Auto-Thermal Reforming Based Refueling Station at SunLine

2005 DOE Hydrogen Program Review
Arlington, VA
May 24, 2005

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This presentation does not contain any proprietary or confidential information.

Project: TVP6
Overview - Project Timeline

- Project began: January 2003
- Project competed: August 2004
- Percent complete: 100%
Overview - Partners

- HyRadix Inc.
- SunLine Services Group / SunLine Transit
- DOE/State of Illinois
- South Coast Air Quality Management District of California
Overview - Budget

- Total project funding: $1,126,000
  - DOE share: $563,300
  - Contractor share: $212,700
  - SCAQMD share: $350,000
- FY-04 funding: $243,300
Overview - Project Objective

Demonstration of Auto-Thermal Reforming based refueling station

DOE Objectives

- Demonstrate H₂ fueling station for HCNG and H₂ vehicles
- On-site auto-thermal reforming of natural gas
- Cost analysis vs. target of $3/gge in 2008
- Evaluate fill rates of fuel cell bus and car
- Public education of hydrogen and fuel cells
Overview – Barriers Addressed

C. Hydrogen Refueling Infrastructure
This project primarily addresses factors from the Hydrogen Refueling Infrastructure technical barriers as noted in the Technology Validation section of the Hydrogen, Fuel Cells & Infrastructure Technologies Program

- Interface technology to fast-fill tanks requires reliable demonstrations
  - SunLine has gained significant experience with and understanding of rate-of-fill factors and the optimization of a cascaded storage and dispensing system for servicing different types of vehicles.

- The high cost of hydrogen
  - The hydrogen generator used for this project represents a big step forward in reducing the cost of hydrogen production.
    - Feedback from this project is providing further cost reductions for HyRadix.
Overview – Barriers Addressed

C. Hydrogen Refueling Infrastructure

- Low availability of hydrogen production systems
  - This project demonstrates one of the first hydrogen refueling stations in the US using small scale reforming technology for on-site hydrogen generation. This project helped lead to a hydrogen generator that is now commercially available.

- Integrated facilities with footprints small enough…
  - Implementation of a compact skid-mounted hydrogen generator. This project also furthered the participants understanding of siting and configuration criteria for future refueling station design.
## Project goals

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Hydrogen Purity</td>
<td>&gt;99%</td>
</tr>
<tr>
<td>$\text{H}_2$ Production Rate</td>
<td>90% of 100 Nm$^3$/hr</td>
</tr>
<tr>
<td>Compression &amp; Storage</td>
<td>6250 psig</td>
</tr>
<tr>
<td>Dispensing</td>
<td>5000 psig</td>
</tr>
<tr>
<td>Refueling rate</td>
<td>15 min per bus</td>
</tr>
<tr>
<td></td>
<td>3-5 min per car</td>
</tr>
</tbody>
</table>
Approach

- On-site natural gas fueled Hydrogen Generator
  - Catalytic Auto-Thermal Reforming (ATR) technology
  - Advanced sulfur removal technology
  - High performance Pressure Swing Adsorption (PSA) system for purification of ATR reformate.

- Multi pressure storage for cascaded hydrogen dispensing
  - Duel fueling capability; H₂ only / HCNG

- Demonstration & Education:
  - Refueling of HCNG buses in commercial operation
  - Refueling of H₂ Fuel Cell and ICE vehicles at a public access facility
  - Provide public tours of the facility
Hydrogen Fueling Station at SunLine

- Hydrogen Produced on-site by Adéo Unit
  - Dispensed at 3000 psig for blending with CNG
  - Dispensed at 5000 psig for use in fuel cell powered bus
Installation of Demonstration Adéo Unit

SunLine Transit Agency
Palm Springs, CA
100 Nm$^3$/h
Technical Accomplishments

Operating Experience

- Demonstrated operation of ATR reformer
  - Acceptance Test Passed in April 2004
    - 10 days continuous operation
    - Capacity >90 Nm³/hr H₂
    - Purity >99%

- Real world validation
  - Production of hydrogen in a revenue generating application
  - Successful integration and automation of production, compression and storage
  - Cost of hydrogen is less than delivered tube trailers
  - Ongoing fueling of FC buses, H₂ ICE bus, and HCNG buses in revenue generating service
  - Occasional fueling for most major automotive OEM FC vehicles
    - Refueling stop for Southern California test drives
Technical Accomplishments

Operating Experience

- Demonstrated low risk of contamination from ATR based reformer
  - Operated the plant from 99.9% to 99.999% purity
    - Verified that the only impurities in this range are N₂ & Ar
    - CO, CO₂, CH₄ & other contaminants remain below detection limits.

- Fully automated hydrogen generator
  - Unattended operation with remote monitoring capability
Technical Accomplishments

**Operating Statistics**

- **Start-up Time**
  - Cold Start: 3 hrs
  - Warm Start: 1½ hrs

- **Emissions (Exhaust)**
  - CO: < 0.03 % (below detection limit of the instrument)
  - CH4: 6-15 ppmv
  - NOx: 0-3 ppmv
  - SOx: < 1 ppmv (below detection limit of the instrument)

<table>
<thead>
<tr>
<th>Feed Nm3/h</th>
<th>Peak Power kW</th>
<th>Energy / Feed kWh / Nm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>17.70</td>
<td>0.885</td>
</tr>
<tr>
<td>35</td>
<td>21.50</td>
<td>0.614</td>
</tr>
<tr>
<td>40</td>
<td>25.00</td>
<td>0.625</td>
</tr>
<tr>
<td>43</td>
<td>27.20</td>
<td>0.633</td>
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<tr>
<td>44</td>
<td>29.00</td>
<td>0.659</td>
</tr>
<tr>
<td>45</td>
<td>29.70</td>
<td>0.660</td>
</tr>
</tbody>
</table>

* Product / Feed Ratio is approximately 2/1 at design purity
Technical Accomplishments

**Operating Statistics**

- One full year of operation (April ’04 – April ’05)
  - 4500 hrs of run time on reformer
  - All H₂ dispensed has been produced by the reformer; back-up supply has not been used
    - Moderate usage pattern has been helpful in allowing problems to be solved without impacting commercial operations
  - Consistent hydrogen quality
    - Hydrogen generator is normally operated to produce 99.999% hydrogen
    - Contaminants are consistently undetectable during routine sampling
Technical Accomplishments

Operating Data

- GHE, Reformer: 79.7%
- Net H₂ Efficiency (LHV / HHV): 57.6 / 61.4%

Product: 82.12 Nm³/hr @ 99.947% H₂
Feed: 42.58 Nm³/hr
Product / Feed Ratio: 1.93
Water Consumption: 26.7 kg/hr
0.63 kg/Nm³ Feed
Exhaust Gas Temp: 124.2°C

Product Purity: 99.947%
## Technical Accomplishments

### Problems Encountered

<table>
<thead>
<tr>
<th>Category</th>
<th>Affected Equipment</th>
<th>Un-planned Shut-downs?</th>
<th>Causes</th>
<th>Resolution / Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating Equipment</td>
<td>Water Pump</td>
<td>Yes</td>
<td>Blown fuses due to electrical shorts.</td>
<td>Re-oriented junction boxes to prevent vibration damage to wiring</td>
</tr>
<tr>
<td>Process Equipment</td>
<td>Heat Exchangers</td>
<td>Yes</td>
<td>Experienced failure of heat exchangers during first commissioning</td>
<td>Re-designed and replaced the exchangers. Re-commissioned the plant in Apr-04</td>
</tr>
<tr>
<td>Support Utilities</td>
<td>Electrical</td>
<td>Yes</td>
<td>Voltage Surges causing faults in variable frequency motor drives</td>
<td>Added electrical line filtering to incoming supply</td>
</tr>
<tr>
<td>Instruments &amp; Controls</td>
<td>Water level switches</td>
<td>Yes</td>
<td>Fabrication debris in system piping</td>
<td>Improved intermittent flushing of water system and modified fabrication specifications for future units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Over sensitive shut-down logic</td>
<td>Improved fault tolerance of water controls</td>
</tr>
<tr>
<td></td>
<td>Solenoid valves</td>
<td>Yes</td>
<td>Fabrication debris in system piping</td>
<td>Cleaned and repaired valves / Modified fabrication specifications for future units.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Valve sticking due to residue build-up</td>
<td>Modified condensing arrangement to prevent the cause.</td>
</tr>
<tr>
<td></td>
<td>Thermocouples</td>
<td>No</td>
<td>Failures due to vibration</td>
<td>Modified thermowell design – failures have stopped.</td>
</tr>
</tbody>
</table>
Dispensed Hydrogen Cost
(100 Nm³/h)

NG @ $4.50/MMBTU
Electric @ 8.5¢/kWh
Capital rec. factor 15%
On-stream factor = 85%

Total cost of production = $3.68/kg
Responses to previous year comments

- Request for more performance data
  - Additional performance data is included with this poster presentation

- Potential for degradation of H2 purity
  - Routine sampling shows no degradation of purity.
    - Any degradation in performance would result in reduced efficiency rather than reduced purity

- More information on future development and how this technology will be introduced in the expansion of the H₂ infrastructure
  - Information follows…
Future Goals

**Adéo Hydrogen Generator**

- Efficiency improvements
  - High performance PSA with improved recovery
  - Continued optimization of process design and heat integration
- Cost reduction
  - Process simplification
  - Economies of Scale
  - Parts count reduction (DFMA)
  - Key Vendor participation
- Market introduction
  - HyRadix is commercializing this hydrogen generator technology into the industrial H₂ market as well as refueling applications
    - *To build sales volume faster and reduce costs towards the president’s H₂ Fuel Initiative goals*
  - Continued participation in H₂ refueling demonstrations and early commercial applications

Since the completion of this project much of this work has already been done
The most significant hydrogen hazard associated with this project is…

– An ignition of a hydrogen-air mixture

– This could be caused by an un-intended combustible gas mixture in the surrounding atmosphere (including inside the enclosure).
Hydrogen Safety

- Our approach to deal with this hazard is...
  - Purging and inerting requirements including an interlock to prevent start-up without a suitable purge
  - Containment: Pressure containing components meet ASME & ANSI B31 requirements
  - Class 1 Div 1 area classification per NFPA 497
  - Enclosure geometry and ventilation prevent accumulation of combustible gas mixtures
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