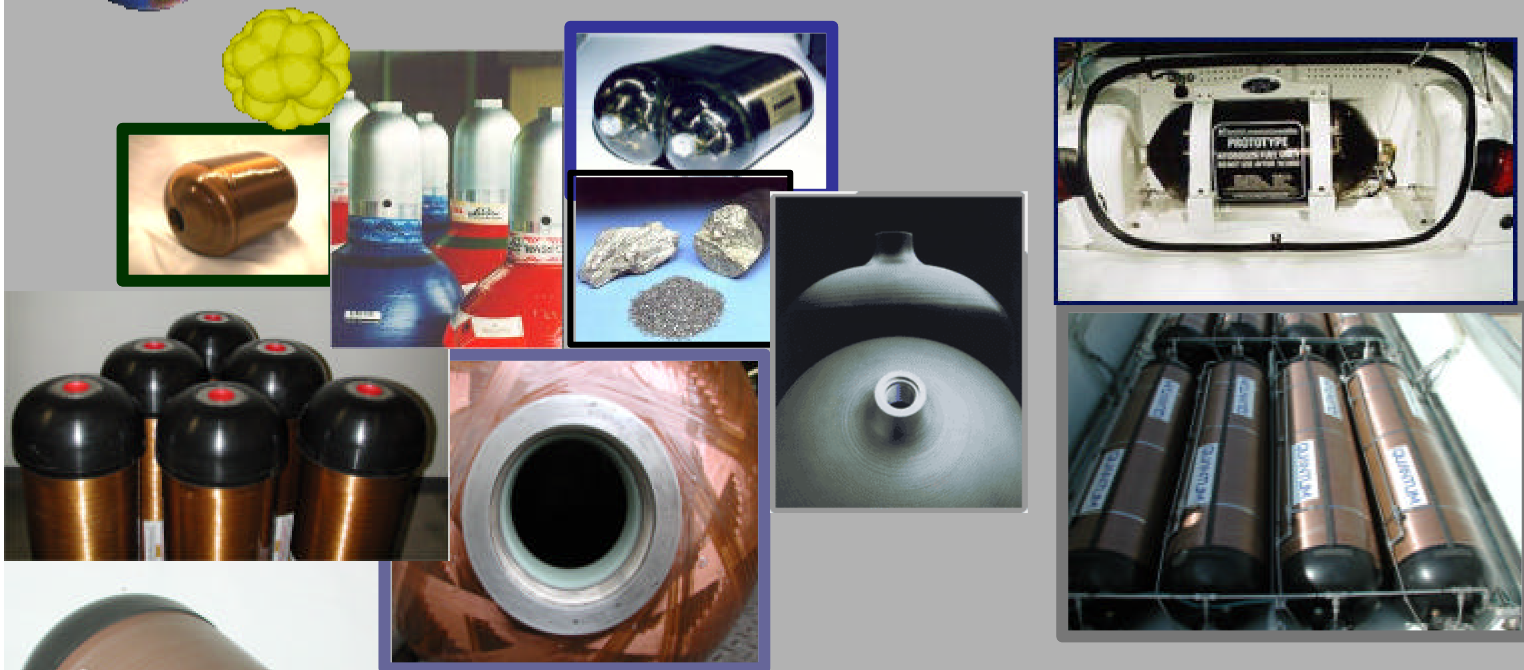
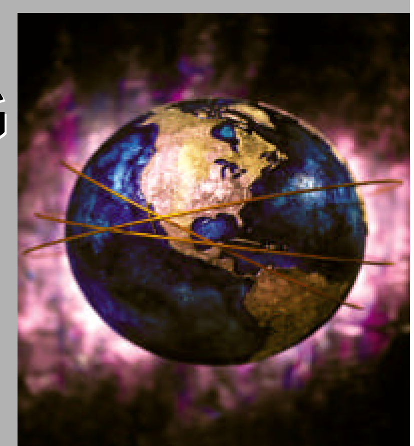
HYDROGEN STORAGE



HYDROGEN VISION MEETING



Alan Niedzwiecki

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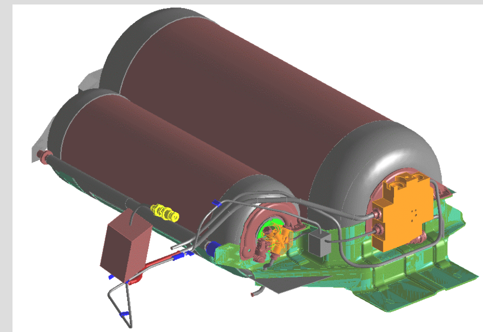
QUANTUM Technologies WorldWide, Inc.

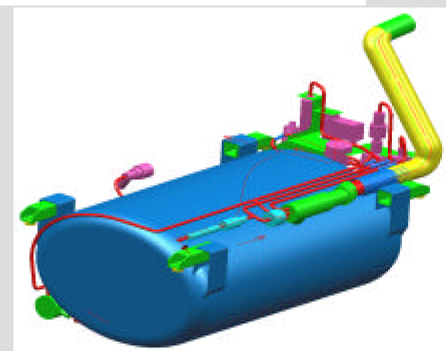
November 2001

Hydrogen Storage Alternatives

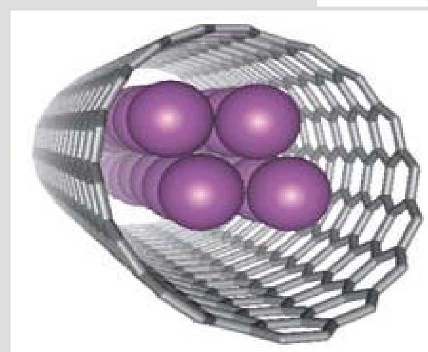
- **Compressed Fuel Storage**
  - Cylindrical Tanks
  - Quasi-Conformable Tanks



- **Liquid Hydrogen Storage**
  - Cylindrical Tanks
  - Elliptical Tanks

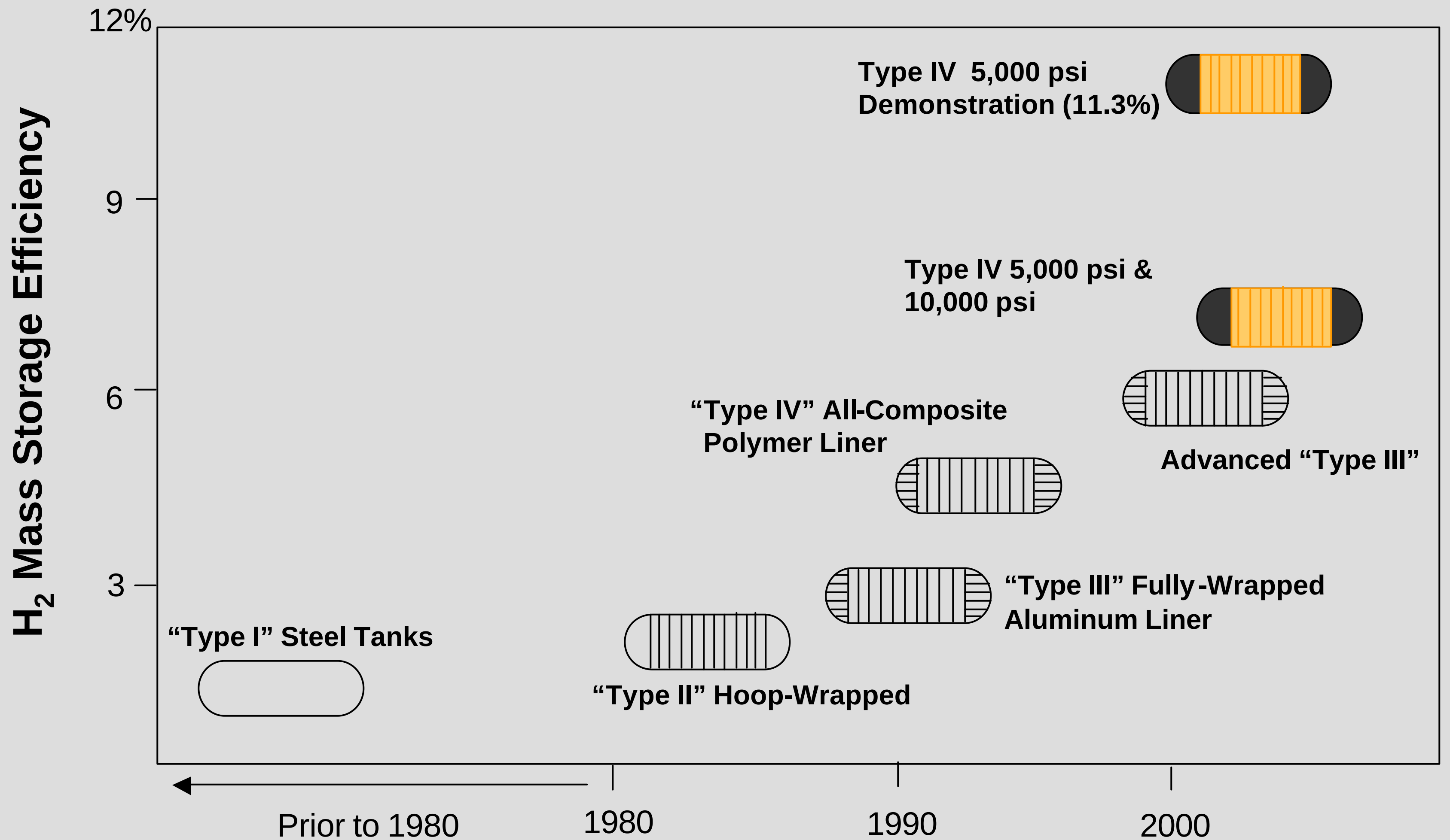


- **Solid State Conformable Storage**
  - Hydride storage material
  - Carbon adsorption
  - Glass microspheres



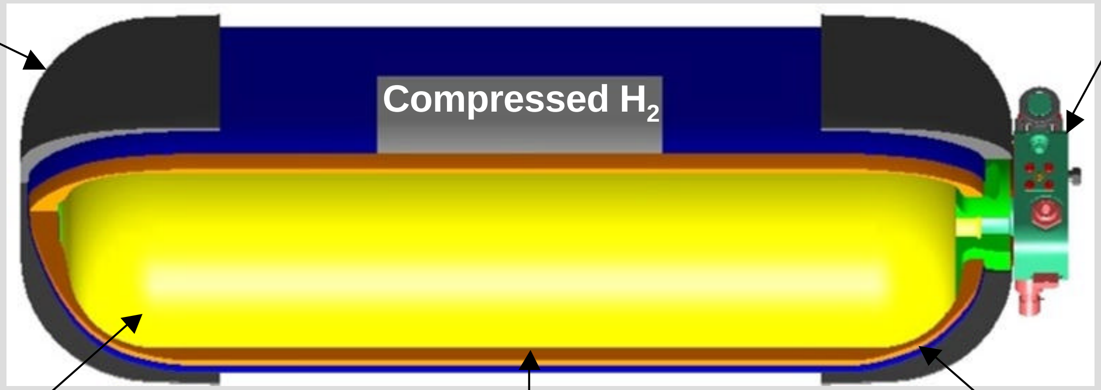
QUANTUM TECHNOLOGIES

Compressed Fuel Storage Evolution



QUANTUM TECHNOLOGIES

Compressed Fuel Storage (Example)



Impact-Resistant Dome

- Light-weight
- Energy Absorbing
- Cost-Competitive

Manual Valve, or Electrical Valve or In-Tank Regulator

Polymer Liner

- Light-weight
- Corrosion resistant (hydrogen embrittlement)
- Permeation barrier
- Cost-competitive
- Flexible in Size

Carbon-fiber Reinforced Shell

- Corrosion resistant (acids, bases)
- Fatigue/Creep/Relaxation resistant
- Light-weight

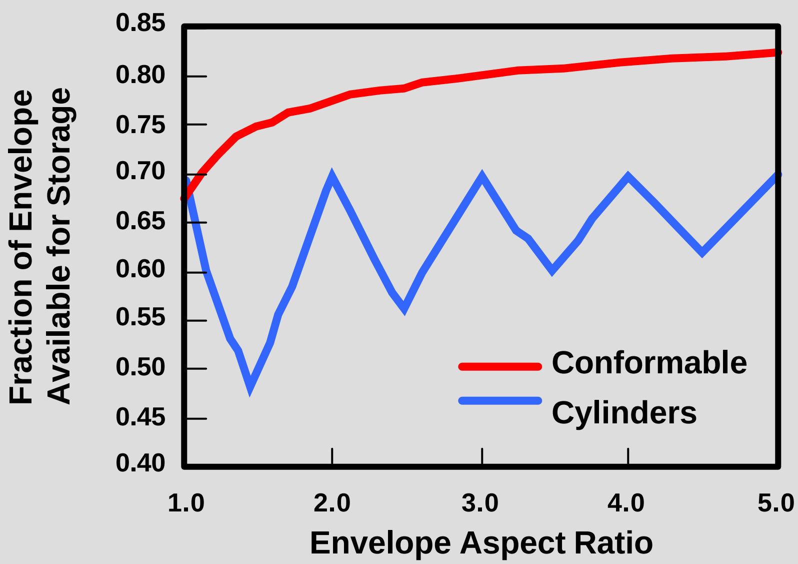
Reinforced External Protective Shell

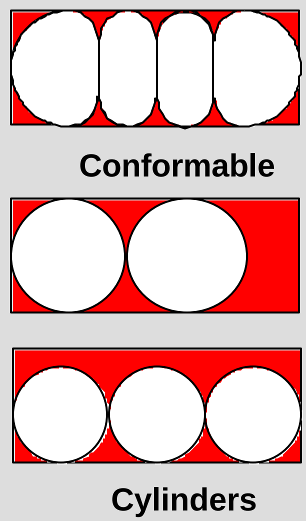
- Gunfire safety
- Impact safety
- Cut/Abrasion Resistance

QUANTUM TECHNOLOGIES

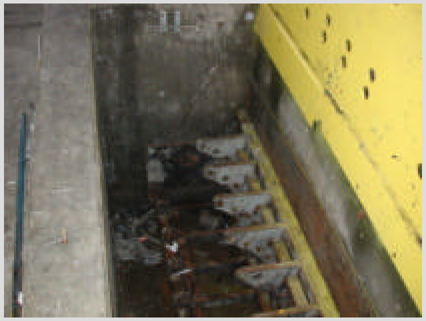
Compressed Hydrogen Conformable Tanks

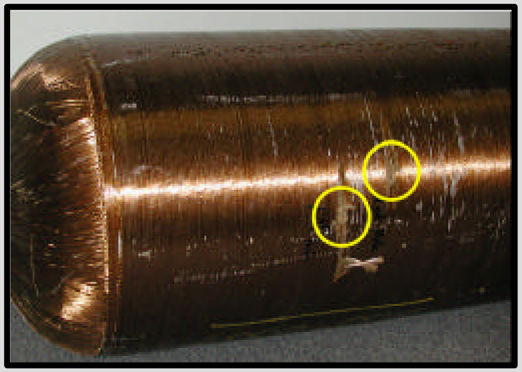
- Construction:
  - Polymer ‘D-Cell’ liner
  - Composite shell
- Advantage: Improved space utilization
- NGV2 validation completed for CNG





Compressed Fuel Storage: Validation Testing





Compressed H2 Storage

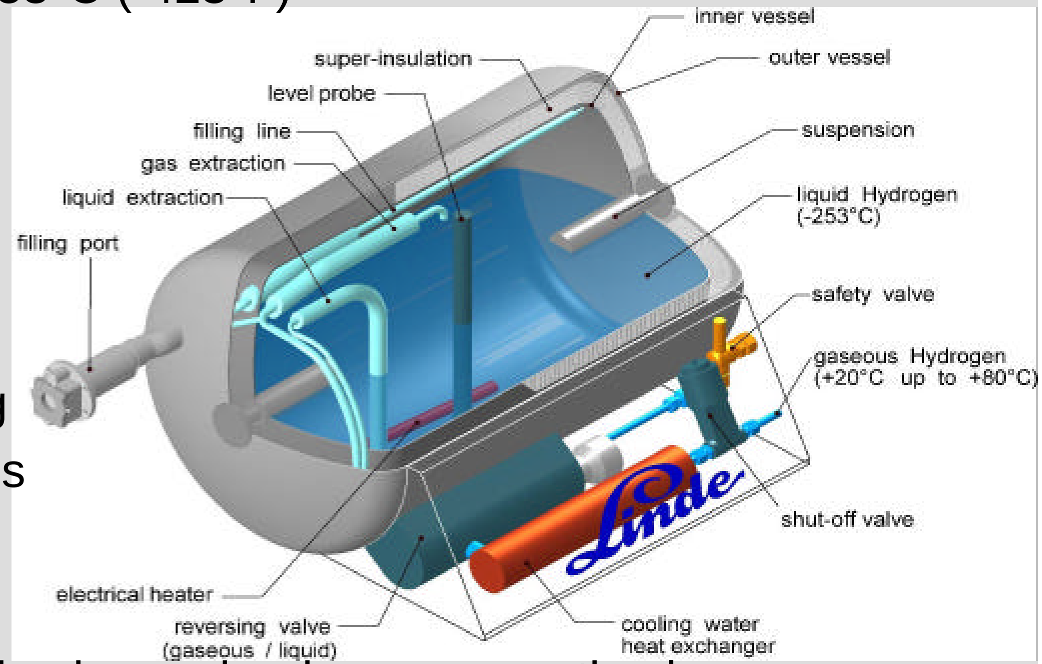
Validation Testing Requirements

Regulatory Agency	Validation Tests
ISO 15869 International	Hydrostatic Burst
NGV2 US/Japan/Mexico/Argentina	Extreme Temperature Cycle
FMVSS 304 United States	Ambient Cycle
NFPA 52 National Fire Protection	Acid Environmental
KHK Japan	Bonfire
CSA B51 Canada	Gunfire Penetration
TUV Germany	Flow Tolerance
Drire France	Accelerated Stress
Bureau Veritas Argentina	Drop Test
	Permeation
	Hydrogen Cycle
	Softening Temperature
	Tensile Properties
	Resin Shear
	Boss End Material

QUANTUM TECHNOLOGIES

Liquid Hydrogen Storage

- Cryogenic storage of hydrogen @ -253°C (-423°F)
- Advantages
  - Low pressure
  - High storage density
- Disadvantages
  - Energy required for liquefaction
  - Evaporative losses during fueling
  - Evaporative losses during periods of inactivity, i.e. when parked
  - Consumer Acceptance



- Future developments to improve packaging and reduce evaporative losses
  - Linde AG
  - Lawrence Livermore National Laboratory

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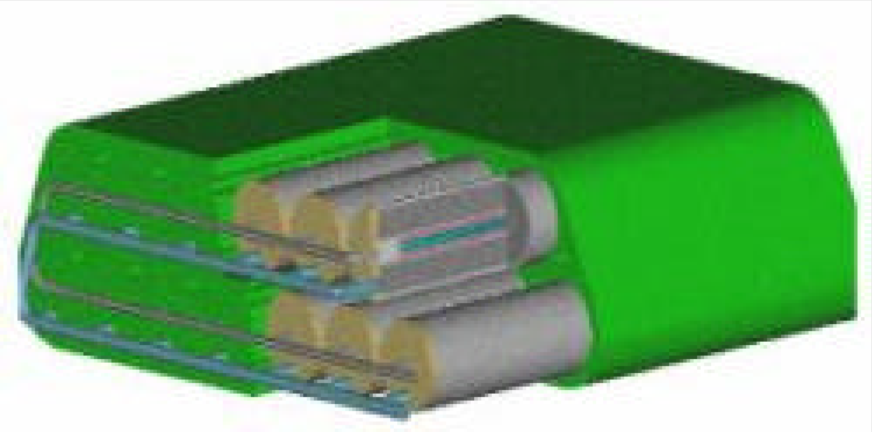
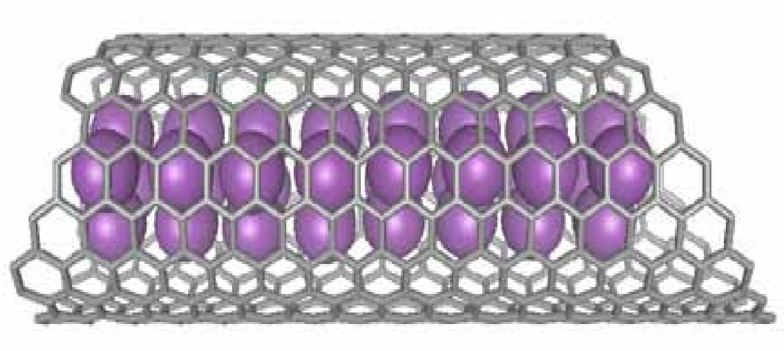
Metal Hydride Storage

- Current metal hydride systems = 1.5 – 5 wt.% H_2
  - Operate @ 300 – 400 C and 20 bar
  - Primary challenge is thermal management
- Low-temperature hydrides under development
  - Goal: 5.5 wt.% H_2 @ <100 C
  - U of Hawaii – Alanates
  - Sandia National Laboratory
  - United Technologies



ECD/Ovonic Onboard Solid Hydrogen Storage System

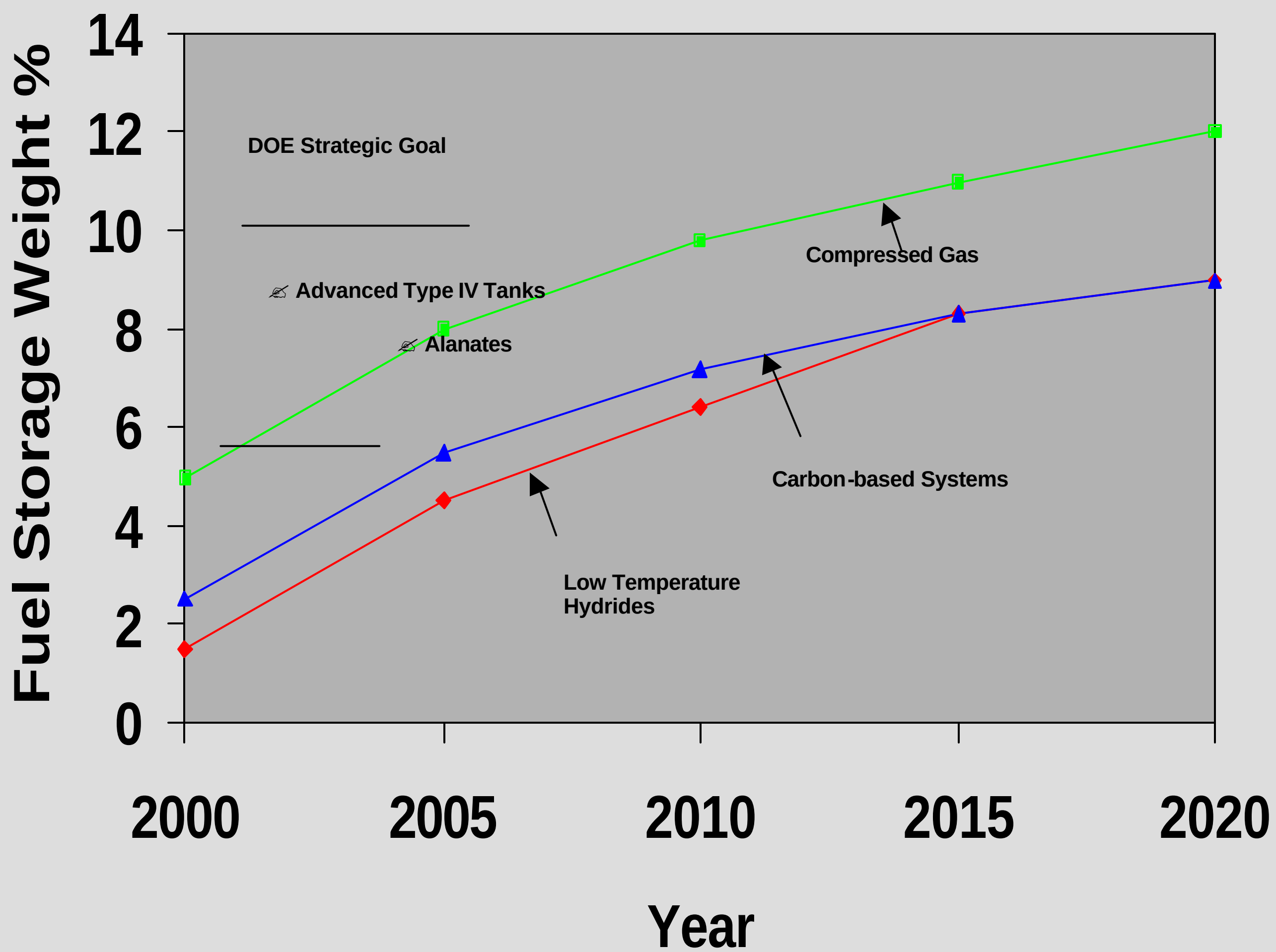
Advanced Solid-State Storage



- Carbon nanotubes
  - High surface area carbon structures for adsorption
  - Goal > 6 wt. % hydrogen
  - Challenges: synthesis, processing, hydrogen absorption/desorption
- Carbon fullerenes
  - High surface area carbon structures for adsorption
  - Status – feasibility study underway
- Glass microspheres
  - Proof-of-principle demonstrated with > 10 wt % H_2
  - Potential for low cost, high-capacity conformable storage
  - Challenges: synthesis, processing, thermal/pressure management of absorption/desorption

QUANTUM TECHNOLOGIES

DOE Hydrogen Program Strategic Goals



On-Board H_2 Storage Alternatives

Short-term Goal: 3 kg H_2 (215 km)

Technology	Storage System Volume	Storage System Weight	Technology Readiness
5,000 psi Compressed Hydrogen Tanks	145 L	45 kg	■■■■■
10,000 psi Compressed Hydrogen Tanks	100 L	50 kg	■■■■□
Low Temperature Metal Hydrides	55 L	215 kg	■■■□□
Liquid Hydrogen	90 L	40 kg	■■■■■

On-Board H_2 Storage Alternatives

Long-term Goal: 7 kg H_2 (700 km)

Technology	Storage System Volume	Storage System Weight	Technology Readiness
5,000 psi Compressed Hydrogen Tanks	320 L	90 kg	■ ■ ■ ■ ■
10,000 psi Compressed Hydrogen Tanks	220 L	100 kg	■ ■ ■ ■ □
Alanate Hydrides	200 L	222 kg	■ □ □ □ □
Carbon Nanotubes	~ 130 L	~ 120 kg	■ □ □ □ □

QUANTUM TECHNOLOGIES

OEM Fuel Strategies

	Compressed H2	Liquid H2	Gasoline Reformer	Methanol Reformer
GM	✓	✓	✓	
DaimlerChrys	✓			✓
Ford	✓			✓
Toyota	✓			
Honda	✓			
Hyundai	✓			
Opel	✓	✓		
BMW		✓		
Volkswagon	✓	✓		
Nissan	✓			
Renault	✓			
Suzuki	✓			

Early Adopters

How do we get there from here?

- Automakers need
  - Hydrogen storage solution (vehicle range, weight, volume, safety, and cost)
  - Assurances that refueling infrastructure will be there
- Suppliers need
  - Production volume to reduce costs through economies of scale
  - Demand sufficient to justify capital expenditures
- Consumers need
  - Vehicles that are transparent to own and operate (cost, vehicle range, comfort, convenience, refueling ease, reliable, …) compared to today's conventional gasoline ICE vehicles
  - Convenient refueling and cost-competitive fuel

QUANTUM TECHNOLOGIES

H_2 Storage Commercialization Pathway

Building economies of scale

- Stationary premium power (e.g. UPS, emergency back-up)
  - 2002 – 2005 PEM fuel cell product introduction
- Infrastructure
  - High pressure storage for fast-fill refueling
  - Bulk transport and distribution
- Fuel cell automobiles
  - 2003 - 2005 introduction
  - 2008 - 2010 start of mass production
- Transit buses
  - Near-term production
- Personal mobility
  - Expected to follow fuel cell automobiles

QUANTUM TECHNOLOGIES

Where Do We Go From Here: Conclusions

Compressed → Near To Long Term

- Portable Fuel Cell
- Stationary Fuel Cell
- Infrastructure
- Transportation

- Storage Efficiency Improvements
- Cost Reduction
- Safety
- Regulatory Codes/Standards Developed
- Mass Commercialization Potential

Liquid → Near To Long Term

- Infrastructure
- Transportation

- Conformable Shapes
- Boil-off Containment
- Technology Development
- Niche Market

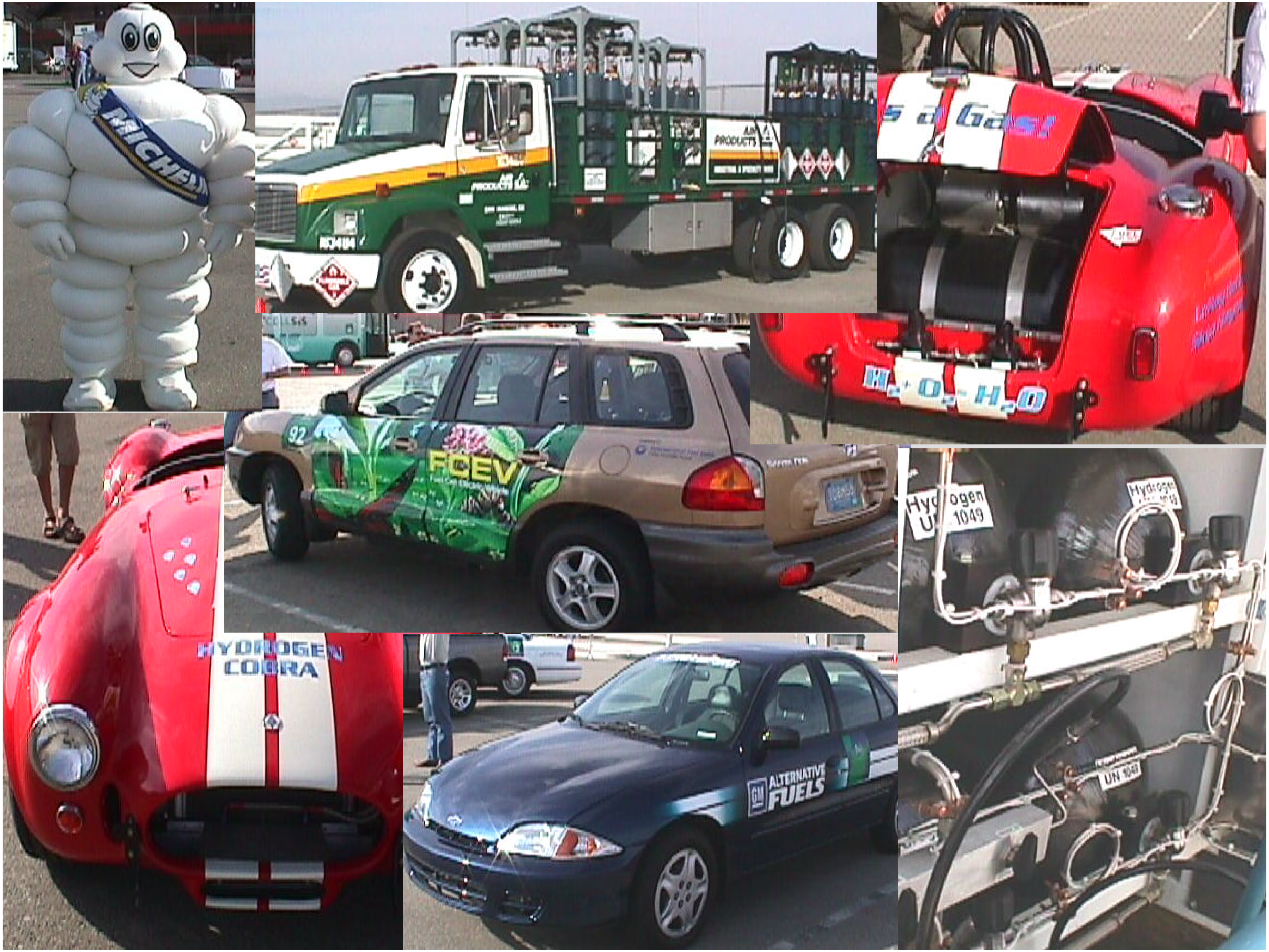
Solid State → Long Term

- Portable
- Stationary Fuel Cell
- Transportation

- Materials and Materials Processing
- Cost Reduction
- Weight Reduction
- Mass Commercialization Potential

QUANTUM TECHNOLOGIES


Covie
FC-EV
FUEL CELL ELECTRIC VEHICLE
TH!NK
OPEL
FCHV-5
TOKICO
CHF
GG-FC 201
FC-EV
mazda
HYDROGEN3


MICHELIN
AIR PRODUCTS
FCEV
HYDROGEN
COBRA
ALTERNATIVE
FUELS
GM
Hydrogen
UN 1049
Hydrogen
UN 1049

HYDROGEN STORAGE

THE END

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QUANTUM Technologies WorldWide, Inc.

November 2001

QUANTUM TECHNOLOGIES

Consumer Acceptance

Three Keys To Success

- Vehicle must offer same or better features, performance ad pricing as gasoline vehicles
- Refueling interface must be simple and easy to use
- The storage system must be transparent; i.e., vehicle designed around the storage system