Development of a Turnkey H_2 Refueling Station

Project ID # PD4

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U.S. D.O.E. – Hydrogen Program Annual Review
May 2005

Program Objectives

- To demonstrate the economic and technical viability of a stand-alone, fully integrated H_2 Fueling Station based on reforming of natural gas
  - To build on the learnings from the Las Vegas H_2 Fueling Energy Station program.
  - Optimize the system. Advance the technology. Lower the cost of delivered H_2.
- To demonstrate the operation of the fueling station at Penn State University
  - To obtain adequate operational data to provide the basis for future commercial fueling stations
- To maintain safety as the top priority in the fueling station design and operation

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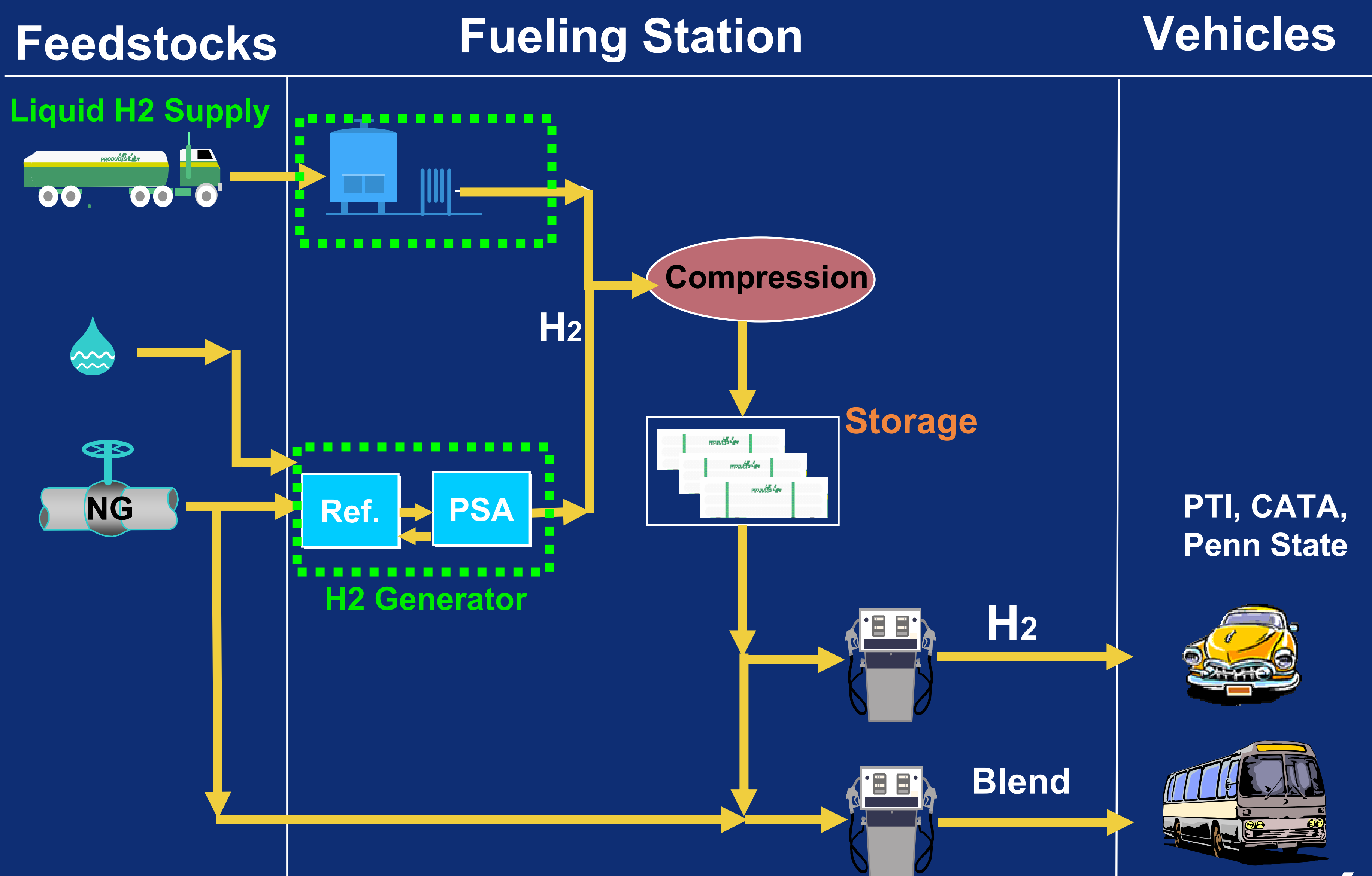
- Goals for Past Year:
  - Complete Phase 2 – Subsystem Development (Accomplished)
  - Execute Phase 3 – Subsystem Deployment (Underway)

H_2 Fueling Station at Penn State



Budget

- Total Project Budget:
  - $8.929 MM
- Cost Sharing:
  - DOE - $5.169MM
  - APCI and Partners – balance.
- FY2005 Funding
  - $2,083,508 Total
    - DOE = $1,187,560
    - APCI = $ 895,948

Forecast is on-budget completion of program

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Goals & Targets

- DOE Technical Barriers
  - Technical Validation (Section 3.5.4.2 of HFCIT Program Report), Task #3.
    - B. Storage (fast fill)
    - C. H_2 Refueling Infrastructure (cost of H_2; interface for fast-fill)
    - D. Maintenance & Training Facilities (train personnel for H_2)
    - E. Codes & Standards (lack of adopted codes & standards)

- Goal per RFP – Subtopic 5C
  - *"To design, develop, and demonstrate a small-scale reformer and refueling system that can produce H2 at a cost that is within 5% of the cost, on a miles-equivalent basis, of commercially available premium gasoline."*
  - >40 kg/d. $2.00 - $2.50 / kg (miles equiv basis). Utilize concepts of mass production.
  - Phase 1 Study showed pathway to achieve goal.

- DOE Targets
  - **H_2 Production** (Table 3.1.2 of HFCIT Program Report), Task #3.
    - **Price of H_2 into Vehicle:**
      - $3.00 / kg in 2005.
    - **Efficiency:**
      - PSA: 82% in 2005 (not mentioned in Jan 2005 Table)
      - Overall: 68% in 2005 (changed to 65% in Jan 2005 Table)
  - Program is expected to validate these targets

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Three Phase Industry-DOE Project

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Phase 1: Conceptual Design & Economic Evaluation

- Formulated & costed subsystem conceptual designs
- We believe we can demonstrate the roadmap to providing H2 fuel equivalent to gasoline prices
- **Completed, on-schedule.**

Phase 3: System Deployment

- Scale-up & detailed engineering
- Fabricate & install at Penn State
- Operate and Test – Vehicles Filled
- 6 Month Operations

Operation

Oct 2001 **May 2002** **Fall 2003**

Oct ‘04 LHy Tank & Fueling Station Installed

Oct ‘05 Generator Installed & On-Line

Phase 2: Subsystem Development

- Develop Subsystems and Test Components
- Advance **every** aspect of station
- Begin station aesthetics work

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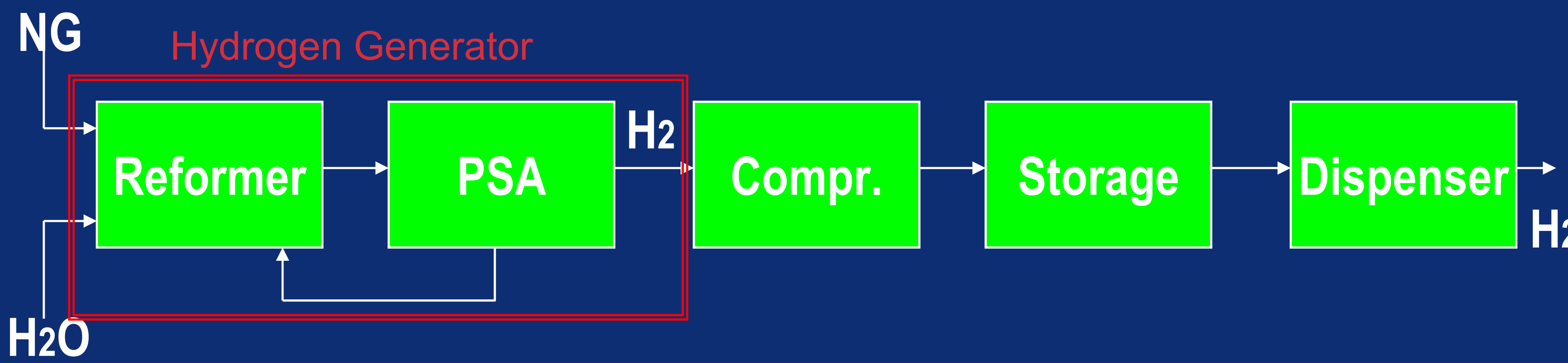
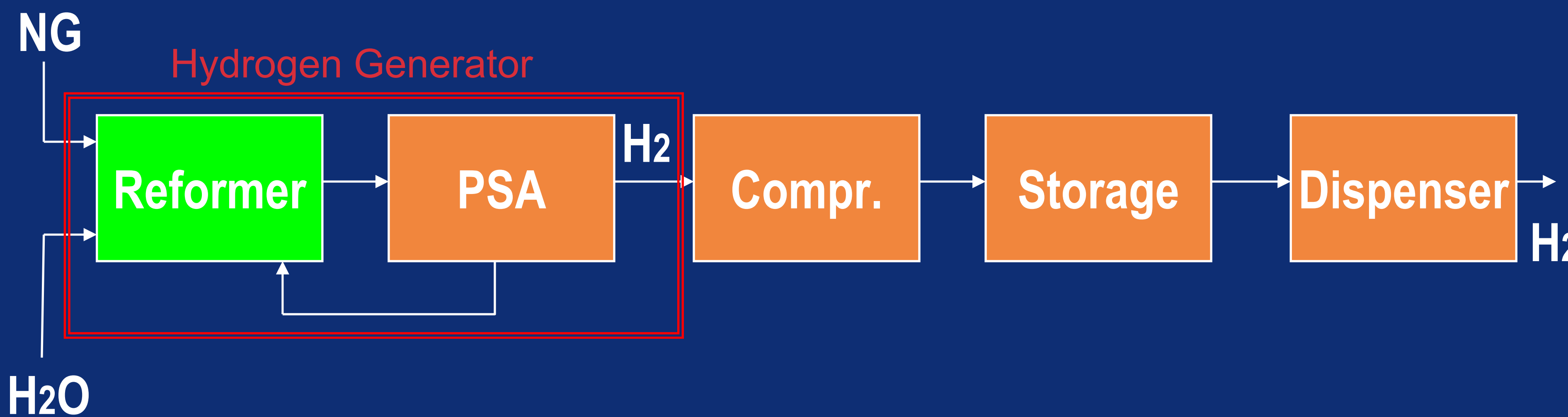
Approach Sub-System R&D



- **Comprehensive Development Program**
  - Work organized by sub-system
  - Combination of simulation, lab R&D, Real-world component testing, collaboration with vendors, and engineering design work
  - Significant progress towards DOE Targets and Barriers

Hydrogen Generator



Goals:

1. Advance the most cost effective natural gas reforming technology for fueling station applications.
2. Improve efficiency, reliability, capital cost, aesthetics, and footprint

Hydrogen Generator

- **Advanced SMR chosen by comprehensive technical and cost evaluation**
  - Evaluated SMR, POX, ATR, CPOX
  - Received 10 quotations for commercial or near-commercial systems
  - Advanced Technology SMR’s are more cost competitive than the other evaluated technologies for small scale reforming applications used in hydrogen fueling stations

Hydrogen Generator

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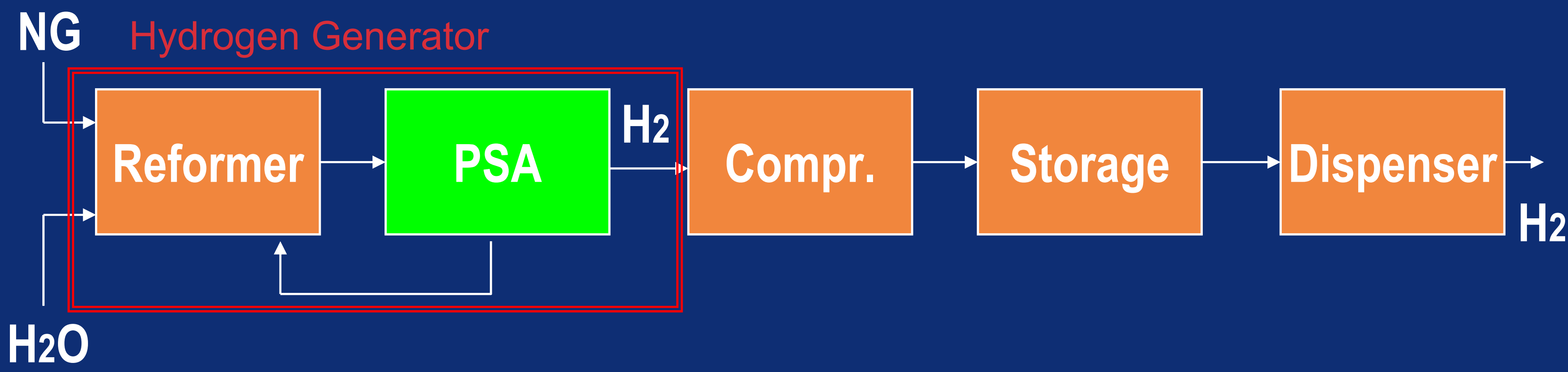
  - Received 10 quotations for commercial or near-commercial systems
  - Advanced Technology SMR's are more cost competitive than the other evaluated technologies for small scale reforming applications used in hydrogen fueling stations
- **Operation and testing of Las Vegas H_2 Energy Station**
  - Nothing better than real-world operating data
  - Incorporating lessons learned
- **Engineering Development Complete**
  - Optimization of desulfurization, reformer, and shift catalysts
  - Improved heat recovery system
  - Improved efficiency
  - Improved capital costs

H_2 Generator Development

- **Improvement in All Areas:**
  - Desulfurization
  - Shift
  - Syngas Compression
  - PSA
  - Heat Exchange Train
  - Boiler, Pump
  - Utilities
    - Water Treatment
    - N_2 Purging
  - Controls
  - Packaging
  - Layout
  - Aesthetics

Purifier Development



Goals:

1. Reduce capital and operating costs of PSA system
2. Reduce footprint (volume) of PSA system
3. Increase efficiency (H_2 recovery) of PSA

Purifier (PSA) Development

- **PSA Technology Chosen**
  - High H_2 Recovery at <1 ppm CO in H_2
  - Low capital cost
  - Maintainable

- **Innovation in Multiple Areas and Functions**
  - Exotic adsorbents developed for higher recovery
  - Cycle optimization to reap benefits of new adsorbents
  - Valve development for rapid cycles
  - Process/Material/Mechanical integration
  - Low cost manufacturing / systems assembly (DFMA)
  - Lab and operating plant data collected

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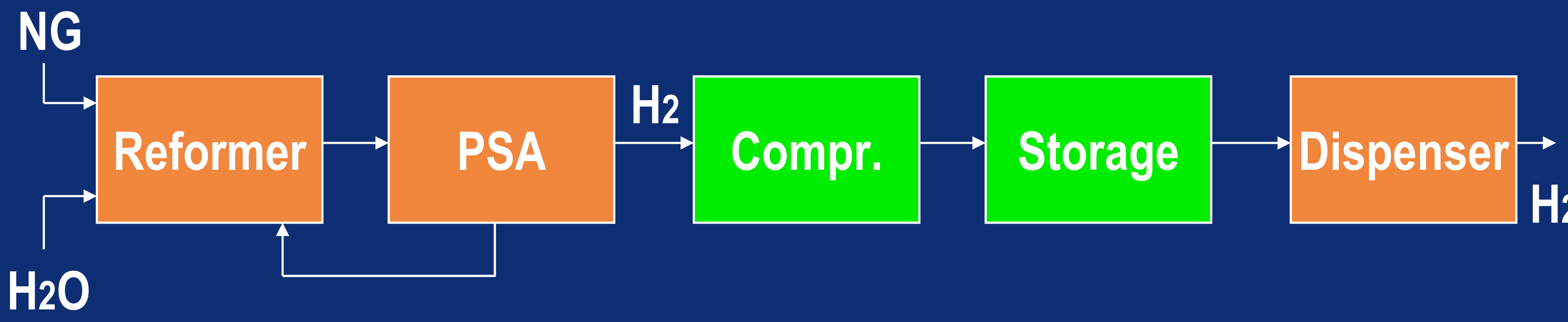
PSA Summary

- **Engineering Work Completed**
  - System components specified
  - Mechanical design & manufacturing improvements implemented
  - DFMA, DfX, Flow CI Tools Used
  - System running at APCI H_2 Production Facility (>1.5 yrs)
- **Goals Met**
  - Achieved 2 – 4x reduction in cost of PSA when compared with commercially available units
  - New PSA Unit Much smaller than commercially available units
  - Efficiency Meets DOE 2005 Target of 82%

Compression & Storage



Goals:

1. Improve footprint, aesthetics, and cost of compression and storage.

Compression & Storage

- **Investigated Storage Materials**
  - Steel
  - Composites
  - Hydrides
  - Steel chosen as most cost effective for both 350 and 700 barg fueling
- **H_2 Compression**
  - Economic Study
    - Reciprocating, diaphragm, novel concepts
      - Spawned new DOE/APCI program – Novel H2 Compression
    - DFMA for packaging & aesthetic impact
  - Diaphragm compressor chosen – driven by capital cost & maintenance benefits

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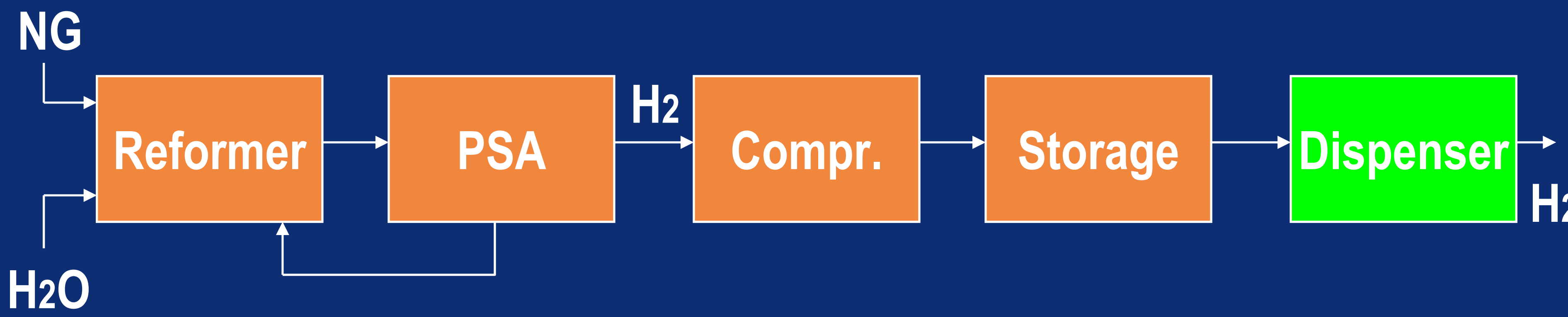
Compression and Storage

Compression/Storage Sub-System Attributes

- High reliability, automated operation
- Totally integrated compression and cascaded fueling module
- Integrates to storage system that can be matched in size to varying fleet requirements
- Designed to operate from any large hydrogen source – electrolysis, reformer, tube trailer, liquid tank, or pipeline
- Reduced installation complexity and cost

Dispenser Development



Goals:

1. Use Sacramento and Las Vegas as starting point. Make dispenser less "industrial" and more aesthetic. Continue validation of control program.
2. Improve metering alternatives and test plan. Implement test plan.
3. Reduce cost.

Dispenser Development

- **Component Selection Completed – Dispenser Built**
  - Good for classified area – Class 1 Div 1.
  - High Pressure - Components selected for 14,000 – 20,000 psig

- **Design for Manufacturability and Aesthetics**
  - Continuous Improvement Tools – DFMA, Flow, DfX, Mistakeproofing
  - Involved fabricator in DFMA
  - Significant cost reduction and parts list reduction

External Design

- From:

External Design

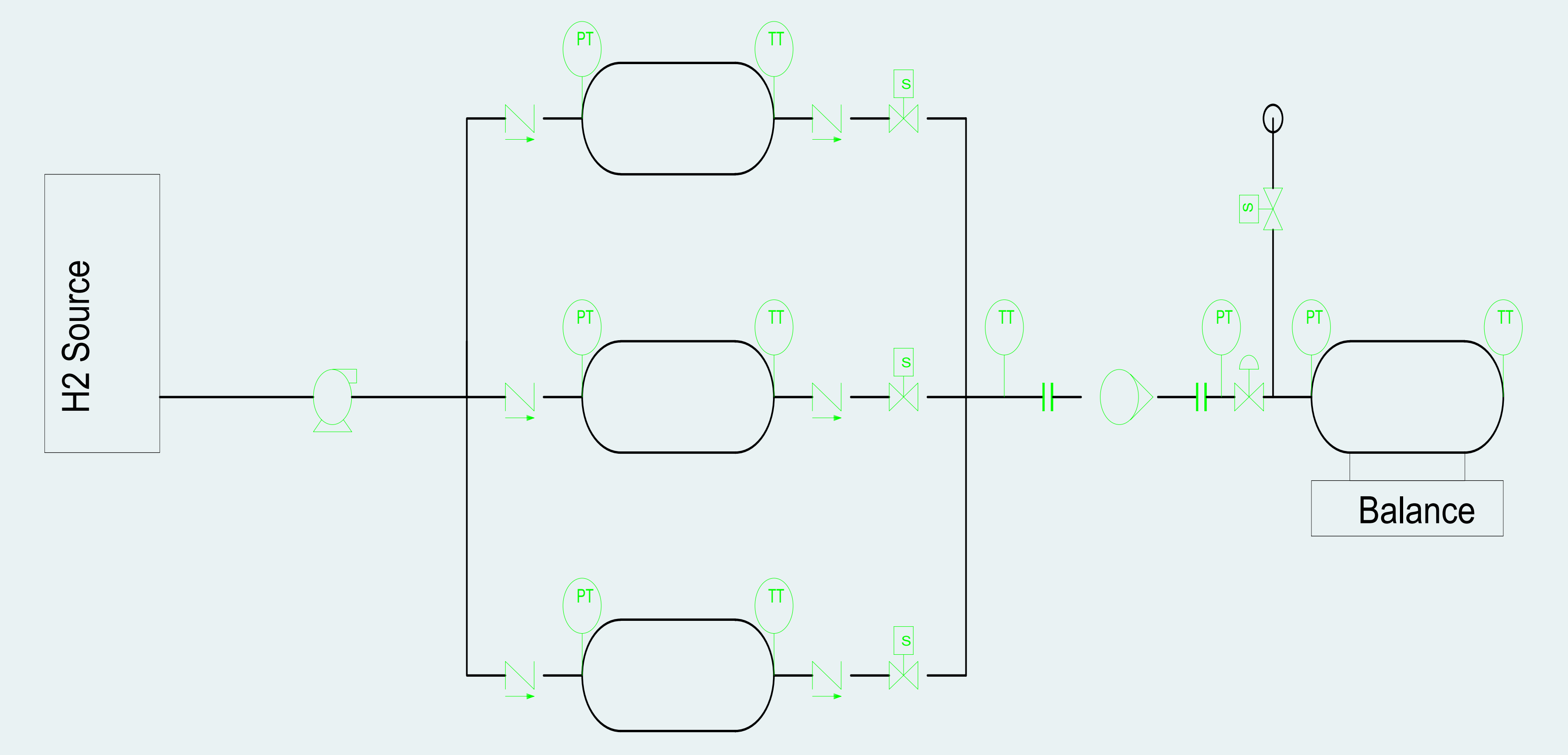
- To:

Dispenser Development

- **Control Program (with communications)**
  - Proven accurate to within limits of instrumentation
  - To date, over 12,000 successful fills in the field – real cars
  - Ongoing lab testing (outdoors) at APCI to continue to improve
- **Some customers and/or regulations may demand a separate "custody transfer" paymeter**
- **Flow Meter Testing & Development**
  - Test skid built and in service. Test program underway.
  - 10 Meters Investigated
  - 3 Chosen for Test. All 3 Tested to Date.

Flow Meter

- Test program:



- Options: Coriolis, single and twin turbine meters

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Dispenser Development

- **Metering (continued)**
  - Flow Meter Testing & Development
    - Test skid built and in service. Test program underway.
    - 10 Meters Investigated
    - 3 Chosen for Test. All 3 Tested to Date.
      - **Several meters achieve acceptable steady-state flow accuracy**
      - **However, best measured batch accuracy to date is +/- 5% over entire range of fill pressure & flowrate**
        - Improvement from original +/- 30%
        - None performs to acceptable accuracy
        - Testing and vendor development continues
      - **Interfacing with NIST to help write certification rules**

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Dispenser Progress

- **Customer Feedback used to Improve Aesthetics & User Interface**
- **DFMA, Hazop, DFX, Flow, CI Tools**
- **Cost Reduction**
  - Factor of >2 reduction from starting point
- **Fast-Fill with Vehicle Communications**
  - Accurate by calculation: +/- 0.2%
  - Much improved metering during project.
  - Metering work needs to continue in this area for the entire industry

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Siting - Before

- **APCI, Penn State, and PTI Chose Site**
  - Choice: At current CNG vehicle filling site
  - East end of PSU campus, by Beaver Stadium
    - Meets needs of PTI – for test track
    - Near ECEC where fuel cell research is done (Dr. Wang)

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After (during)

- **LHy supply system, H_2 compression, H_2 storage, H_2 dispenser and Blend dispenser installed Oct. 2004.**

Validation of DOE 2005 Targets

- **Las Vegas**
  - Validated <$5.00/kg
- **Penn State**
  - Capital cost reduction, maint. cost improvement, efficiency boost
- **Efficiency**
  - Integrated Station with Advanced SMR, Novel PSA, and Optimized Process
  - Meets DOE 2005 Target of 68% Overall Efficiency (LHV)
- **Refueling Station Costs**
  - Studied effect of scaling:
    - To larger H_2 production per generator
    - To mass production of stations (100 units)
  - $2.72/kg H_2 Price at Dispenser is feasible based on this program's technology*
    - Meets DOE 2005 Target of $3.00/kg H_2
    - Pathway Re-Validated that a Stand-Alone H_2 Station can be Technically and Economically Feasible

* DOE HFCIT May 2004 Assumptions: 690 kg/day, 11% capital factor, >100 units annually, $4/MMBTU(HHV) NG, 90% utilization

Future Work

- **Operation of Station with LHy Supply**
  - Continue data collection in field
  - Support vehicle hydrogen demand
- **H2 Generator (reformer based)**
  - Integration of H_2 Generator Sub-systems
  - Installation / Start-Up in October 2005
- **Vehicles**
  - Continue to collaborate with PSU, CATA, and State of PA on vehicle plan and funding for plan
  - PSU
    - OPP: 1 H2/CNG blend van. Converted by Collier Technology
    - PTI – HyLion FCV. Converted EV1.
  - CATA Buses – 1st Bus Operational Late Spring 2005
    - H2/CNG Blend
  - Additional funding for more buses expected.

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Response to Reviewers' Questions

- **Next Generation Station**
  - Build on learnings of Las Vegas Station
  - Advance technology – improve efficiency
  - Address all aspects of H_2 refueling facility design
  - Reduce cost of H_2 delivered
- **Technical Advancements**
  - PSA System Efficiency Increased
  - H_2 Generator Efficiency Increased
  - Dispenser Metering Advanced
  - System Integration Optimized
  - Results in Reduced Cost of Dispensed H_2
  - Meets DOE Targets
- **Vehicles "Not Part of Work Scope" is Unacceptable**
  - Significant effort was spent with PSU and State of PA
    - Proposal Approved by PA DEP for funding vehicle conversions and stations operating costs
      - by PSU H_2 Institute, PSU PTI, CATA, Air Products
  - Contract changed to include CNG/H_2 blend dispenser and to match the timing of station start-up with vehicle availability

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Thank you

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Publications / Presentations

- DOE Annual Review Meeting – 2002-2004
- DOE Regional Meeting in Annapolis, MD - 2004
- NHA Annual Meeting – March 2005
- SAE Annual Meeting – 2004

Hydrogen Safety

- **The most significant hydrogen hazard associated with this project is:**
  - *This is a comprehensive project which includes the operating demonstration of an integrated hydrogen generation, hydrogen refueling, and CNG/hydrogen refueling station. As such, several potentially hazardous situations are possible and are covered in Air Products' safety and design reviews. The detailed HAZOP identifies the hazards and the safety measures taken to mitigate them.*

Hydrogen Safety - Approach

- **Our approach to safety issues is comprehensive and is based upon a tremendous experience base:**
- **Safety**
  - APCI has >40 years experience in safe design, construction, & operation of H_2 plants.
    - > 12,000 H_2 fuel fills complete to date (>75-120 per week now)
    - Leader in Management of Change, Near Miss Reporting, and Quantified Risk Assessment Procedures
  - PHR: Phase 1
  - HAZOP: Phases 2 & 3
  - All applicable industry codes are followed
  - APCI participates in SAE, ICC, ISO, HFPA, IETC, and EIHP2 committees.
- **Site Selection and Personnel Training**
  - Site concurrent with existing CNG filling station
  - Personnel will be trained in H_2 handling and maintenance of H_2-related equipment

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