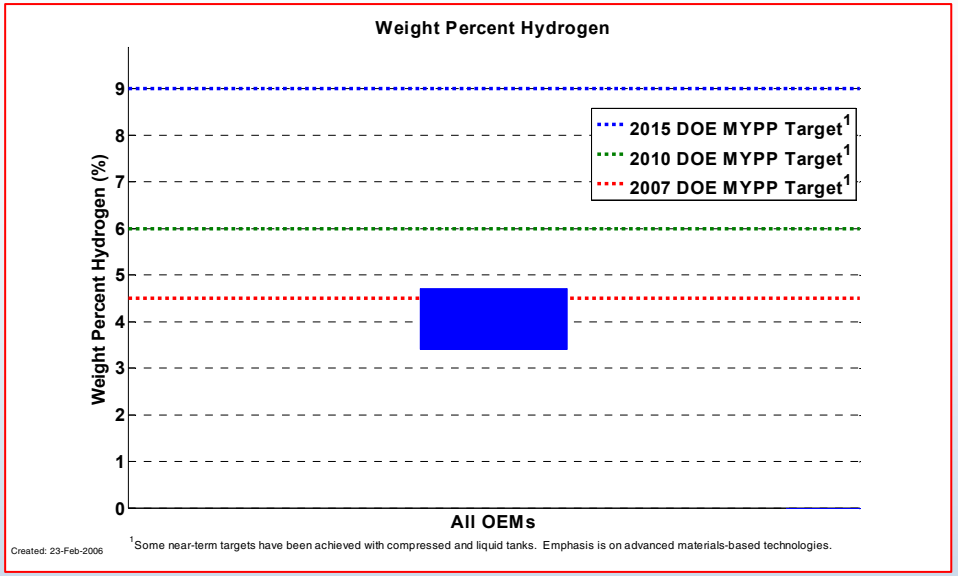


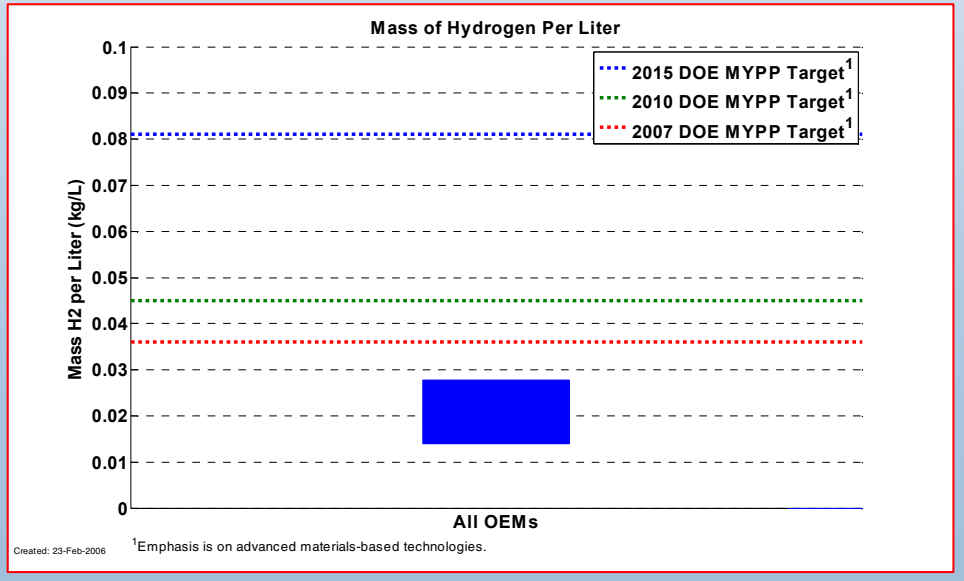
Vehicle H_2 Storage Technologies Include 350 bar, 700 bar, and Liquid H_2



Technical Status of On-Board H_2 Storage Technologies Being Validated

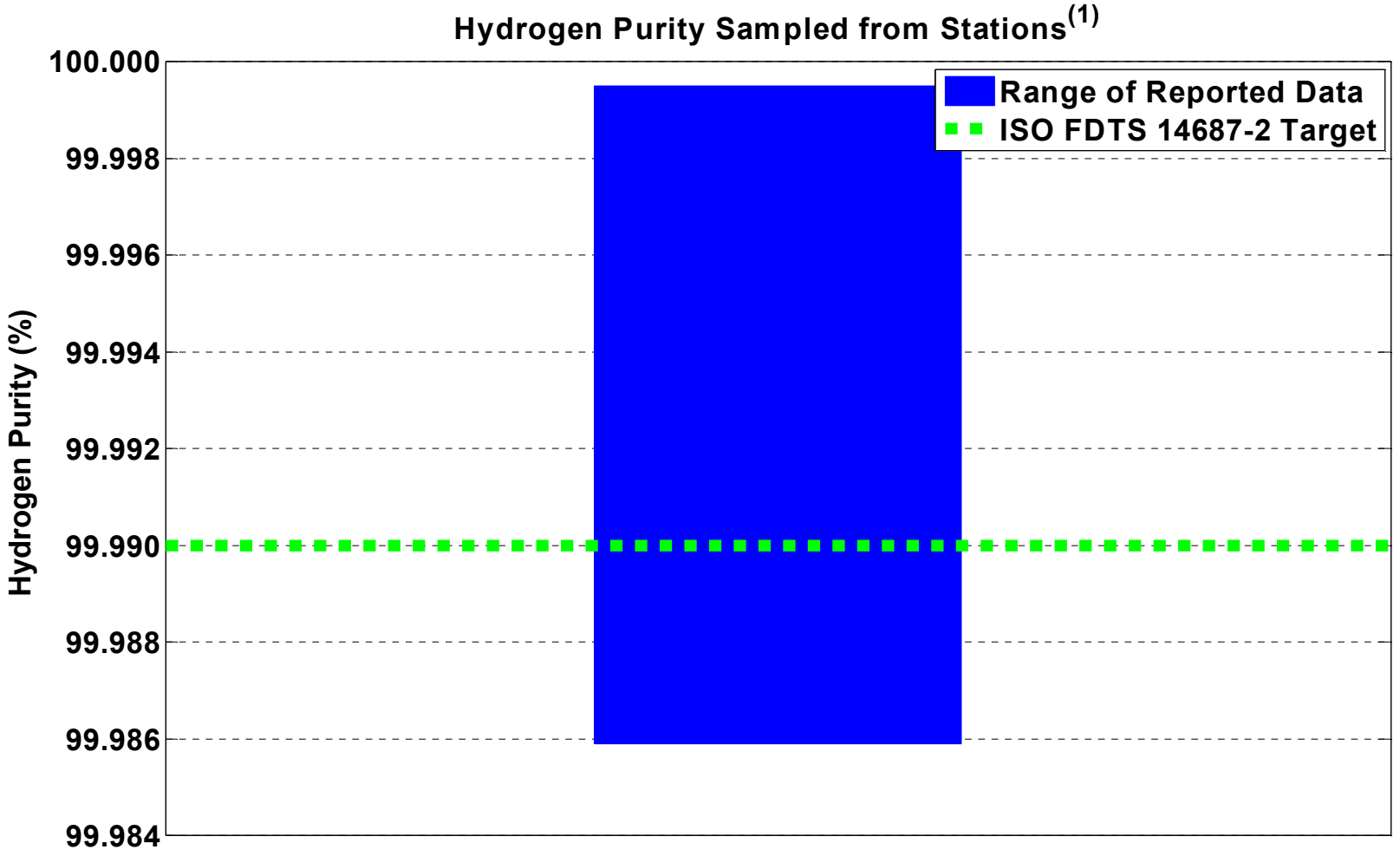






Compressed and liquid H_2 tanks meet durability and short term weight %, but don't meet long-term weight % or volumetric capacity targets for vehicles

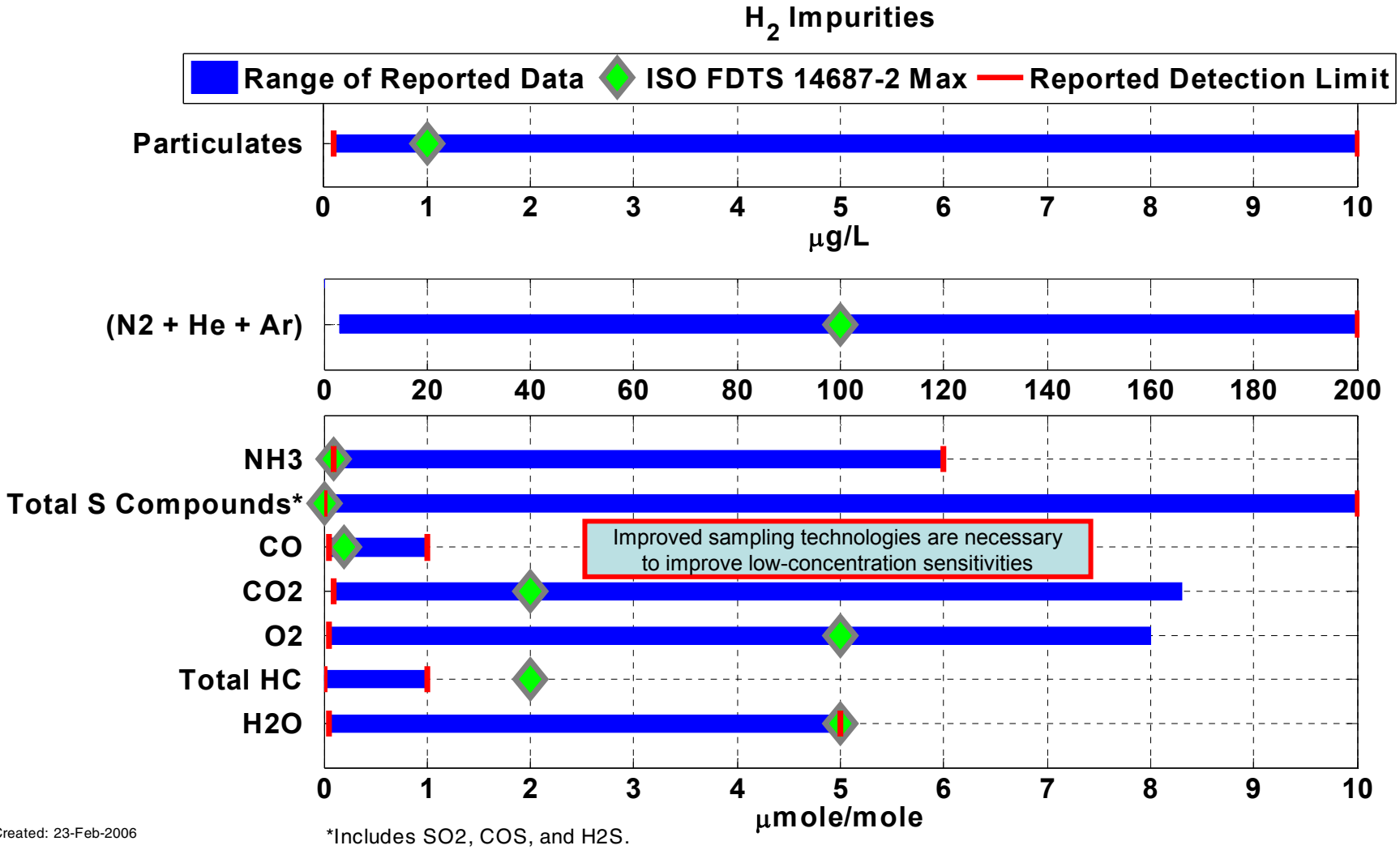
Hydrogen Purity Sampled from Stations Meets Target Majority of the Time



(1) Includes sampling from both electrolysis and reforming

Created: 21-Feb-2006

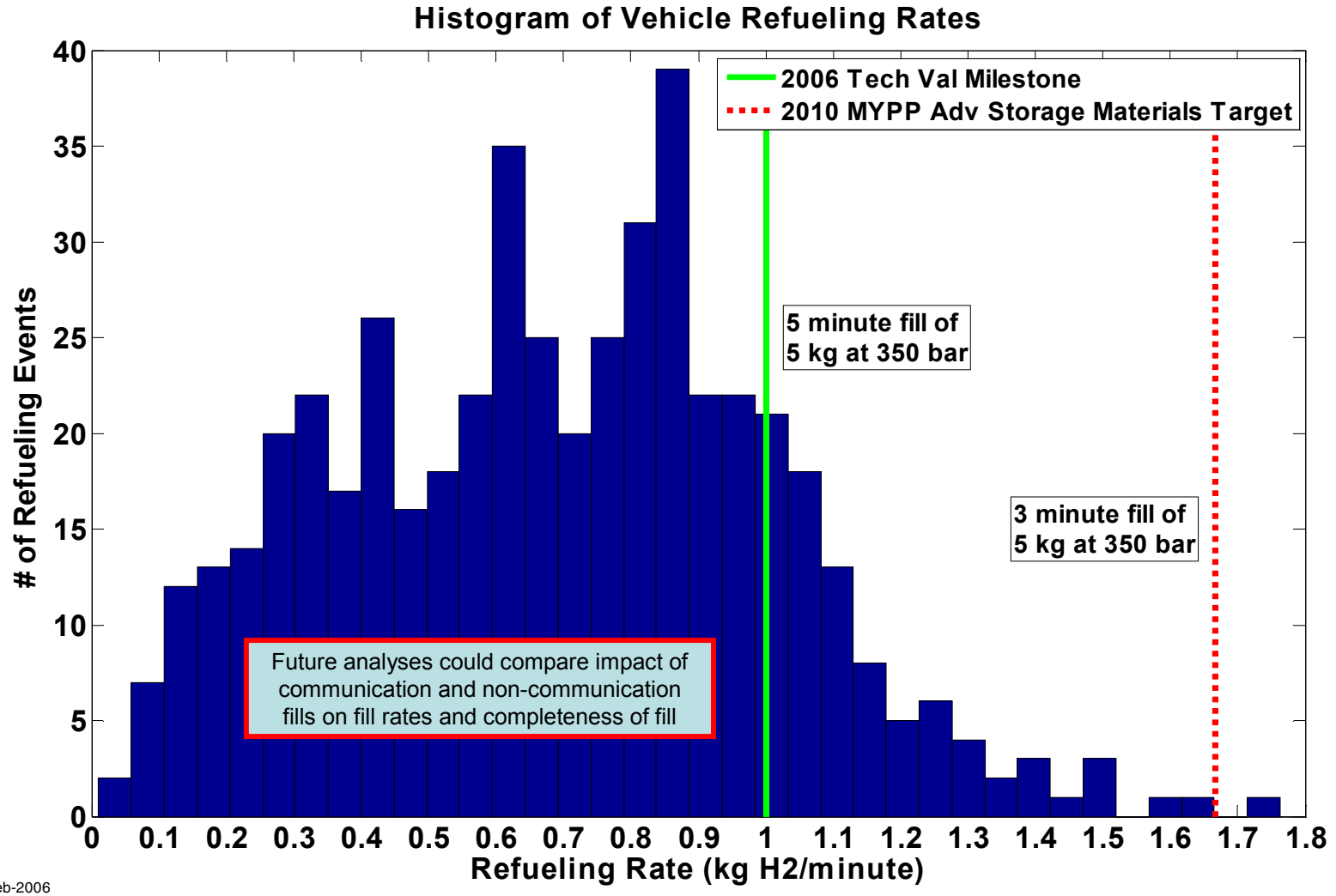
Hydrogen Impurities Sampled from All Stations – Includes On-Site Reformation, Electrolysis, and Delivered H_2



Created: 23-Feb-2006

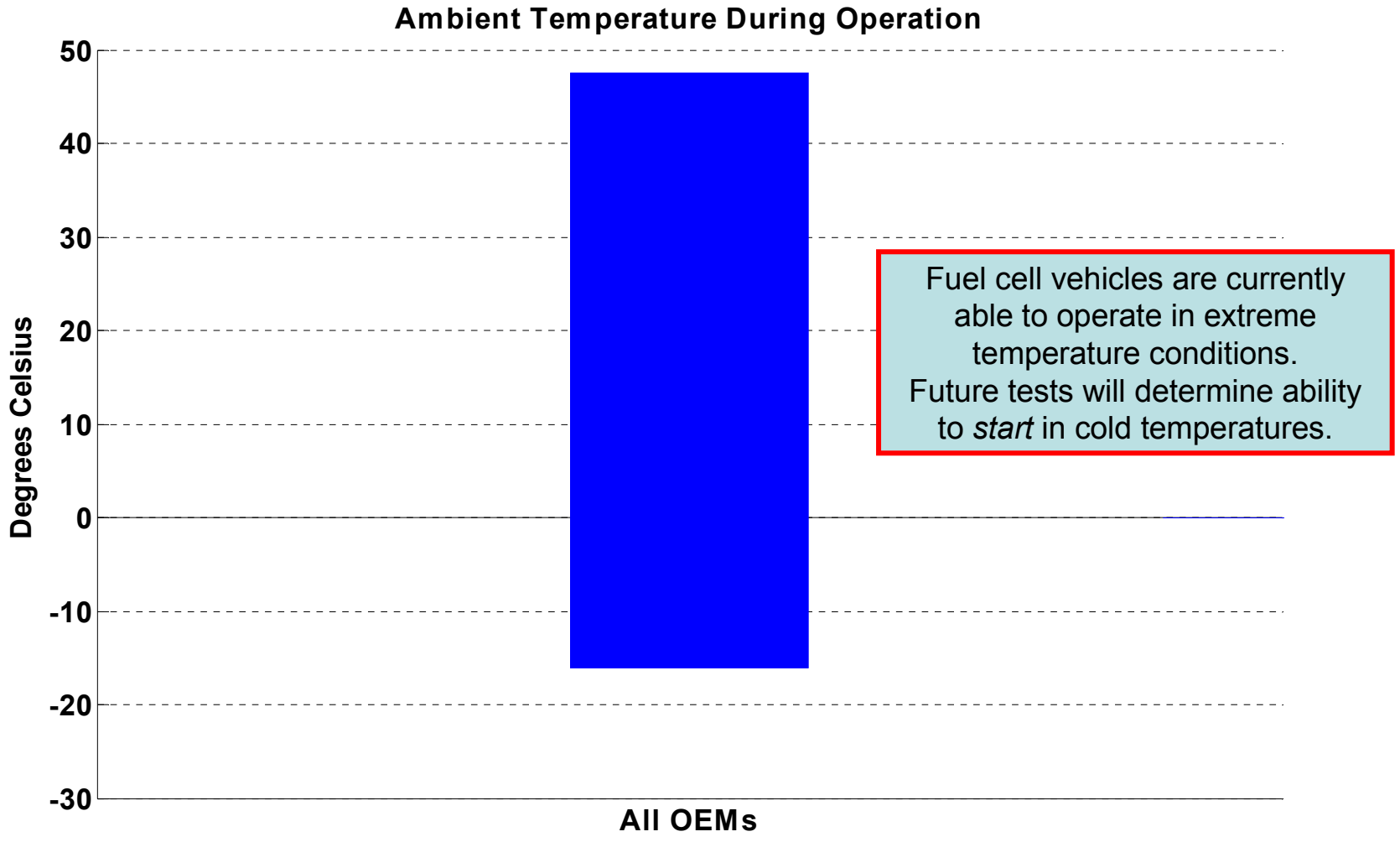
*Includes SO2, COS, and H2S.

Actual Vehicle Refueling Rates: Measured by Stations or by Vehicles



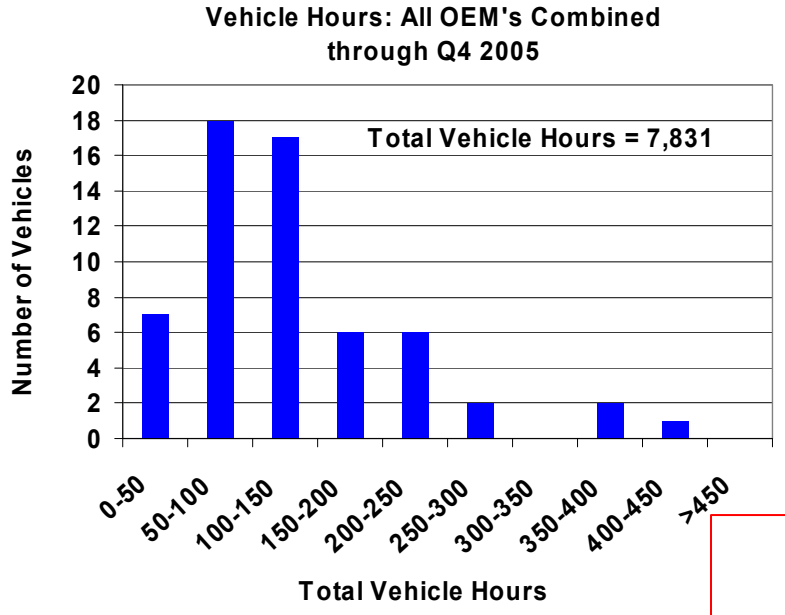
Created: 21-Feb-2006

Range of Ambient Temperature During Vehicle Operation



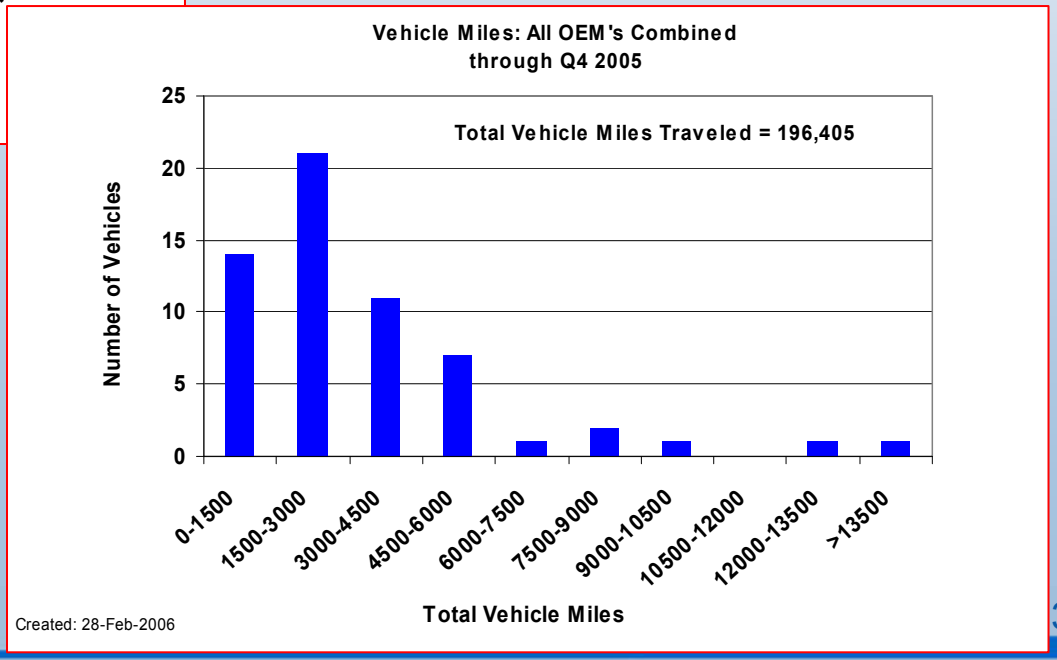
Created: 16-Feb-2006

Vehicle Operating Hours and Miles Traveled Distribution



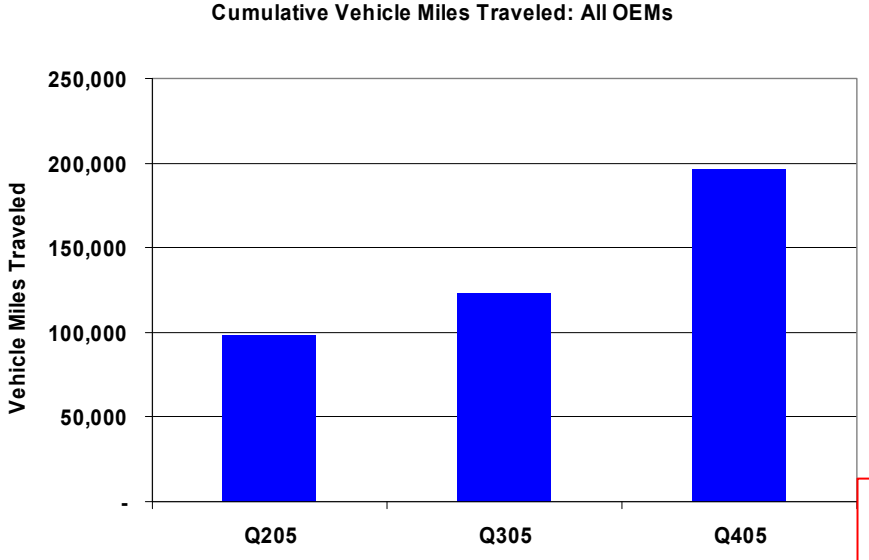
Created: 16-Feb-2006

Data reflect youthful nature of current fleet



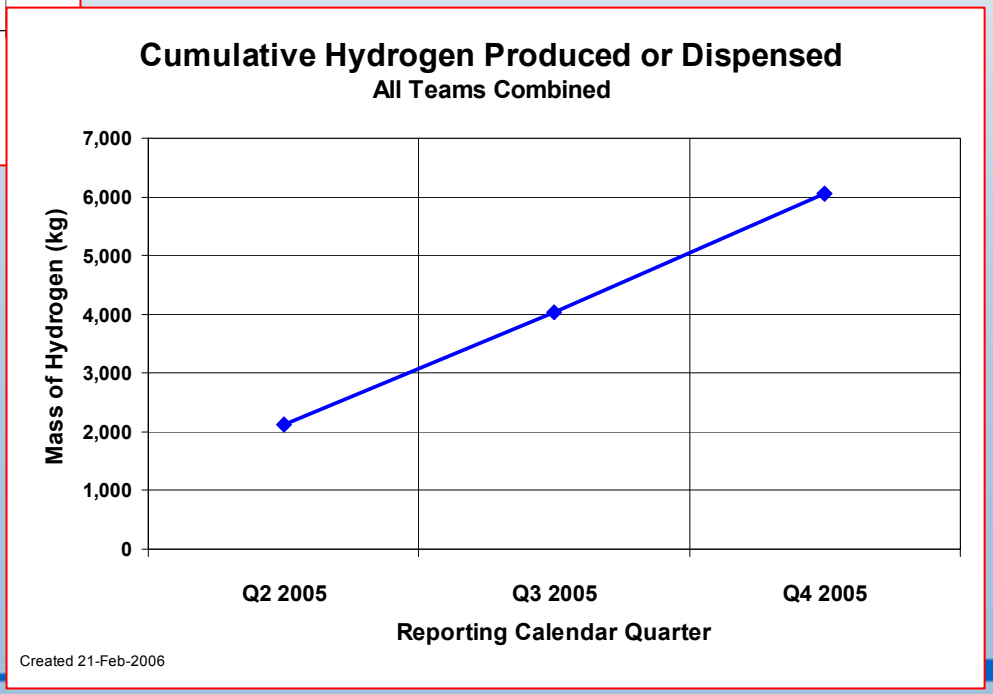
Created: 28-Feb-2006

Cumulative Vehicle Miles Traveled and Mass of H_2 Produced or Dispensed

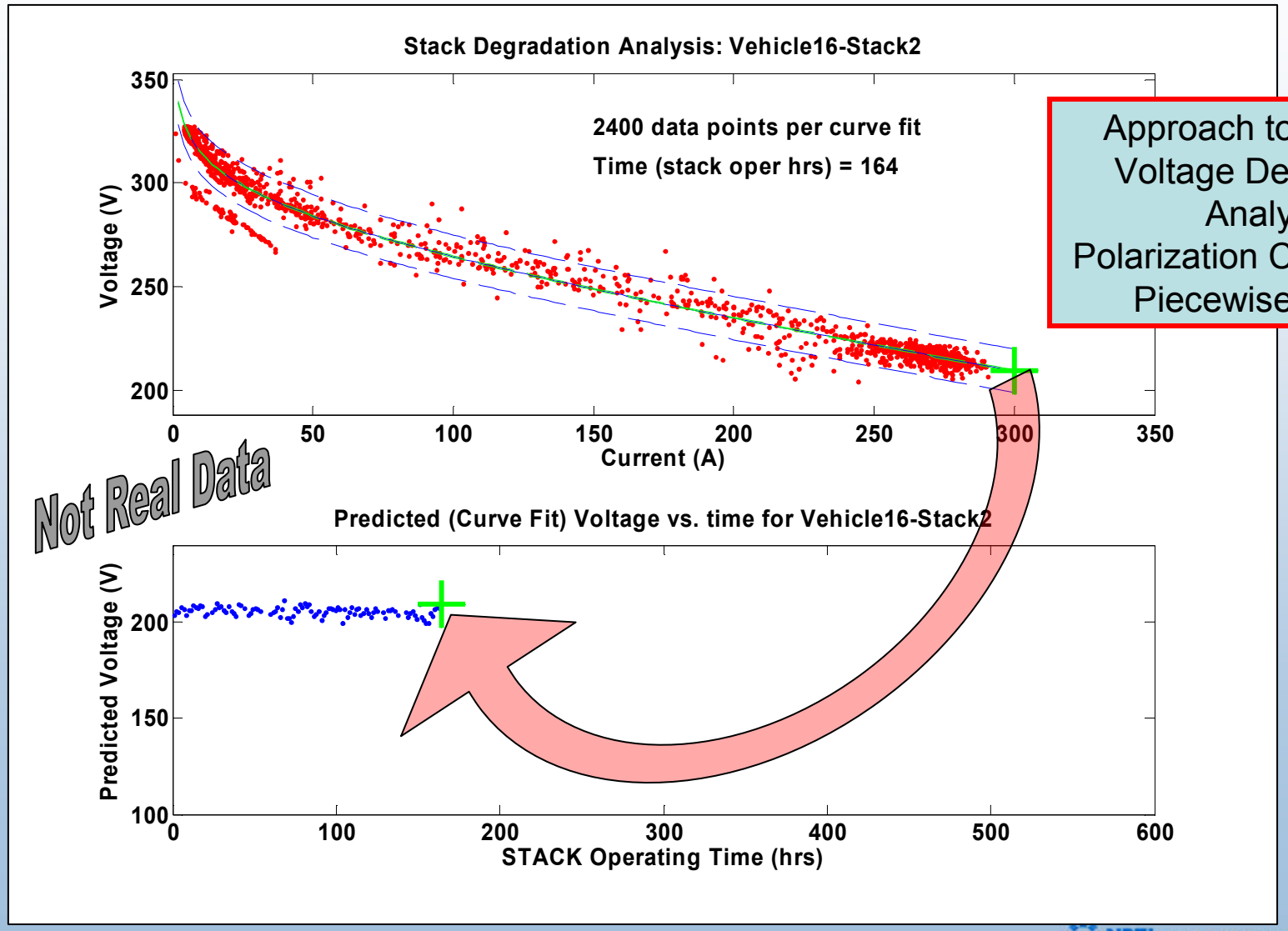


Current deployment of new H_2 refueling stations for this project is about 20% complete

Rate of mileage accumulation increasing as initial fleets approach full Gen 1 vehicle deployment

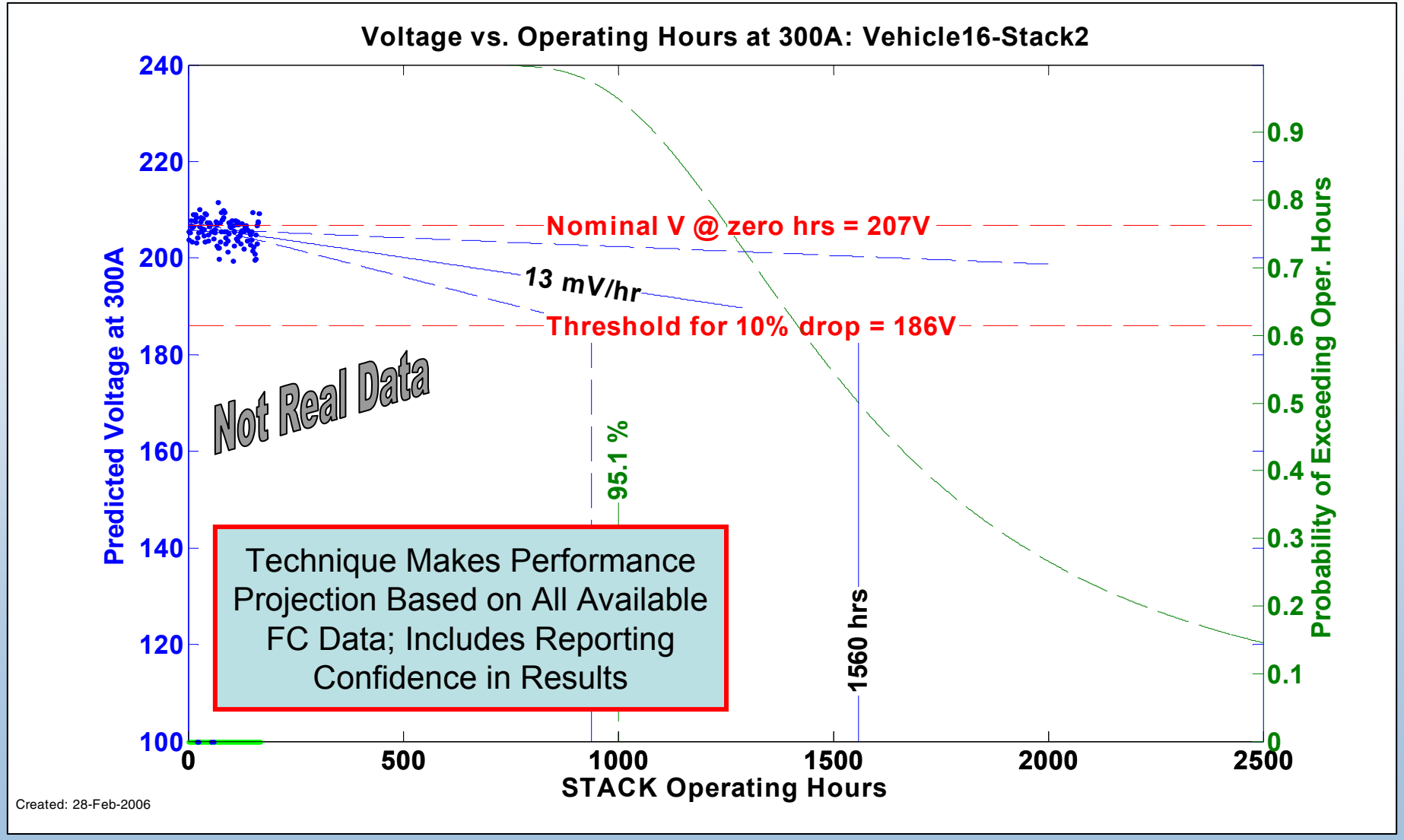


Accomplishments: Automated Analysis Updated for Analyzing Stack Current/Voltage Degradation

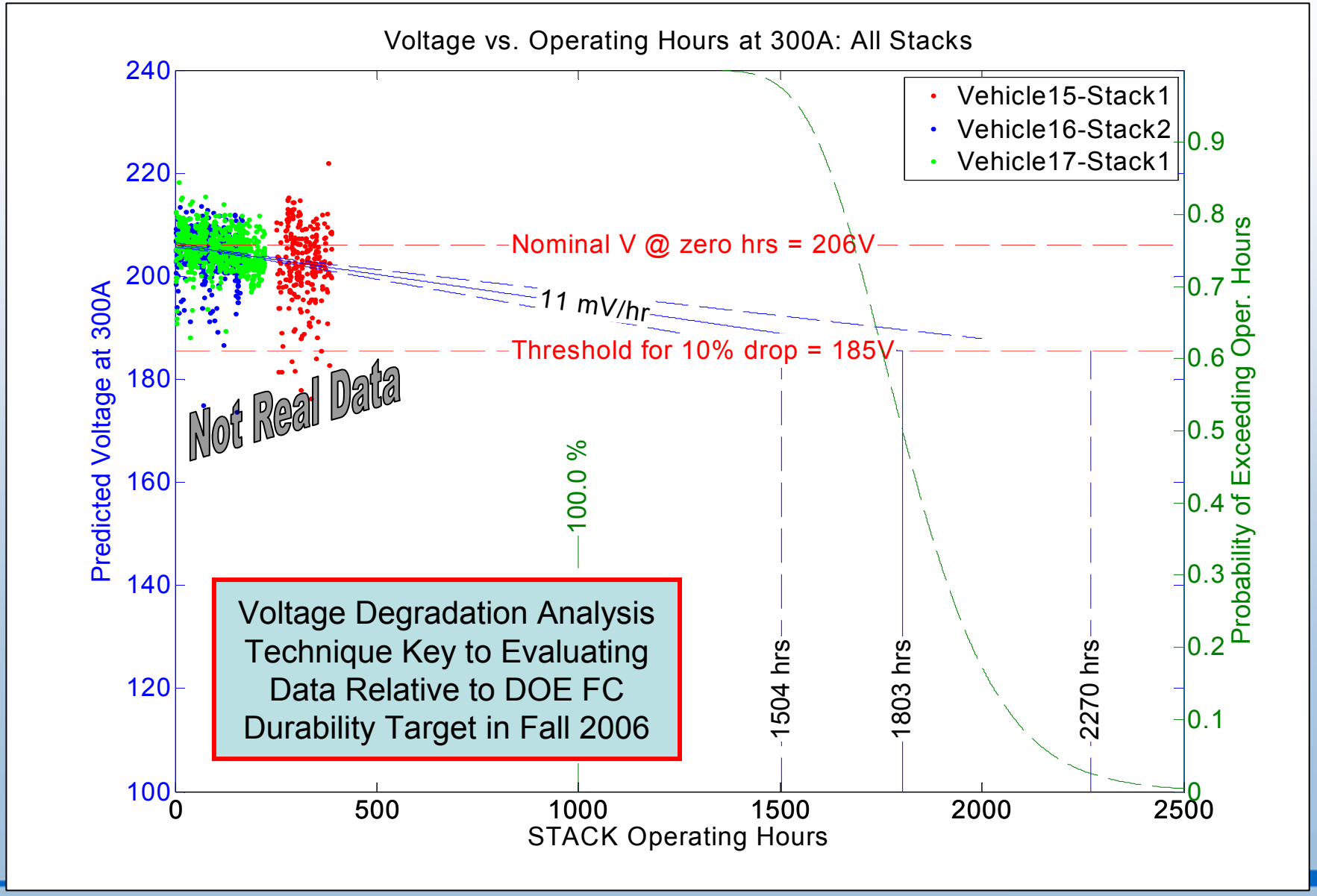


Approach to On-Road Voltage Degradation Analysis: Polarization Curve Fitting, Piecewise in Time

Voltage Degradation Analysis: Individual-Stack Methodology

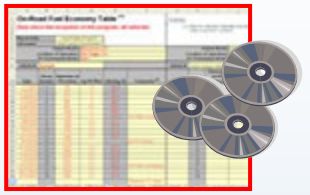


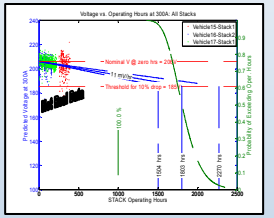
Voltage Degradation Analysis: Multiple-Stack-Average Methodology



Interactions and Collaborations

- Provided feedback to industry teams on data submissions to ensure maximum benefit of data being reported while minimizing extra effort by industry
- Performed industry site visits to participate in vehicle chassis dynamometer testing
- Compiled detailed data products for two of the four industry teams and made site visits to present and discuss the results
  - Similar meetings will be held with remaining two teams in summer/fall 2006
- Participated in annual project review meetings with all four teams (March 2006)
- Interacted with relevant codes and standards teams
- Participated in CAFCP DemoNet sharing meetings
- Presented technical results to H_2 community as a whole at NHA meeting
  - good interaction in Q&A and subsequent discussions
- Helped other countries/states establish data collection protocols for their projects based on our experience





Future Work

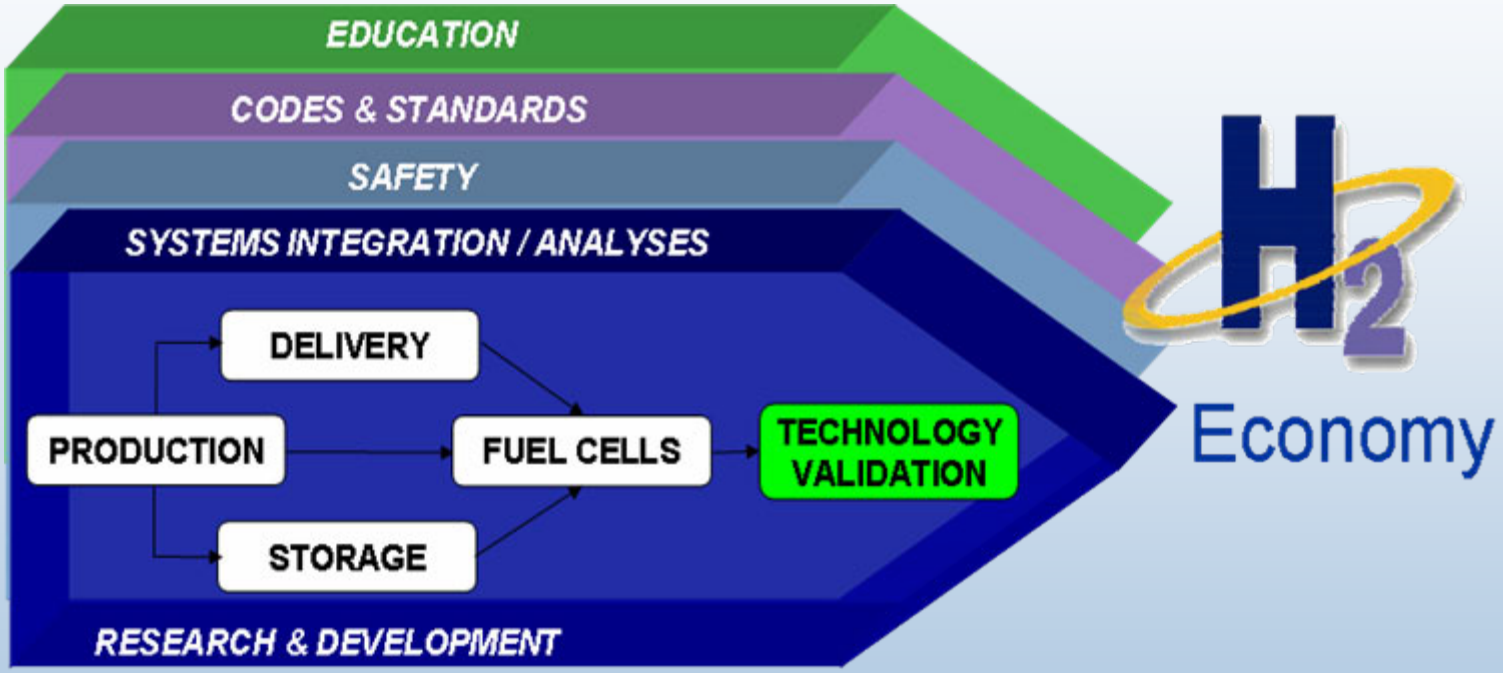
- **Remainder of FY06:**
  - Analyze first 1.5 years' data (through 8/06)
    - Create remaining 10 Composite Data Products (CDPs)
    - Update existing 16 CDPs with latest results/status
    - Develop new CDPs based on suggestions from industry teams and get buy-in from all teams
    - Prepare results for publication at EVS-22 and 2006 Fuel Cell Seminar
  - Support September 2006 DOE MYPP and Joule milestones to evaluate current status of FCV technology relative to
    - 1000 hour intermediate durability target
    - Vehicle refueling time of 5 minutes or less
  - Support DOE Go/No-Go Decision on purchasing 2nd generation FCVs in 2007 based on progress toward targets above (9/06)
  - Present detailed data products to two remaining industry teams
  - Write quarterly validation assessment reports (5/06, 8/06)

- **FY07 and beyond:**
  - Semi-annually (spring/fall) compare technical progress to program objectives and targets
    - Provide public outputs through publication at conferences
  - Actively feed findings from project back into HFCIT program R&D activities to maintain project as a "learning demonstration"

Summary

- First year of the 5-year project completed
  - 59 vehicles now in fleet operation
  - Several new refueling stations opened
  - No major safety problems encountered
- Project has identified current technical status relative to program targets
  - Will track improvements from 2nd generation stacks/vehicles introduced mid-way through project
- Future public results will include:
  - FC durability, reliability, efficiency, and start-up times
  - H_2 production cost, efficiency, and maintenance

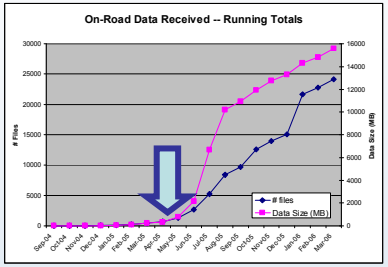
Questions and Discussion



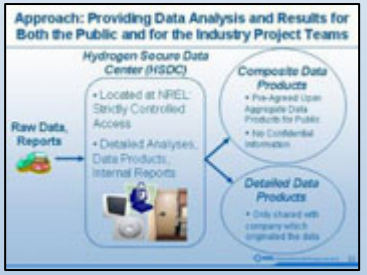
Contact: Keith Wipke, National Renewable Energy Lab
303.275.4451 keith_wipke@nrel.gov

Responses to Previous Year (FY05) Reviewers' Comments

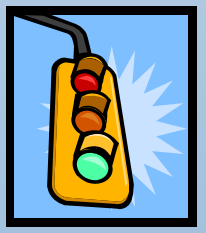
- Q: "Technical Accomplishments:…for a project starting in 2003 results seem too modest"
  - FY2003-2005 built the foundation of this project (solicitation, data templates, HSDC, agreement on blank CDPs)
  - Sufficient quantity of data for analysis/publication only began to be available in spring 2005 (see slide 6, reproduced at right)
  - In FY2006 the accomplishments were more visible/public



- Q: "Lack of clarity of how the HSDC assures a meaningful data sharing with stakeholders"
  - Efforts made to clarify the data sharing in this presentation
  - Composite Data Products shared with H_2 community, public, decision makers
  - Detailed Data Products shared with DOE (within the HSDC) and with the company which originated the raw data



- Q: "Go/no-go milestone criteria must be quantified"
  - This is the first year for a go/no-go decision (9/06)
  - 2006 targets are clear; status will measured against targets
  - Working with NREL Systems Integration office to facilitate the process and establish formal criteria for decision



Publications and Presentations

(Since FY05 Review)

- Welch, C., Wipke, K., Thomas, H., Sprik, S., "DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project: Quarterly Validation Assessment Reports," (HSDC internal documents)
  - 1Q 2005, May 2005.
  - 2Q 2005, August 2005.
  - 3Q 2005, November 2005.
  - 4Q 2005, February 2006.
- Welch, C., Wipke, K., "Fuel Cell Durability," June 2005. Written in support of DOE Joule milestone. (HSDC internal document)
- Wipke, K., "Hydrogen Secure Data Center: Procedures to Protect Technical Data Submitted Under the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," *updated* September 2005. (NREL document)
- Welch, C., "Composite Data Products for the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project," *updated* January 2006. (NREL document)
- Chalk, S., Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., "Status of U.S. Hydrogen Infrastructure and Fuel Cell Vehicle Technology Learning Demonstration," Japanese Fuel Cell Demonstration Seminar (JHFC), March 2006 (public presentation only)
- Wipke, K., Welch, C., Thomas, H., Sprik, S., Gronich, S., Garbak, J., Hooker, D., "Hydrogen Fleet & Infrastructure Demonstration and Validation Project: Progress Update," NHA Annual Hydrogen Meeting and Exposition, Long Beach, CA, March 2006. (public paper and presentation)

Critical Assumptions and Issues

- Assumption: Linear Voltage Drop for Voltage Degradation Prediction
  - Linear degradation currently assumed for robustness of curve fit on the relatively short data set received to-date (i.e., using a non-linear curve at this point would provide unreliable predictions)
  - Proposed solution: As more data is received, non-linear fits may be used if the voltage data appears to have a non-linear behavior (it might flatten out or accelerate its degradation, for example)

- Issue: Timing of regularly reported data for critical September 2006 milestones and go/no-go decision.
  - DOE Cooperative Agreement data minimum reporting frequency is quarterly (some companies provide monthly)
  - Data must be submitted to HSDC 1-month after conclusion of previous quarter (eg. by end of October for FY06Q4)
  - If no special actions are taken, this would result in data from April-June 2006 (reported at end of July) to be used for Sept. 2006 milestone status
  - Proposed solution: we will be requesting an early delivery of on-road data covering July-August 2006 so that we have 2 more months of data to evaluate the technology status for the milestone

Project Safety

- Safety an important part of Controlled Fleet & Infrastructure project Cooperative Agreements.
  - NREL's role in this project is analytical, so typical office environment safety measures are being followed.
  - Industry partners have responsibility for ensuring the safety of their hydrogen vehicles and refueling infrastructure.
- Industry includes the following aspects in each of their projects:
  - Failure modes and effects analysis (FMEA) on the project
  - Safety assessment
  - Risk mitigation plan
  - Measuring and monitoring safety performance
  - Communication plan, including reportable accidents, management response, and independent reviews
- All projects are reporting safety incidents on both vehicles and infrastructure
  - Current safety record presented at NHA as part of Composite Data Products (and in this presentation)
  - Periodic presentations made before Safety Review Panel
  - Any unresolved safety concerns will be brought before Panel