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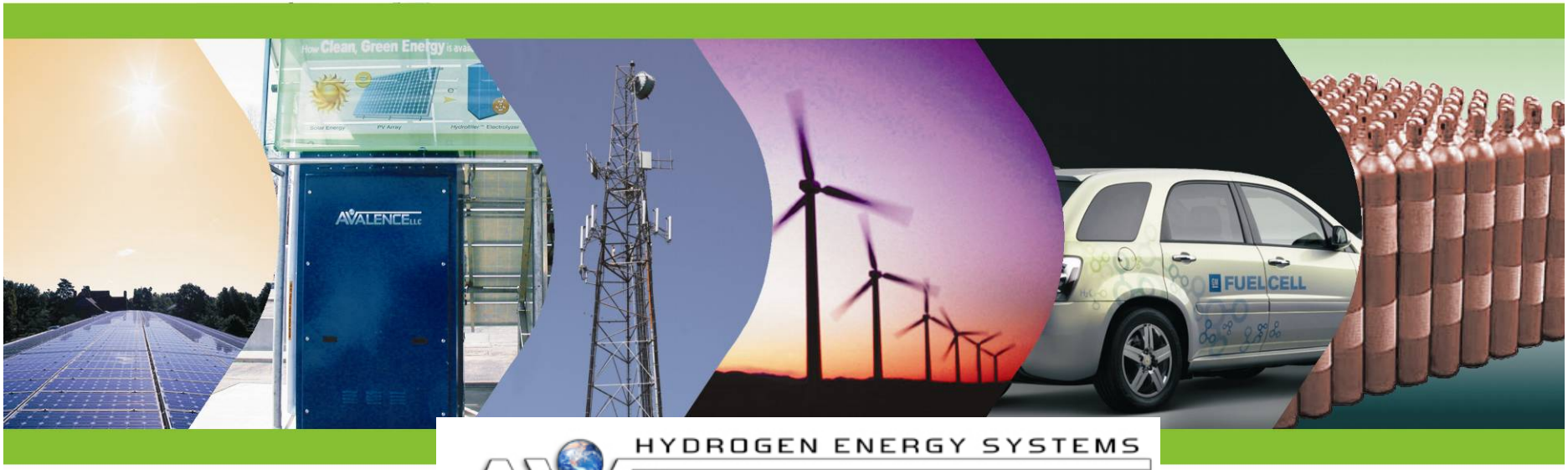

HYDROGEN ENERGY SYSTEMS
AVALENCE™ LLC

DOE Hydrogen and Fuel Cells Program Review

High-Capacity, High Pressure Electrolysis System with Renewable Power Sources

Dr. David Brengel and Paul Dunn, Avalence LLC

DOE Merit Review, 16 May 2012

Project # PD029

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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

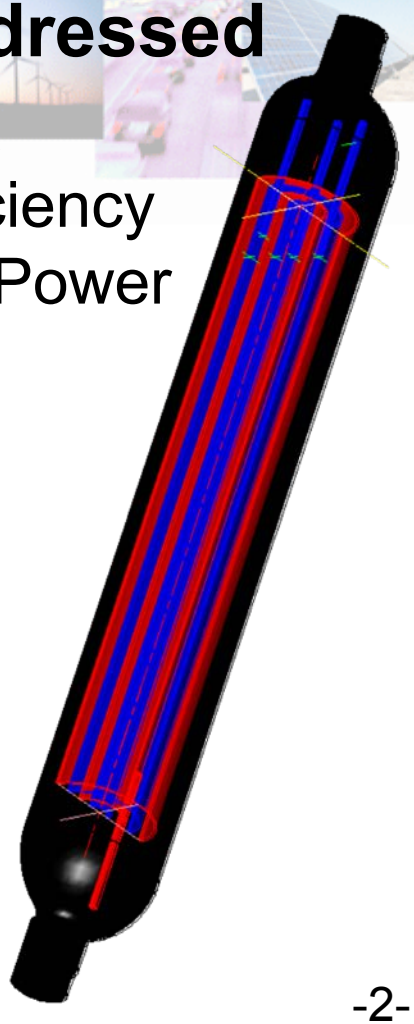
- Funding received FY11 : $375K
- Planned Funding for FY12 : $362K

Barriers Addressed

- Capital Cost
- System Efficiency
- Renewable Power Integration

Partners

Avalence:
Lead
Gas Equipment:
Sister-company
HyperComp:
Composite Wrapping



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DEVELOPMENT PROGRAM MILESTONES

Project Milestones	
Description	**Status**
Determine a Manifolding and Sealing Arrangement for Nested Cell 1) H_2 and O_2 Gas Separation 2) Electrical Connection to Electrodes 3) Electrolyte Replenishment	Complete (2010)
Determine Containment Penetration Size and Design 1) Compatible with Composite Wrapped Vessel Constraints, 2) Support Cell Electrode Current Magnitudes (>1000 amp) 3) H_2 and O_2 Gas Off-Take 4) Electrolyte Replenishment	Complete (2010)
Design a Functional Shape of Outer Metal Jacket For Dual Purpose: ➢ Outer Electrode's Inner Surface ➢ Vessel Liner that is the Foundation for Composite Wrap	Complete (2011)
Demonstrate the Performance of the Nested Cell Core so that Accurate Projections of Energy Use can Be Integrated into the Cost Model	Completed, Partial (Membrane Issue)
Demonstrate the Ability to Implement a Composite Fiber Outer Wrap Over the Nested Cell Core	Completed (August 2011)
Produce a Pilot Plant Design For Use as a Basis for a Sound Economic Analysis of Plant Fabrication and Operating Cost	In Process
Demonstrate the Operation and Efficiency of the Pilot Plant ➢ Laboratory Testing at Avālence ➢ Field Testing at NREL	Not Yet Started
Have a Site Ready to Accept the Completed Plant for Commercial Operation ➢ 100 kW of Renewable Power in Place ➢ Sale or Use of the Plant Products Defined	Completed Ft. Collins (December 2011)

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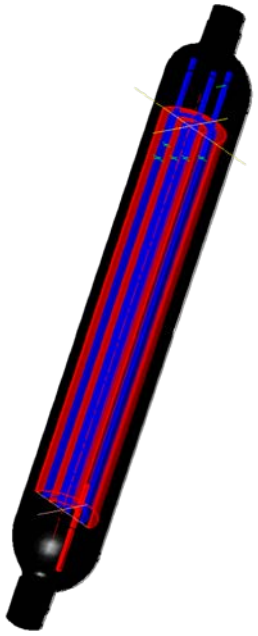
What's Different About Avālence?

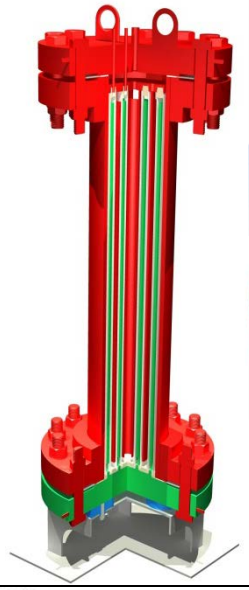
- **Company formed as a spin-off of two established entities**
  - **Gas Equipment Engineering Corp.**
  - **Electric Heating Equipment Company**
- **Avālence *Hydrofillers* operate via Alkaline Electrolysis (KOH Electrolyte)**
- **Avālence *Hydrofillers* operate at a pressure of not less than 2,000 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 15 X 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

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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

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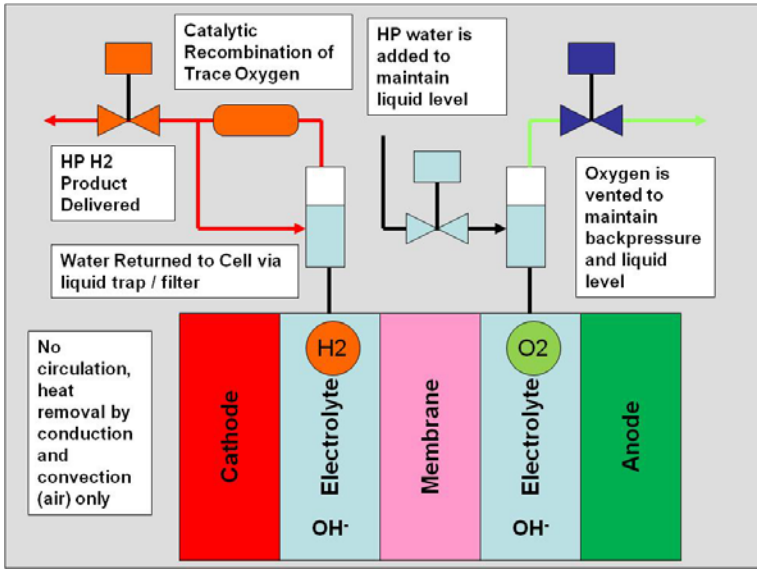
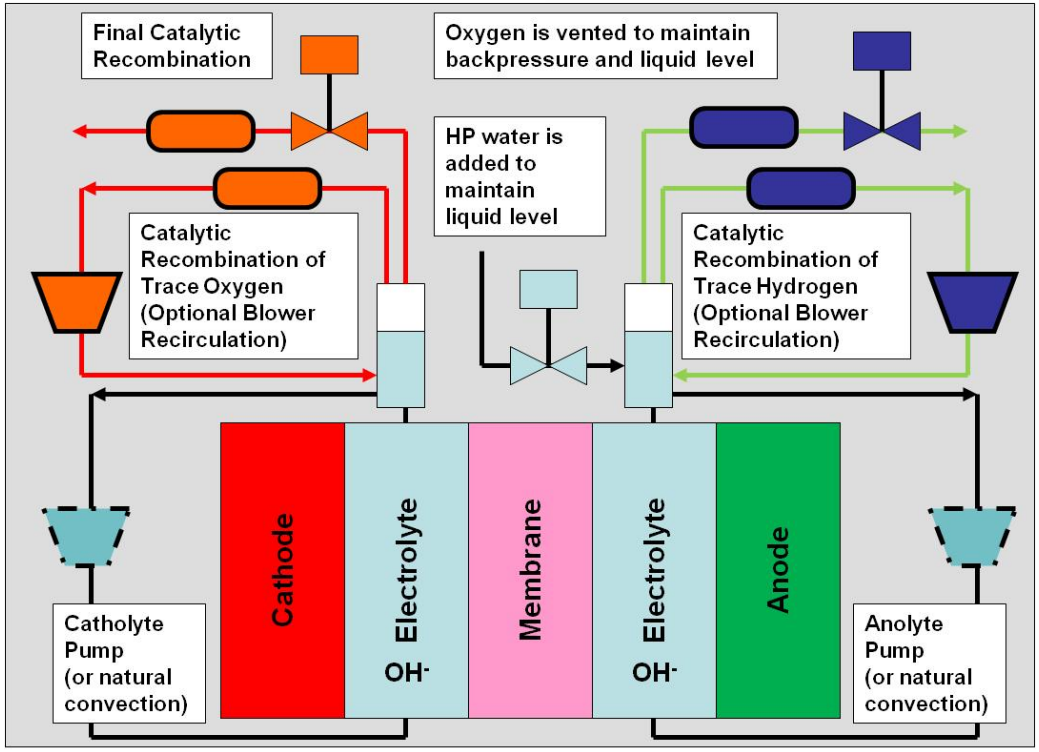
Approach: Evolution from Legacy



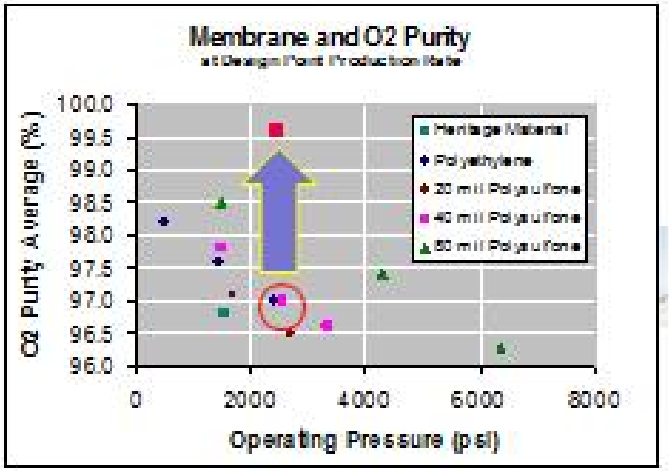


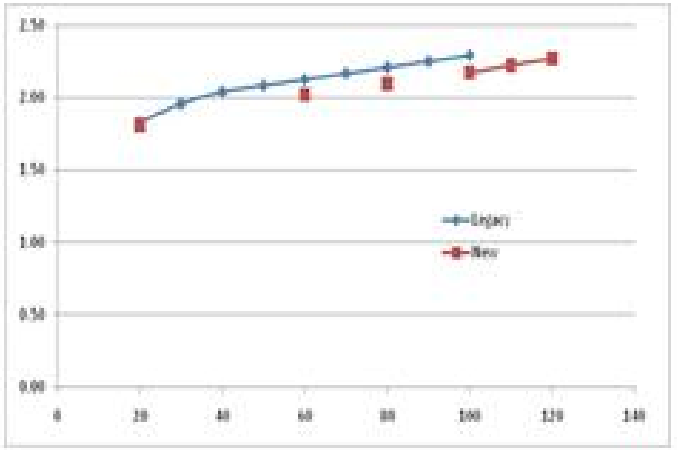
- **Legacy approach demonstrated to 6,500 psig**
- **New approach includes recirculation, demonstrated to 2,500 psig, with better performance**
- **Cell geometry has also changed as we progressed**

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





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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 <u>monsters</u>**
    - **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…)

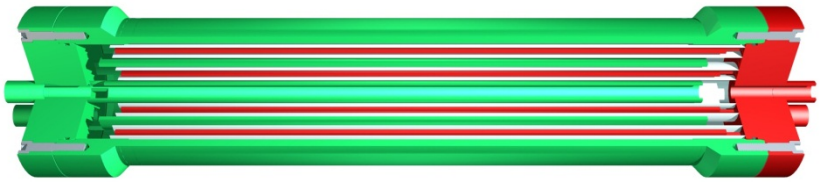
- 5,000 psig is a standard pressure for industrial vehicles
  - Buses
  - Forklifts
  - Other logistics support vehicles

- 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**
  - **In sufficient space for supporting structure**

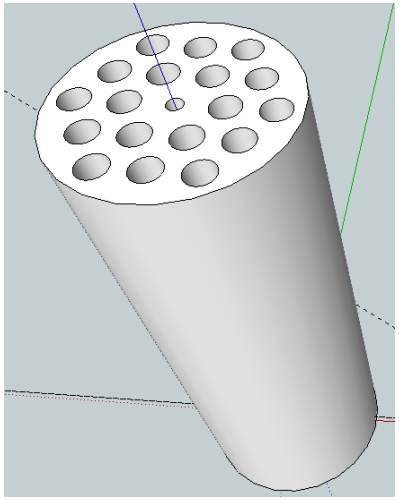


Accomplishments and Progress: As A Result…

- 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



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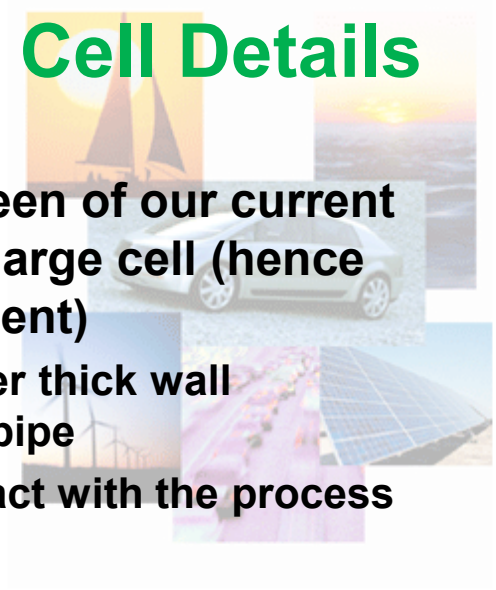
Collaborations: Cell Details

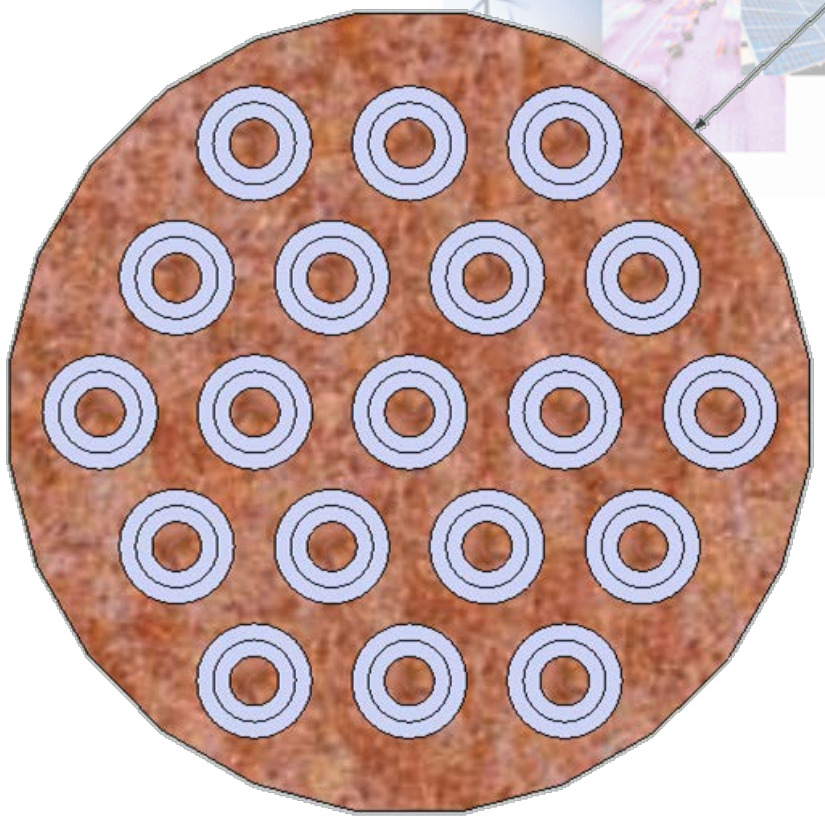
- We worked with HyperComp Engineering on the original composite work and 8” diameter nested prototype cell
- The composites were good structurally, but too costly, and didn’t support electrical conductivity to the degree desired
- We are now working with Yankee Casting, on the alternative



- 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



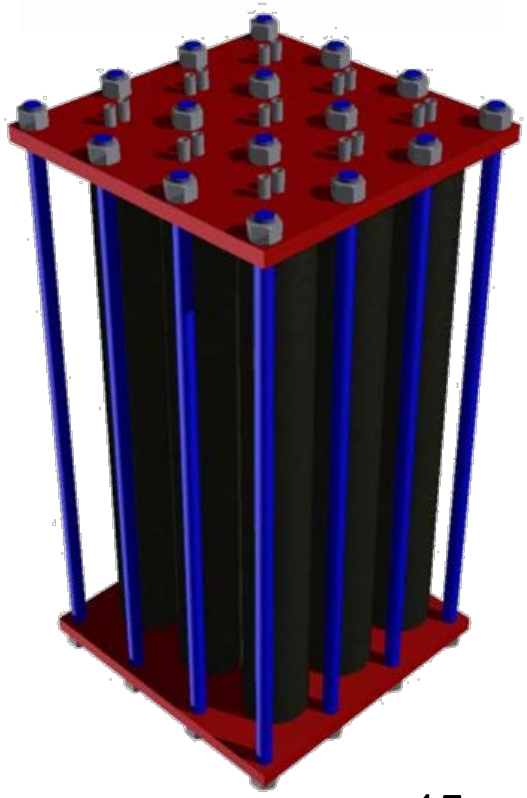
Future Work: Pilot Plant Design

- **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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Alpha Unit with >40,000 hours Operation