Autothermal Cyclic Reforming Based H₂ Generating & Dispensing System

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BP

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Goals & Approach

DOE Goal
Cost of Delivered H₂ < $2.50/kg

Phase I (2002) – System Design
- Design
- Assess the technical & economic feasibility

Phase II (2003-4) – Sub-System Development & Integration
- Develop the subsystems
- Reduce cost of components critical to achieving the economic goal

Phase III (2004-5) – Prototype Fabrication & Demonstration
- Fabricate, install, & operate a H₂ refueling station
- Verify the operational performance
- Verify that the cost of producing & dispensing H₂ meets the targets
## Schedule & Milestones

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
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<tr>
<td>1</td>
<td>Phase I - Design &amp; Analysis</td>
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<td>2</td>
<td>Literature search</td>
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<td>3</td>
<td>Functional analysis</td>
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<td>Conceptual design</td>
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<td>Economic analysis</td>
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<td>6</td>
<td>Business plan</td>
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<td>7</td>
<td>Phase II - Subsystem Development</td>
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<td>8</td>
<td>Bench-scale durability testing</td>
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<td>9</td>
<td>Component Development &amp; Testing</td>
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<td>10</td>
<td>Design of the Prototype System</td>
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<td>Economic feasibility assessment</td>
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<td>12</td>
<td>Update Business plan</td>
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<td>13</td>
<td>Phase III - Prototype Demo.</td>
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<td>14</td>
<td>Prototype Detailed Design</td>
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<td>15</td>
<td>Environmental health &amp; safety</td>
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<td>16</td>
<td>Fabrication &amp; procurement</td>
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<td>17</td>
<td>Site planning and infrastructure</td>
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<td>18</td>
<td>Unit checkout, testing &amp; installation</td>
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<td>19</td>
<td>Operation &amp; maintenance at user</td>
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### Notes:
- **Design**
- **Projected Cost of H₂**
- **Reliability**
- **Availability**
- **Maintainability**
- **Optimize**
- **Design for Manufacturability**
- **Safety**
- **Fabrication**
- **Validate**
- **Installation**
Autothermal Cyclic Reforming

\[
\begin{align*}
\text{H}_2, \text{CO, CO}_2 & \rightarrow \text{Shift Reactor} \\
\text{CH}_4 + \text{H}_2\text{O} & \rightarrow \text{CO} + 3 \text{H}_2 \\
\text{H}_2, \text{CO, CO}_2 & \rightarrow \text{Purifier} \\
\text{NiO} + \frac{1}{4} \text{CH}_4 & \rightarrow \text{Ni} + \frac{1}{4} \text{CO}_2 + \frac{1}{2} \text{H}_2\text{O} \\
\text{NiO} & \rightarrow \text{Air Regeneration} \\
\text{Air} & \rightarrow \text{Fuel Regeneration} \\
\text{Vent} & \rightarrow \text{ACR offers lower capital cost & inherent CO}_2 \text{ separation}
\end{align*}
\]
High Pressure vs. Low Pressure Reforming

**High Pressure Reforming**

100 psig

100 psig

**Low Pressure Reforming**

5 psig

5 psig

Thermal Efficiency = HHV of $H_2$ Produced / HHV of NG Fed

PSA – Pressure Swing Adsorption
# High Pressure vs. Low Pressure Reforming Comparison

<table>
<thead>
<tr>
<th>Configuration</th>
<th>High-Pressure Reforming</th>
<th>Low-Pressure Reforming</th>
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</thead>
<tbody>
<tr>
<td>Thermal Efficiency (Excludes Electricity) = HHV of H₂ Produced / HHV of Fuel Fed</td>
<td>70-80%</td>
<td>70-80%</td>
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<tr>
<td>Electricity Consumed / HHV of Fuel Fed</td>
<td>0.5-1%</td>
<td>3-4%</td>
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<tr>
<td>Efficiency (Includes Electricity) = HHV of H₂ Produced / (HHV of Fuel Fed + Electricity Required / Efficiency of Grid Electrical Generation-35%)</td>
<td>68-78%</td>
<td>65-74%</td>
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<tr>
<th>Advantages</th>
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<tr>
<td>Higher Efficiency</td>
<td></td>
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<tr>
<td>Lower Overall System Capital Cost</td>
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<tr>
<td>Higher Reliability</td>
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<tr>
<td>(Eliminates Syngas Compressor)</td>
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<tr>
<td>Lower Capital Costs for Reformer Reactor Only</td>
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**High Pressure ACR is more cost effective**
ACR reactors produce a continuous stream with ~70% H₂.

CH₄ slip out of the ACR reactors is <5% corresponding to >90% fuel conversion in the ACR reactor.

Detailed design completed
Low pressure reformer operated successfully
Moving to high pressure reformer design and fabrication

ACR was operated successfully for extended periods of time

150 kW thermal NG unit
Multi-Bed Praxair PSA Design

- 3-bed process
- Accepts continuous feed from ACR and delivers uninterrupted hydrogen product
- Cyclic Reformer simplifies Cyclic PSA considerably, due to ease of integration by matching cycle times of Reformer and PSA
- Tail Gas from PSA can be used for fuel regeneration
- Product Hydrogen Specifications
  » < 5 ppm CO
  » < 10 ppm CO₂
  » < 10 ppm CH₄
  » < 10 ppm H₂O
  » ~ 1,000 ppm Nitrogen
  » ~ 99.99 % Hydrogen

Synergy in integrating cyclic PSA with cyclic reformer
Conceptual 3-Bed PSA Skid Assembly

- Designed for easy valve maintenance
- Employs low cost conventional components
- System costs are highly competitive

Cost Competitive Design

Product Hydrogen 99.99%

Crude Hydrogen Feed from ACR

Tail Gas to ACR
Hydraulically Driven H₂ Compressor

- Oil-free nonlubricated design
- Long slow stroke results in longer packing and check valve life, and much higher compression ratios in each stage
- Piston design allows easy replacement of high pressure seals
- Variable inlet pressure capabilities
- Praxair has prior experience with Hydro-Pac in high pressure nitrogen and argon applications
Vehicle Filling - @ 5000 psig

- **Cascade Dispensing**
  - Direct tank to tank pressure transfer through a series of pressure transfers from 3 banks.
  - One bank may be filling while other is being emptied.

- **Fill Pump Dispensing**
  - Filling method requires 1/3 the amount of storage.
  - Each vehicle can be “topped off” to the same target pressure within 5 minutes.
  - Requires the use of two packaged compressors with low utilization on the fill pump.
Stationary Storage

NGV2-3 Composite Cylinders - $54,000

ASME Steel Cylinders - $51,000
Refueling Station System Footprint Summary

60 kg H₂/day
3 consecutive fills

60 kg H₂/day
1 consecutive fill

15 kg H₂/day
3 consecutive fills

15 kg H₂/day
1 consecutive fill

Hydrogen storage tanks are the largest subsystem component
Capital Cost Breakdown

120 kg/day H₂ Commercial @ 100 Units/year

- Facility Charge: 23%
- Contingency: 4%
- Installation Cost: 13%
- Manufacture Engineering: 3%
- Skidding Cost: 12%
- Dispenser: 8%
- Reactor Components: 15%
- PSA Components: 3%
- H₂ Compressor: 7%
- Storage Tanks: 7%
- Fuel and Steam Supply: 5%

Total: 100%
Market Assessment - Commercial Price Targets

- **Price Targets**
  - DOE Hydrogen Targets: $2.50/kg non-taxed; $3.30/kg taxed
  - Gasoline Equivalent Price: $2.62/kg untaxed; $3.49/kg taxed
  - DOE price targets Met at 15,000 scfh taxed; 5,000 scfh non-taxed
  - Commercial Plants require Steady flow, High utilization, Long term contracts
Short Term Market:
Capital Cost
Availability
O&M

Long Term Market:
Efficiency &
NG Price
25% market share to any one individual supplier

Various size unit could be manufactured ranging from 1000 - 15,000 scfh

Opportunity summary based upon an expected average size of 5,000 scfh

Conservative estimates are used for each market sector
Business Case Analysis

- Assumed 6 year R&D Period

- Current:
  - Break even year: 17
  - NPV @10%: $6,000K

- Target:
  - 30% capital cost reduction with R&D
  - Break even year: 15
  - NPV @10%: $29,000K

- If larger hydrogen generation and dispensing units are mass produced, the $2.50/kg cost target can be met. Further R&D for 30% capital cost reduction can make the business model viable.

- It is expected that it would require as long as 15 years to make the business profitable. Government legislation could help accelerate this.

Further R&D & government legislation is required to make business model viable.
After all chemical reactions you get CO₂ 16%, at 800°C. However, not quite sure how this process progresses.

- Included a slide with better explanation of chemical reactions. Data shown is with out CaO. CO₂ is lower if CaO is used.

Is there enough data to scale up an ACR.

- Easily scaleable. Practical experience in scaling from 30 kW to 100 kW to 150 kW

Future Work

- Subsystem Testing: Test components on test stand & Catalysts in bench-scale
- Modify Economic Model to Match System Development
- Prototype Design
- Design for Reliability

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