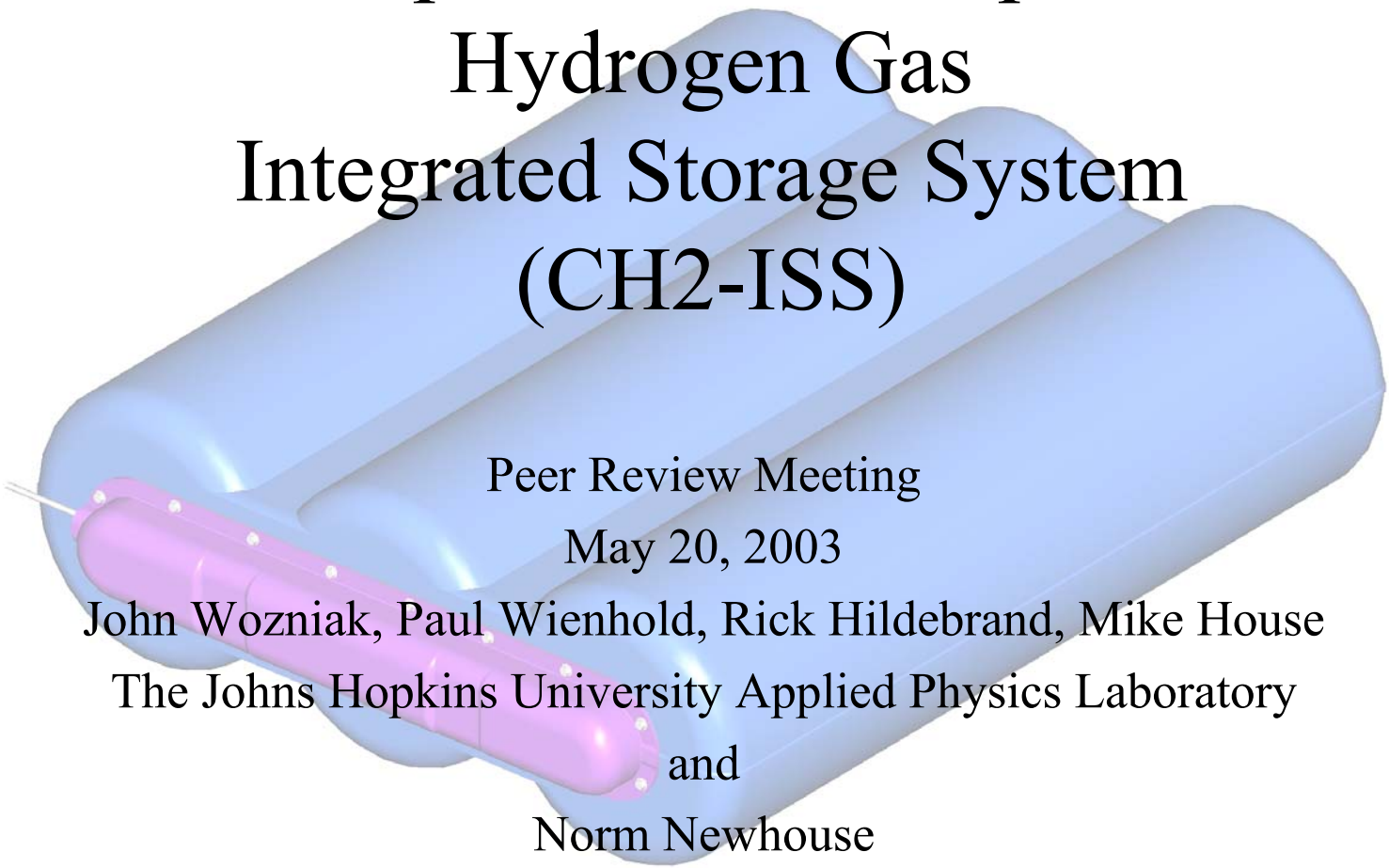
Development of a Compressed Hydrogen Gas Integrated Storage System (CH2-ISS)



Peer Review Meeting

May 20, 2003

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The Johns Hopkins University Applied Physics Laboratory

and

Norm Newhouse

General Dynamics Advanced Technical Products

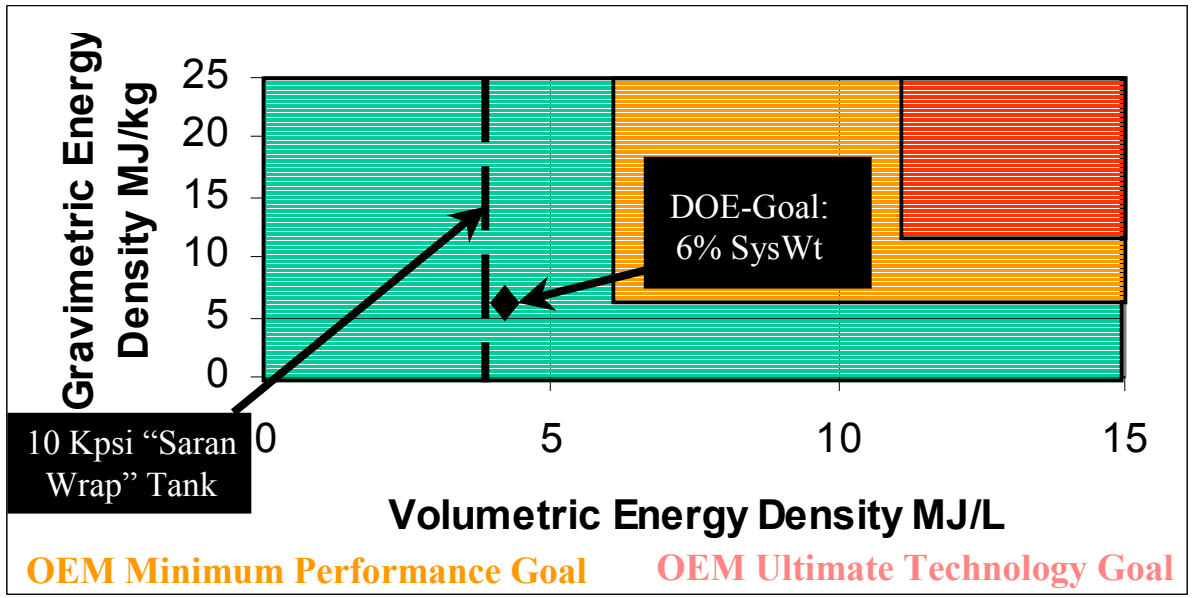
Peer Review Meeting Agenda

- Overall project relevance/objective
- Project Background
- Tasks – Goal/Approach/Accomplishment
  - Tank Technology – Overwrap/Permeation/Design
  - Shell Fabrication
  - Gas Control System
  - Vehicle Interface Technology
- Project Timeline
- Plans/Future Milestones

Project Relevance/Objective

DOE/FreedomCAR Hydrogen Storage & Vehicle Interface Technologies

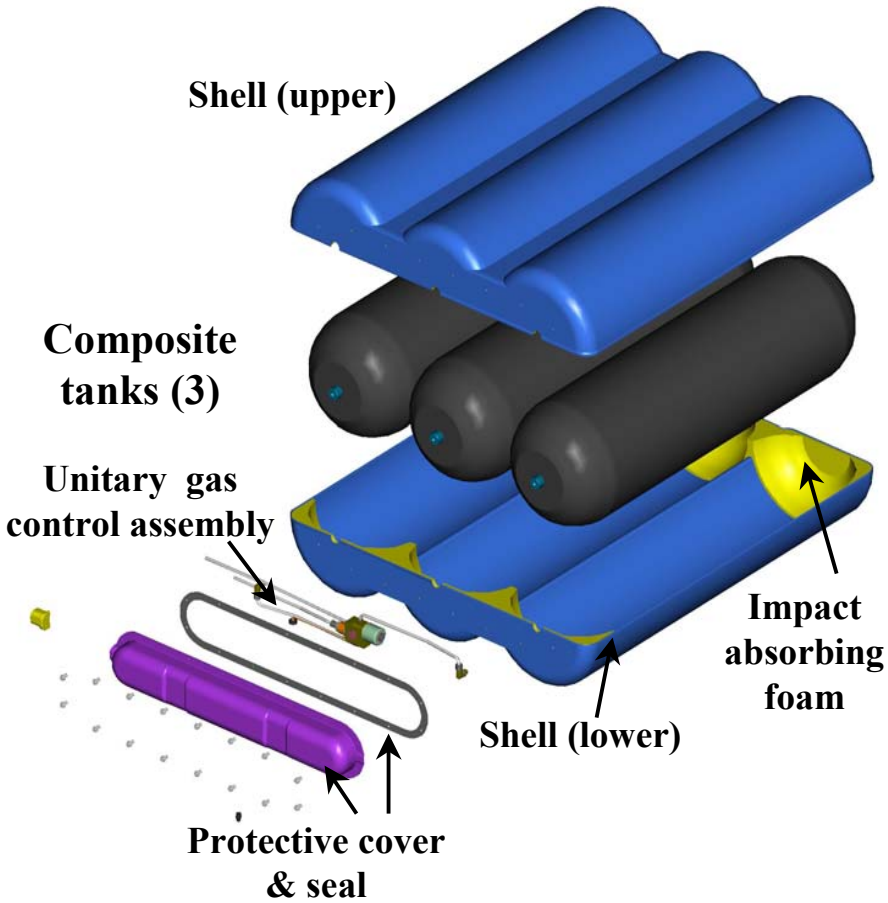
Energy Density for Hydrogen Storage Systems



" Advance the development of a cost effective, semi-conformable compressed hydrogen gas storage system and vehicle integration technology to enable FCEVs to have driving ranges comparable to conventional vehicles while not compromising passenger and cargo space or vehicle safety"

Integrated Storage System - Background

- High-pressure storage unit composed of tanks, outer shell, protective foam and gas control system all in an integrated package
- Role of pressure containment and abuse tolerance partitioned and optimized through design and materials selection
- Semi-conformable shape and lightly coupled to vehicle chassis to facilitate passenger "crumple zone"
- Protected by U.S. patents 6,257,360 (Compressed Gas Fuel Storage System, July 2001) and 6,321,775 (Gas Manifold, Nov 2001)
- NGV versions safety certified to FMVSS # 304 and undergoing long-term evaluation in experimental automobiles



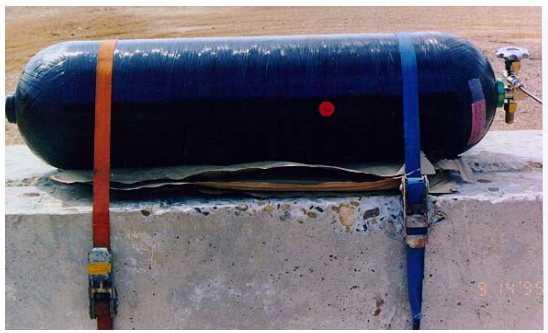
Integrated Storage System - Background Component and System Tests

Hydrostatic Burst Tests

ISS Safety Qualification Drop

ISS Guided Impact Drop

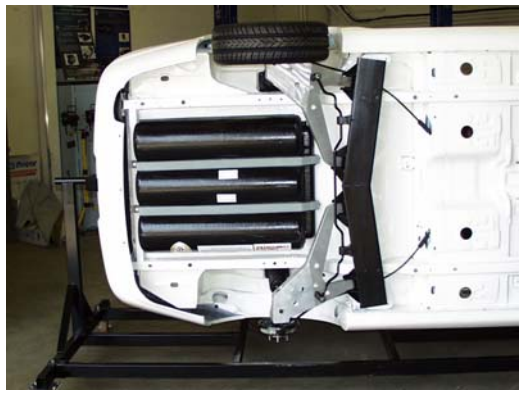
Tank Gunfire Tests



- ISS Gunfire Tests
- Hydrostatic Bursts
- Liner Weldment Cold Impact
- Liner Gas Permeation
- Solenoid 50,000 Cycling
- 50 Cycle Manual Shut-off
- Manifold 14,000 psi Safety
- 18,000 Cycle Pressurization

ISS Bonfire Qualification

Integrated Storage System – Background Vehicle Application Experience



- **ANGV project supported ISS development, safety qualification and demonstrate vehicle packaging value**

- **For FCEV hydrogen gas storage, tasks are focused on :**
  - **Supporting higher service pressures (350/700 bar)**
  - **Scaling up internal volume**
  - **Satisfying hydrogen gas permeation requirements**
  - **Increasing energy density efficiency**
  - **Developing cost effective mass production design**
  - **Developing vehicle interface system design**


Toyota's FCHV

Tank Technology Task

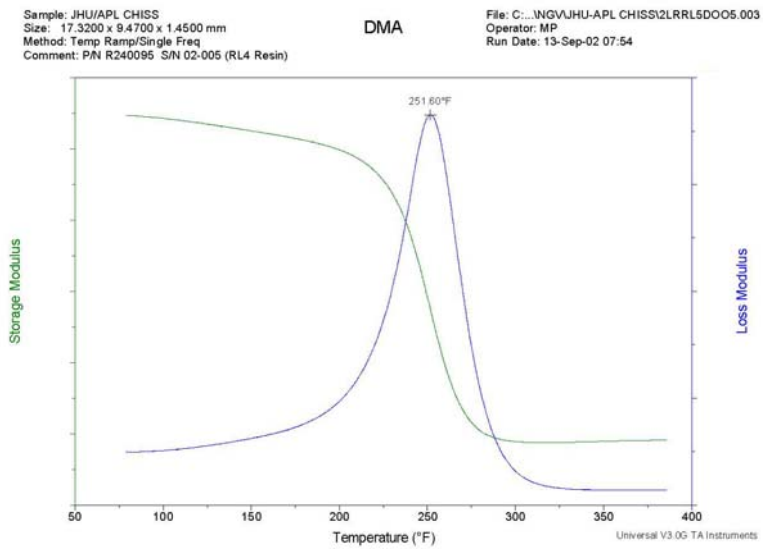
- **Goals**
  - Improve tank gravimetric energy density
  - Reduce permeation through liner
  - Optimize tank overall design for ISS application
- **Approach**
  - Establish baseline design and confirm through burst and gunfire tests
  - Revise design and conduct additional burst and gunfire tests as required
  - Conduct tests to confirm permeation in baseline tank construction
  - Evaluate materials and processes to reduce permeation
  - Develop design elements to optimize tank performance

Tank Technology-Accomplishment

(Overwrap)

- **Baseline Tank**
  - **Design**
    - » **T700 carbon fiber overwrap with high interspersed winding pattern with design FOS of 2.45**
    - » **NGV commercial tank resin system ; LRF-600**
    - » **Existing HDPE liner and bosses with 52.7 L capacity**
    - » **350 bar service pressure**
  - **Results**
    - » **Hydrostatic burst at 2.55 FOS**
    - » **Failed gunfire at 2.25 FOS**

- **Revised Tank**
  - **Design**
    - » **Similar design as baseline except for modified resin with toughness additives**
  - **Results**
    - » **Passed gunfire at 2.25 FOS**
    - » **However modified resin formulation lowered glass transition temperature and caused higher viscosity during winding**



Tank Technology-Accomplishment

(Permeation)

- **Permeation allowable per draft spec's is 1.0 scc/hr/liter at 350 bar**
  - **Represents 3% loss of gas per year from a tank**
  - **Some standards had considered reducing to 0.25 scc/hr/l**
  - **OEMs prefer further permeation reduction**
- **Permeation test results**
  - **0.91 - Baseline Untreated HDPE**
  - **0.25 - Option A – HDPE surface treatment**
  - **0.20 - Option B - Alternative liner material**
  - **Material cost, durability and manufacturability need further investigation**

Tank Technology-Accomplishment

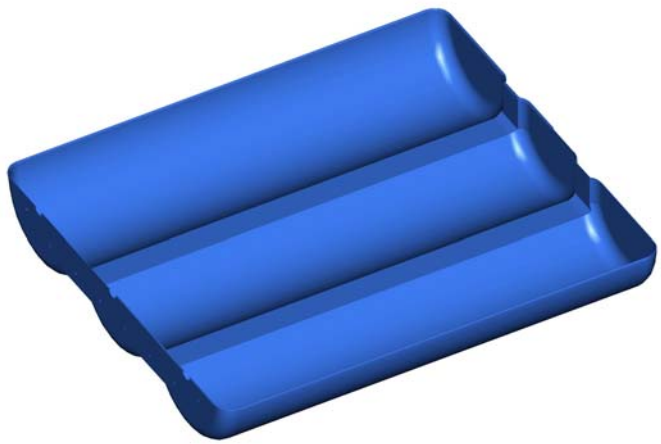
(Overall Design)

- **Design changes relative to baseline**
  - **Optimized bosses**
  - **Ultra-thin HDPE liner**
  - **All-carbon, 2.25 FOS overwrap**
  - **Maximized diameter**

- **Performance improvement over baseline**
  - **8% decrease in factor of safety**
  - **11% increase in internal volume**
  - **24% increase in gravimetric efficiency**

Shell Fabrication Task

- **Goals**
  - **Investigate appropriate fabrication processes for mass production of ISS shell and gas control system protective cover**
  - **Evaluate advantages and disadvantages of each process and material**
  - **Acquire valid estimates for non-recurring and recurring costs**
- **Approach**
  - **Develop CAD design of CH2-ISS shell and protective cover**
  - **Work with manufacturers to evaluate producibility, material recommendations, and cost estimates**
  - **Compile and compare candidate processes/materials**

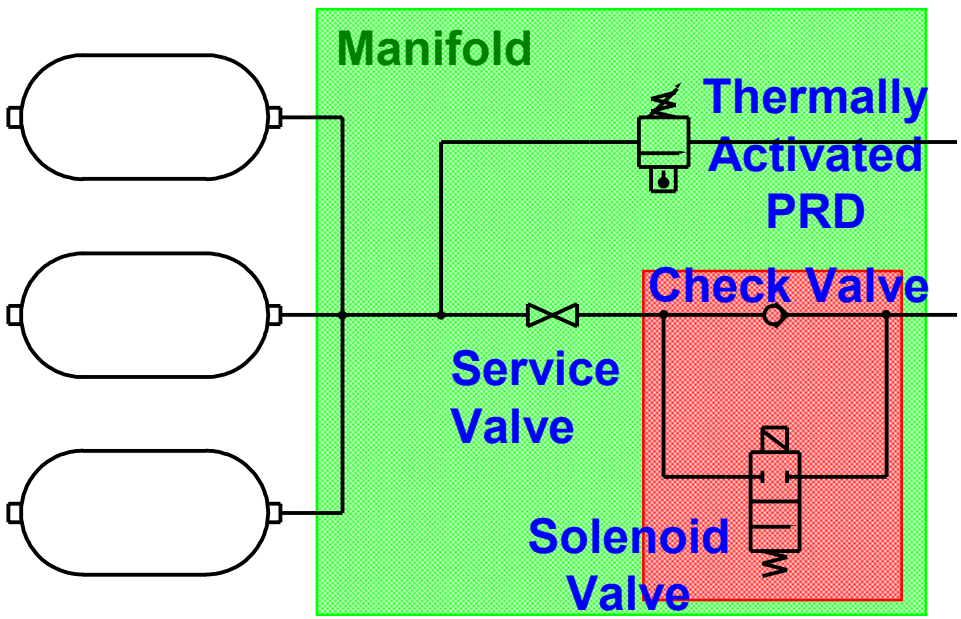


Shell Fabrication-Accomplishments

- Developed CAD solid models for composite and injection shell construction
- Performed shell manufacturing trade study
  - Provided 18 manufacturing suppliers with drawings and system requirements
    - » Part strength, roadway & environment conditions, impact strength, fire resistance
- Subcontracted National Composites Center, Kettering Ohio to evaluate Direct Fiber Preform / Structural Reaction Injection Molding (DFP/SRIM)process
- Compiled data on estimated part properties, nonrecurring cost and mass production part cost
- Downselected DFP/SRIM and compression molding with high-performance SMC as most viable alternatives
- Shell impact/fire property and “Design-for-Producibility” need further investigation

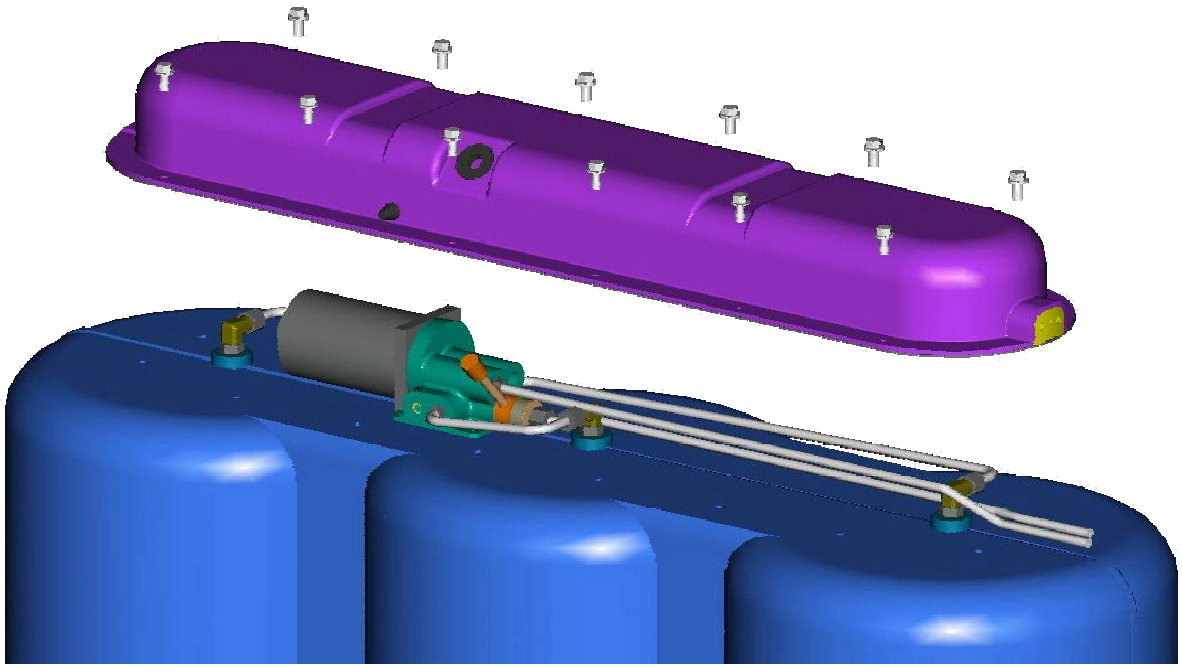
Gas Control System Task

- **Goals**
  - **Design a unitary gas control system featuring:**
    - » **Tank interconnecting manifold with single service valve, thermally activated pressure relief device and operational solenoid valve**
    - » **Low hydrogen permeation, high service cycle reliability, and tolerant to roadway vibration and temperature extremes**
- **Approach**
  - **Develop alternative designs and collaborate with valve manufacturer to support downselect to develop risk reduction prototype for test and evaluation**

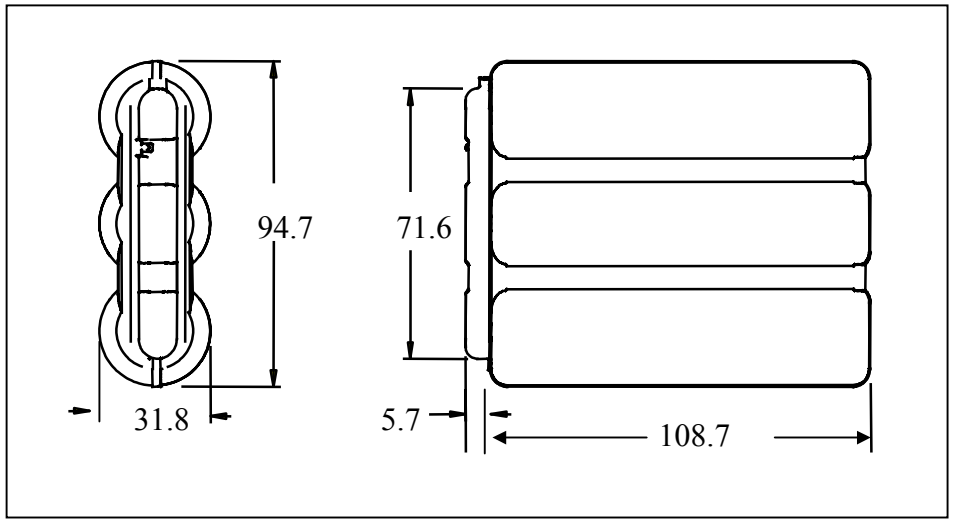


Gas Control System Task -Accomplishment

- **Accomplishments**
  - **Developed two designs using modified COTS elements and unique parts**
  - **Focused design to maximize crashworthiness protection, minimize cost of manufacture and reduce gas permeation**
    - » **Minimum number of o-rings, low permeation materials, high compression seals**
    - » **Calculate permeation rate 0.02scc/hr/liter**
  - **Partnered with Circle Seal for integration of COTS components and fabrication support**



“Current” CH2-ISS Design



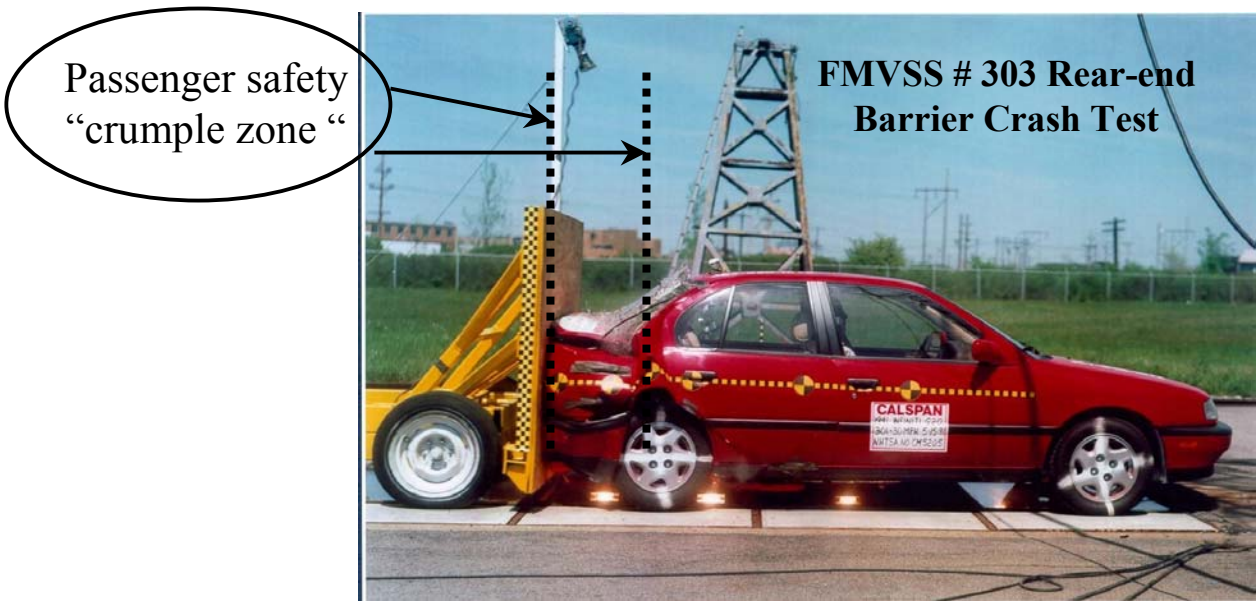
ISS Interface Control Drawing (Dimensions in cm.)

Total Empty Weight	73 Kg
Service Pressure	344 bar
Total Hydrogen Capacity	4.2 Kg
Gas/Container Mass Fraction	5.6%
External Volume	266 liter
Internal Gas Volume	166 liter

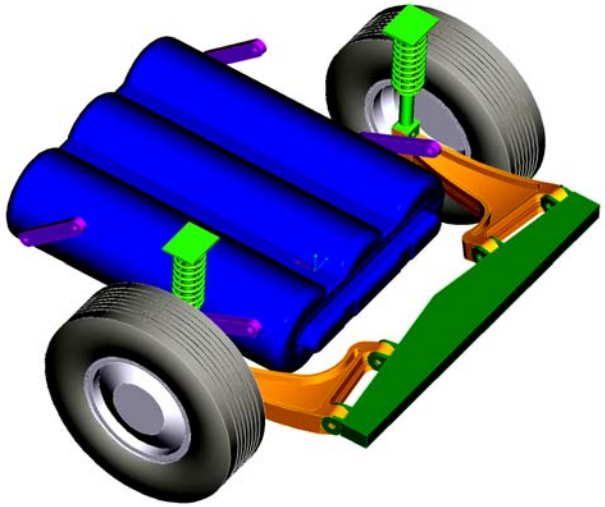
Net Volumetric Energy Density	1.9 MJ/L
Net Gravimetric Energy Density	6.7 MJ/kg
Specific Cost (Est.)	5.0 $/MJ
Hydrogen Loss	0.2 scc/hr/L
Cycle Life	> 10,000
Recoverable Capacity	> 95 %

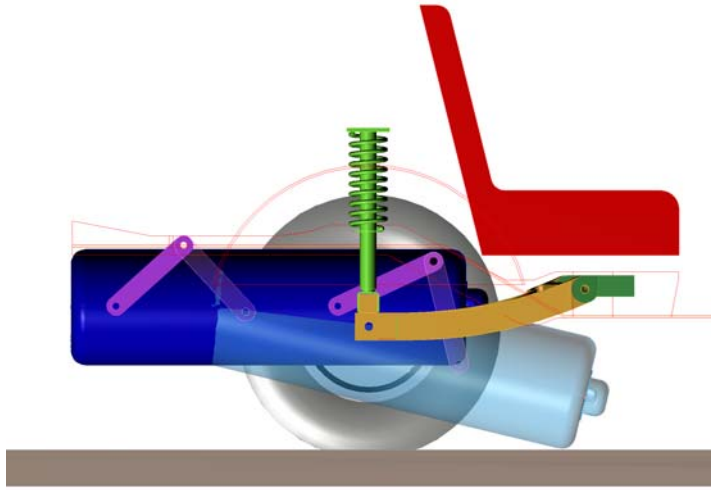
Vehicle Interface Technology Task

- **Goal/Approach**
  - **Develop ISS/vehicle packaging "point design" for FCEV**
  - **Storage system/vehicle interface intertwined for high pressure gas storage**
  - **Vehicle interface considerations**
    - » **Space for sufficient fuel capacity**
    - » **Preserving passenger and cargo space**
    - » **Ground clearance**
    - » **Passenger and fuel system integrity in collision**



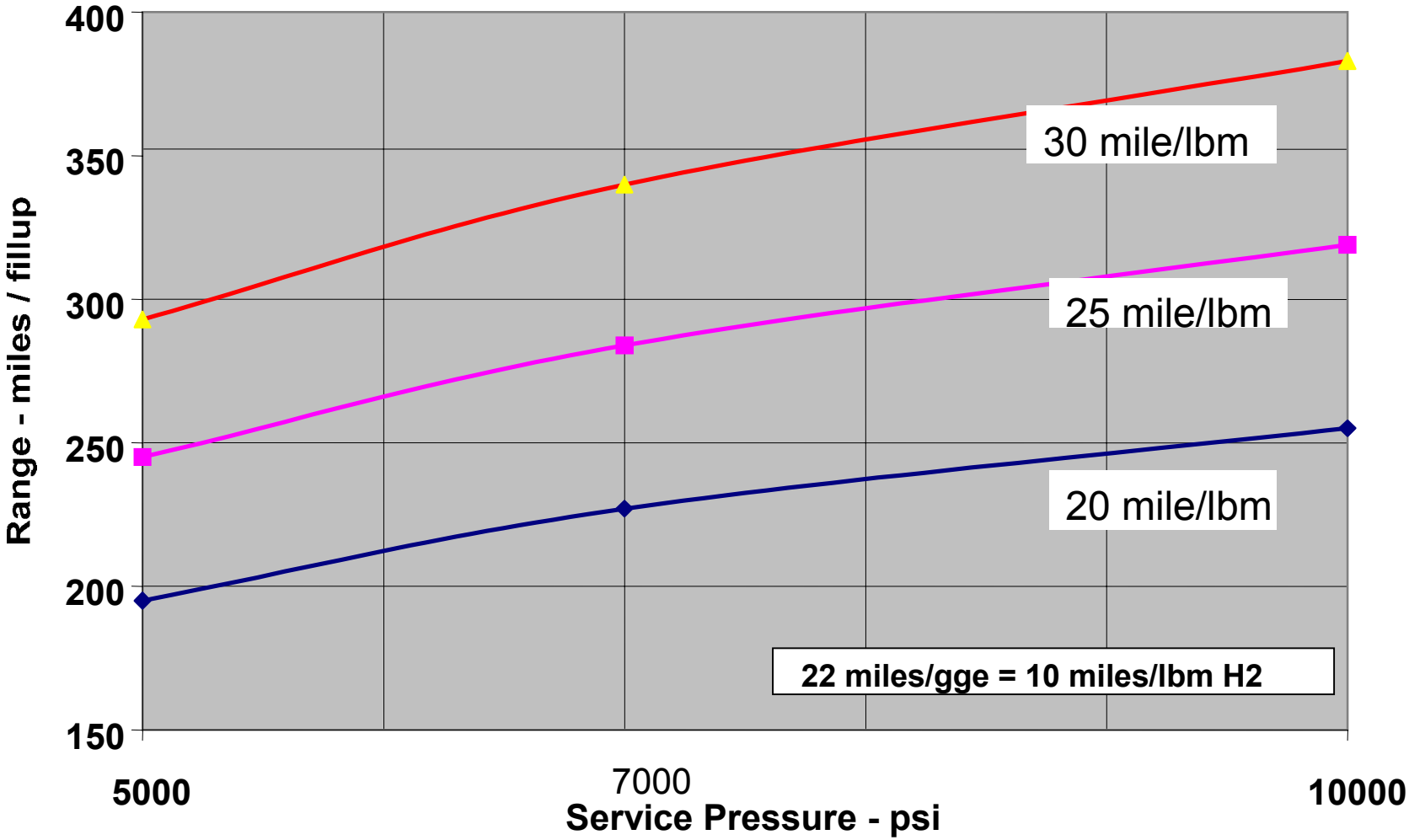
Vehicle Interface Technology-Accomplishments





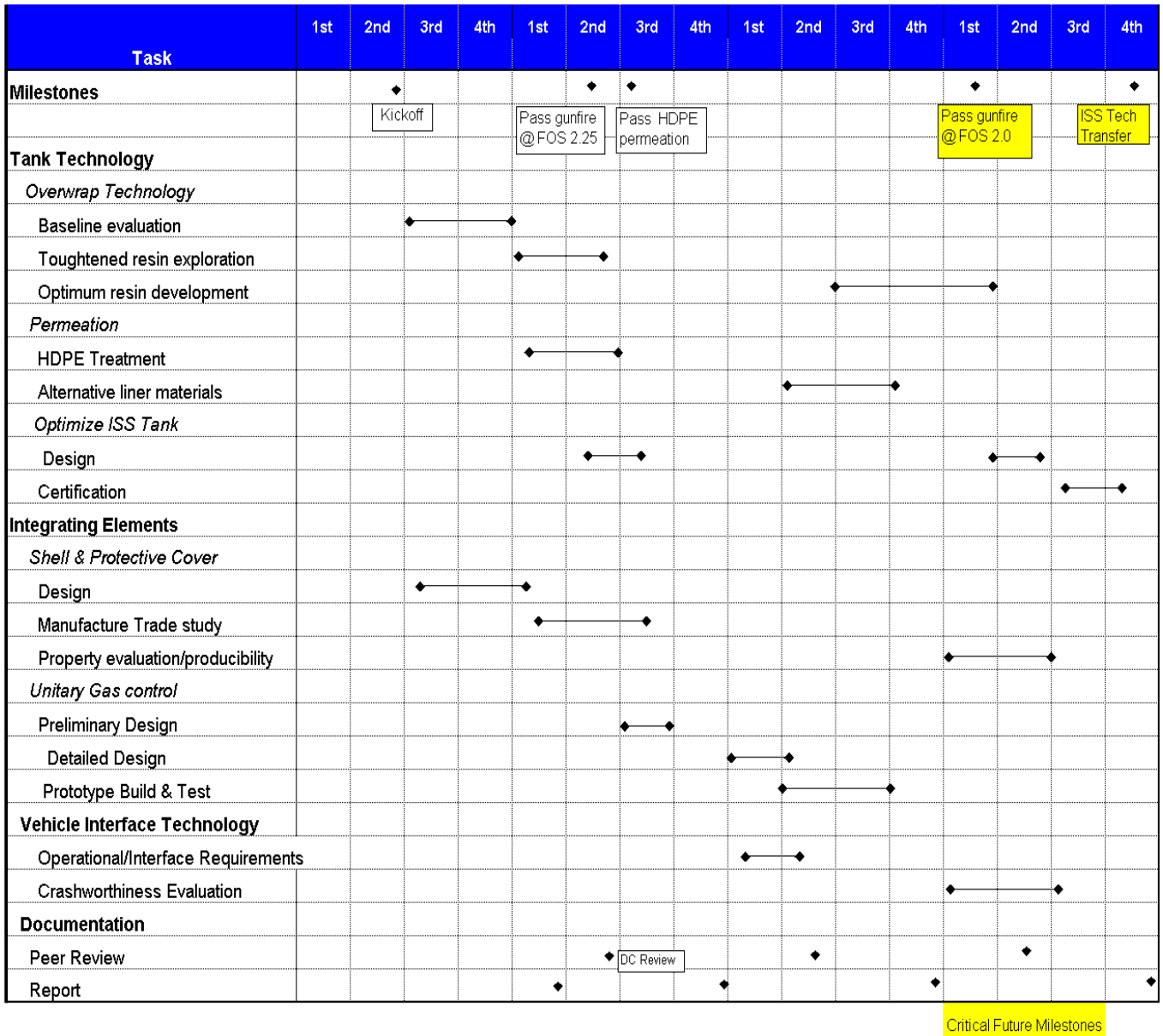
- **Developed preliminary vehicle interface/storage system packaging point design**
  - » CH2-ISS entirely in undercarriage with required ground clearances
  - » No reduction in passenger/cargo space for selected class of OEM platform
  - » Uses space tire space made possible with growing OEM “run-flat” tire trend
  - » Uses semi-trailing arm suspension designed to surround storage system while maintaining ride and handling
- **Initiated design of a “Crash Management System”**
  - » Breakaway linkage system (4-bar) to tip and guide CH2-ISS into undercarriage in high-speed, rear-end collision
  - » Controls collision energy imparted to CH2-ISS
  - » “Crumple zone’ preserved to protect passengers; sensed g-impact shuts off hydrogen gas flow at the CH2-ISS

Estimated FCEV Point Design Driving Range



Based on "current" technology CH2-ISS with an external volume of 266 Liters

CH2-ISS Project Timeline



Plans/Future Milestones

- **Further increase storage energy density with optimized overwrap resin**
  - Formulate optimized toughened epoxy resin
    - » Goals - Improved toughness, increased glass transition temperature, maintain processability with minor cost impact
    - » Approach
      - ✓ In collaboration with Drexel University perform parametric resin improvement study
      - ✓ Use optimized toughened resin(s) tanks for burst and gunfire tests with FOS < 2.25
      - ✓ Address issue : regulatory barriers, stress rupture reliability, blunt impact test
    - » Planned Milestones
      - ✓ Pass gunfire tests at 2.0 FOS with margin
      - ✓ 15% increase in gravimetric energy density and 10% reduction direct material cost
- **Finalize ISS Design**
  - Conduct impact and fire resistance tests on shell candidate flat panel and work out design-for producibility issues
  - Finalize unitary gas control system design and fabricate prototype for test/evaluation
  - Develop CH2-ISS detailed design and cost for full development and certification
  - Seek commercial partner for CH2-ISS technology transfer
- **Complete vehicle interface/packaging analysis**
  - In collaboration with OEM or Tier I supplier support vehicle interface/packaging
    - » Further system design and assess characteristics
    - » Detail elements of Crash Management System
    - » Evaluate system crashworthiness via Large-Scale Deformation simulation