DOE Hydrogen and Fuel Cells Program Review
High-Capacity, High Pressure Electrolysis System with Renewable Power Sources

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Project # PD029
Overview / Relevance

DOE Program Overview & Barriers Addressed

Timeline
- Start Date: May 2008
- End Date: Sep 2012
- Percent Complete: 75%

Budget
- Project Funding: $2.40M
  - DOE share: $1.92M
  - Cost share: $0.48M

  - Funding received FY11 : $375K
  - Planned Funding for FY12 : $362K

Barriers Addressed
- Capital Cost
- System Efficiency
- Renewable Power Integration

Partners
Avalence: Lead
Gas Equipment: Sister-company
HyperComp: Composite Wrapping
<table>
<thead>
<tr>
<th>Project Milestones</th>
<th>Status</th>
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<tbody>
<tr>
<td>Determine a Manifolding and Sealing Arrangement for Nested Cell</td>
<td>Complete (2010)</td>
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<tr>
<td>1) H₂ and O₂ Gas Separation</td>
<td></td>
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<tr>
<td>2) Electrical Connection to Electrodes</td>
<td></td>
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<tr>
<td>3) Electrolyte Replenishment</td>
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<tr>
<td>Determine Containment Penetration Size and Design</td>
<td>Complete (2010)</td>
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<tr>
<td>1) Compatible with Composite Wrapped Vessel Constraints,</td>
<td></td>
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<tr>
<td>2) Support Cell Electrode Current Magnitudes (&gt;1000 amp)</td>
<td></td>
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<tr>
<td>3) H₂ and O₂ Gas Off-Take</td>
<td></td>
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<tr>
<td>4) Electrolyte Replenishment</td>
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<tr>
<td>Design a Functional Shape of Outer Metal Jacket For Dual Purpose:</td>
<td>Complete (2011)</td>
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<tr>
<td>➢ Outer Electrode’s Inner Surface</td>
<td></td>
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<tr>
<td>➢ Vessel Liner that is the Foundation for Composite Wrap</td>
<td></td>
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<tr>
<td>Demonstrate the Performance of the Nested Cell Core so that Accurate</td>
<td>Completed, Partial</td>
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<tr>
<td>Projections of Energy Use can be Integrated into the Cost Model</td>
<td>(Membrane Issue)</td>
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<td>Demonstrate the Ability to Implement a Composite Fiber Outer Wrap Over</td>
<td>Completed (August 2011)</td>
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<tr>
<td>the Nested Cell Core</td>
<td></td>
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<tr>
<td>Produce a Pilot Plant Design For Use as a Basis for a Sound Economic</td>
<td>In Process</td>
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<tr>
<td>Analysis of Plant Fabrication and Operating Cost</td>
<td></td>
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<tr>
<td>Demonstrate the Operation and Efficiency of the Pilot Plant</td>
<td>Not Yet Started</td>
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<tr>
<td>➢ Laboratory Testing at Avālence</td>
<td></td>
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<td>➢ Field Testing at NREL</td>
<td></td>
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<tr>
<td>Have a Site Ready to Accept the Completed Plant for Commercial</td>
<td>Completed Ft. Collins</td>
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<tr>
<td>Operation</td>
<td>(December 2011)</td>
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<tr>
<td>➢ 100 kW of Renewable Power in Place</td>
<td></td>
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<tr>
<td>➢ Sale or Use of the Plant Products Defined</td>
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What’s Different About Avālence?

- Company formed as a spin-off of two established entities
  - Gas Equipment Engineering Corp.
  - Electric Heating Equipment Company

- Avālence Hydrofillers operate via Alkaline Electrolysis (KOH Electrolyte)

- Avālence Hydrofillers operate at a pressure of not less than 2,000 psig – and in some units at much higher pressure
  - Reduced or Zero Compression Power
  - Vastly Reduced Dryer Power / Loss

- Avālence Hydrofiller cells are designed for continuous operation – units in field with 40,000+ hours
Approach: (Background…)

**Electrolyzer Development**

**Original Project Goals**

- Achieving at least a 15x increase in the gas production rate of a single high pressure production cell
- Demonstrate the high pressure cell composite wrap which enables significant weight reduction
- Build and test a 1/10th scale pilot plant
- Perform economic assessment for full scale plant (300 kg/day, 750 kW) that meets DOE 2017 cost target of $3.00/gge

**Project Challenges**

**Design and Fabrication**
- Large diameter membrane formation
- Membrane to manifold sealing
- Fluid and power penetrations
- Composite wrapping “heavy” cylinder
- Process control of a multiple, high-capacity cell array

**Performance Demonstration**
- Long-term operation at 6500 psi (O2 side purity)
- Low/no leakage electrical isolation hoses at 6500 psi

**Design Approach for High-Capacity, High-Pressure Production Cell**

- Maintain cylindrical pressure boundary configuration
- Increase the diameter by using a composite outer wrap
- Place multiple electrode and membrane pairings inside a single cell body
- Electrodes act as two sided unipolar electrodes
Approach: Evolution from Legacy

- Legacy approach demonstrated to 6,500 psig
- New approach includes recirculation, demonstrated to 2,500 psig, with better performance
- Cell geometry has also changed as we progressed
Accomplishments and Progress: (Last Year)

New Cell Results

- 10 cell test string run with:
  - Partial Nested Electrode set
  - Anolyte and Catholyte circulation
  - More efficient membrane
  - New head design (better sealing)

- Improved polarization
  (even when cold)
  (even on a current density basis)
  - Massively reduced masking

- Purity at 2,500 psig 99.7%!!!
  (before catalyst / cleanup)
  - Vs. 97.0% with Legacy Design
  - We now have safety margin ++

- Endurance testing still underway,
  probably 1,000 hours at this point
  - We believe level control and thermal management will be issues (in nested cell), but are resolvable
6,500 psig!! (Why It’s Hard...)

- Electrochemistry still works, but...
  - Bubbles are very small (almost invisible)
  - Velocity of bubbles is low (masking)
  - Since velocity is lower, dwell time in cells increases
    - This by itself can impact purity...
      - More time to react with any electrolyte contaminants
      - Greater time for any side electrolysis reactions (hoses) to accumulate impurity
      - Since diffusion is either steady or increasing with pressure, the additional dwell time amplifies any impurity as a result of diffusion
  - And all other leak paths, which seemed to be trivial before, become monsters
    - NPT threads (we had to remove them from the cell design)
    - Dielectric Hoses (we had multiple attempts before success)
    - Internal cell seals (we have redesigned head on legacy cells, and used those design concepts on large cell)
6,500 psig (Why It’s Worth It…)

- 5,000 psig is a standard pressure for industrial vehicles
  - Buses
  - Forklifts
  - Other logistics support vehicles

- Compressor power can be eliminated (replaced by water pumping power)
  - The compressor (multistage especially) is a major source of complexity, unreliability, and maintenance
  - For those few applications with extreme pressures (10,000-20,000 psig), the compressor will be one stage only (diaphragm)

- Since H2 is saturated in water at electrolysis pressure, higher electrolysis pressure means vastly reduced dryer power
  - In some cases, no additional drying is required
Accomplishments and Progress: This Year…

- Built parts of two large cells
  - Stainless version (~1,000 psig)
  - Composite overwrap version (2,800 to 6,500 psig)
    - 6,500 psig with external axial support
- Membrane support in large concentric cells became insurmountable issue – had problem in subscale testing
  - Insufficient stiffness – membrane collapse due to VERY small differential pressures which caused blockages and led to cell failure
  - Insufficient space for supporting structure
Accomplishments and Progress: As A Result…

• After the punt, we were forced to alter the large cell structure and get back to membrane diameters / support mechanisms that we know are executable (have been demonstrated in our existing designs)

• Yet, we still have to operate at 6,500 psig, about twice the pressure limit of our existing cell design, and we needed to lower cost

• The decision was made to use smaller concentric cells within a low cost cast metal-metal-composite structure
Collaborations: Cell Details

- We worked with HyperComp Engineering on the original composite work and 8” diameter nested prototype cell.

- The composites were good structurally, but too costly, and didn’t support electrical conductivity to the degree desired.

- We are now working with Yankee Casting, on the alternative.

- We are using the ~sixteen of our current design within a single large cell (hence meeting >15x requirement):
  - The cells are no longer thick wall (Schedule 80 or 160) pipe.
  - But materials in contact with the process have not changed.

- The surrounding low cost structure will take the pressure (hoop) stress:
  - A mixture of metal-metal-composite gives the structure the same thermal expansion properties as stainless, and quite high strength – and can be cast at modest temperatures.

- Tie rods will still be required for axial (as was the case with the large concentric cell design).
Accomplishments / Collaborations: Cross Section of Notional Concept (Proprietary Details Omitted)

- 19 cells in a 16+” diameter casting shown

- FEA for actual system (with tie rods, passages, etc) to be provided

- Simple hoop stress in cast block is 16,000 psi (perfect load sharing)

- MMC alloy has allowable stress higher than that of 316SS, our legacy material
Future Work: Pilot Plant Design

- Pilot Plant is now based on 10 kg/day, 6500 psig no compressor operation

- Pilot Plant will have 6 cast cell modules
  - Each cell module will have the equivalent of 16 of the latest model 2.5" Avalence cell
  - The 6 modules will provide the equivalent output of 96 of our existing cells
    - Sufficient for 10 kg/day, with margin
Summary

- Efforts are continuing on DOE Large Cell Grant

- Hugely difficult to get to 6,500 psig, with high purity, but we now think we have a path
  - We will also produce both H2 / O2 products

- The nested cell concept remains, but has transitioned from concentric cylinders to bundled cylinders --- composites outer wrap is no longer required, but a mixed metal composite alloy will be used to give the supporting casting similar properties to the supported tubes
  - We will still deliver to DOE at the end of this year

- We would like to acknowledge the patience and guidance of DOE
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