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Cryo-Compressed Hydrogen Storage: Performance and Cost Review

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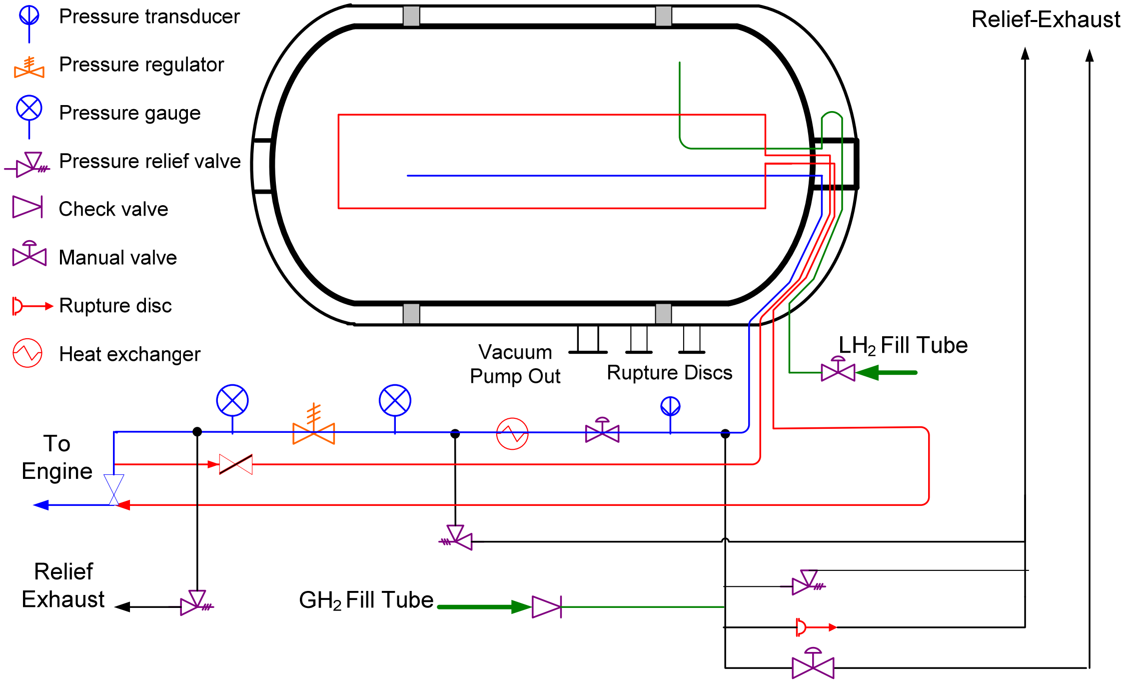
Cryo-Compressed Hydrogen Storage: Performance and Cost Review

- Contributors to the study
  - LLNL: Gen2 and Gen3 design data, Aceves and Berry
  - Argonne: On-board and off-board performance modeling, bill of materials, off-board cost modeling
  - TIAX: On-board cost modeling
- Results
  - Gravimetric and volumetric capacity
  - Refueling dynamics
  - Discharge dynamics
  - Dormancy and boil-off losses
  - WTT efficiency
  - Greenhouse gas emissions
  - Storage system cost
  - Refueling and ownership cost

LLNL Gen3 Cryo-Compressed H_2 Storage System

Modifications from Gen2

- Reduced insulation
- Better packaging
- Vacuum valve box eliminated
- In-tank heat exchanger
- 4000-psi pressure vessel rating



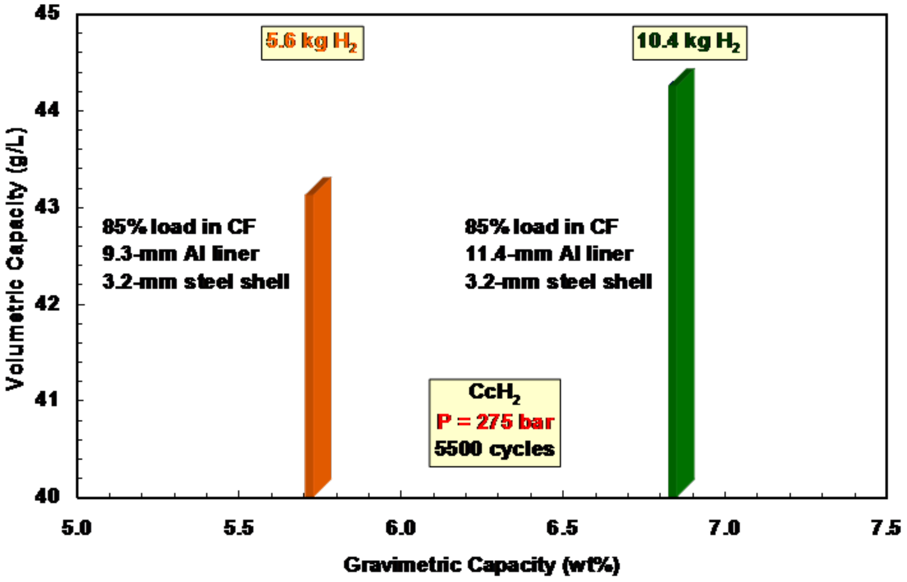
- System Volume: 235 L
  - Storage: 151 L
  - Vessel: 224 L
  - Ex-Vessel: 11 L
  - V Efficiency: 64.3%
- System Weight: 144.7 kg
  - LH_2 Stored: 10.7 kg
  - CH_2 Stored: 2.8 kg
  - Vessel: 122.7 kg
  - Ex-Vessel: 22.0 kg
- System Volumetric Capacity
  - 44.5 kg/m^3:1.5 kWh/L
  - LH_2 density: 70.9 kg/m^3 at 20.3 K, 1 atm
  - CH2 density: 18.8 kg/m^3 at 300 K, 272 atm
- System Gravimetric Capacity
  - 7.1 wt%: 2.3 kWh/kg

System Analysis of Physical Storage Systems

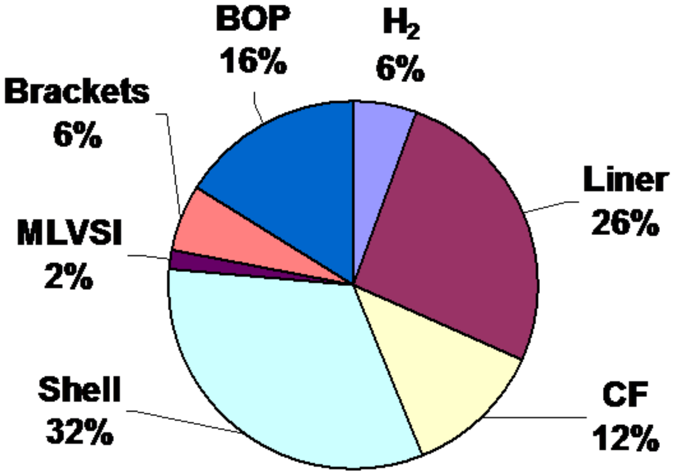
- Benedict-Webb-Rubin equation of State: REFPROP coupled to GCtool
- Carbon Fiber Netting Analysis
  - Algorithm for optimal dome shape with geodesic winding pattern (i.e., along iso-tensoids)
  - Algorithm for geodesic and hoop windings in cylindrical section
- Fatigue Analysis of Type 3 Tanks
  - Algorithm for residual compressive stresses introduced by auto-frettage, pre- and post-proof load distribution between liner and CF
  - Unloading of residual stresses under cryogenic conditions
  - S/N curves for Al 6061-T6 alloy, non-zero mean stresses
  - 5500 pressure cycles at 1.25 NWP (SAE J2579)
- Dynamic models for gaseous/liquid refueling, discharge, dormancy
- Models for off-board analysis
  - FCHtool and GREET for greenhouse gas emissions
  - H2A for pathway analysis
  - HDSAM for scenario analysis

Gravimetric and Volumetric Capacities

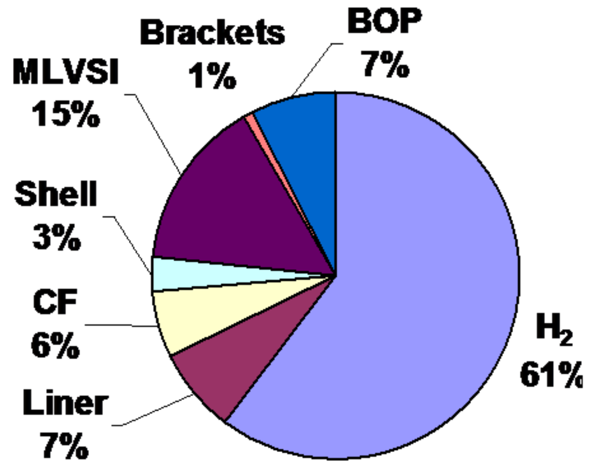
- 5.6-kg system meets 2015 targets
  - Gravimetric capacity > 9% with aluminum shell but higher cost
  - Maximum CF load share limited to 85% at cryogenic T, 276 bar
  - Liner heavier than CF
  - Insulation accounts for 15% of total volume



Weight Distribution



Volume Distribution

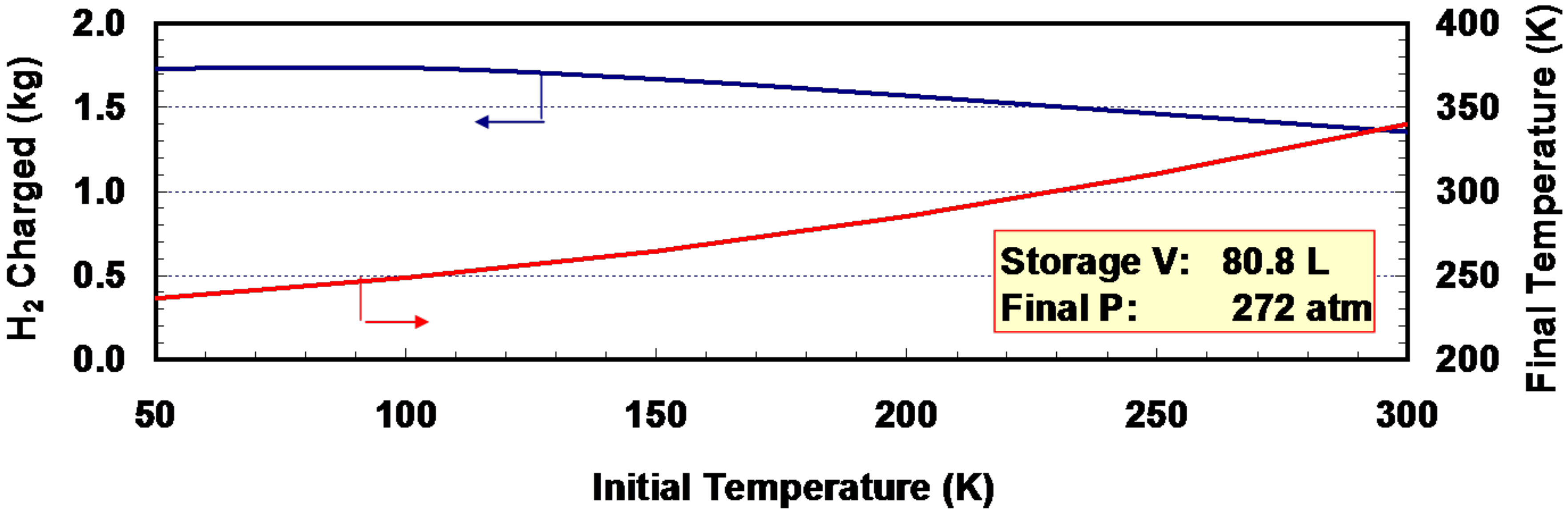


5.6-kg Recoverable H_2 System

Storage Capacity: Compressed Hydrogen Option

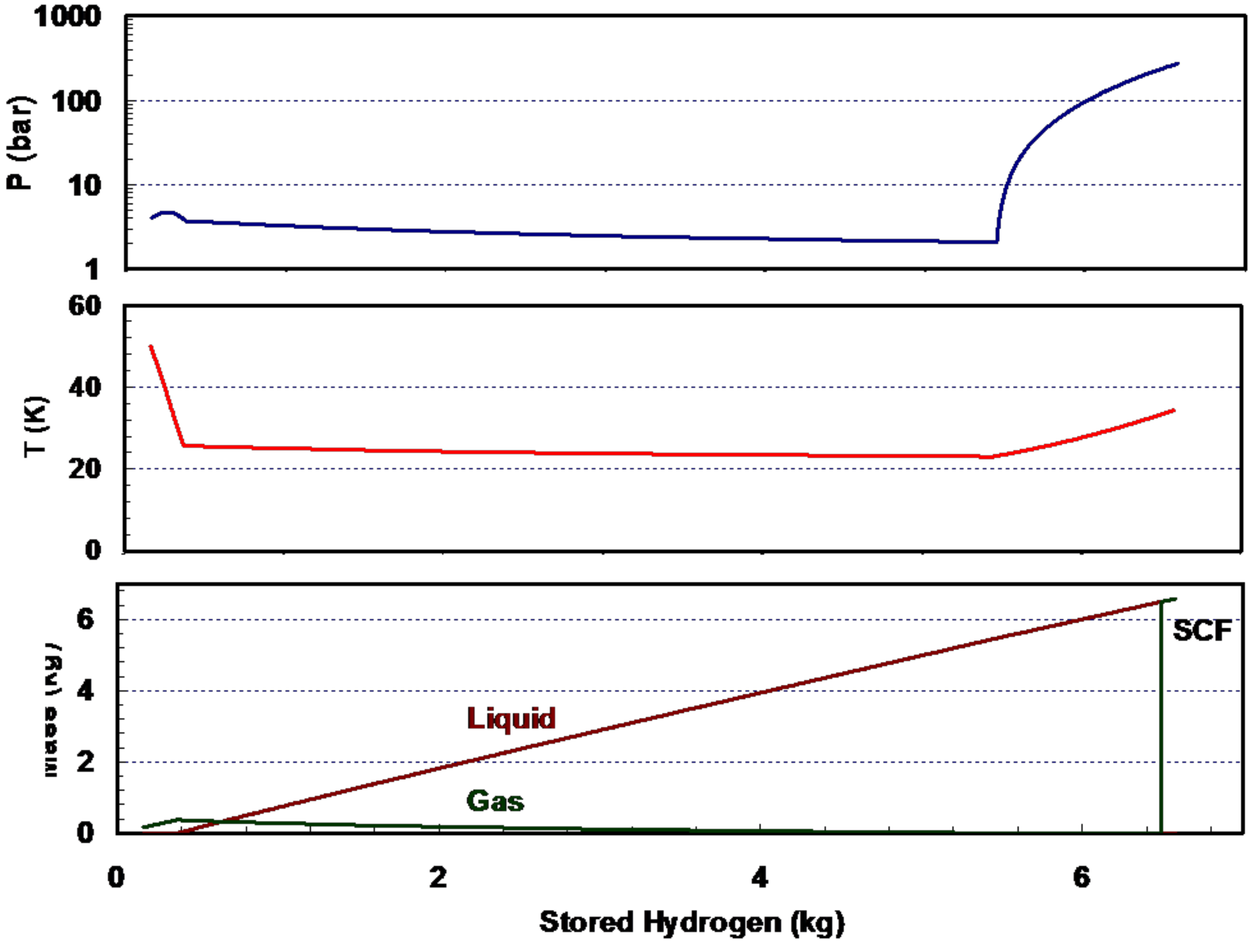
Refueling with compressed H_2 at 300 K

- Adiabatic refueling assuming that liner, CF and gas are isothermal during refueling (maximum possible capacity)
- Tank refueled to 272-atm (4000 psi) peak pressure
- 4 atm initial pressure, variable initial temperature
- Additional storage capacity with pre-cooled H_2 and refueling to higher than design pressure



Refueling with LH2: Cryo-compressed Option

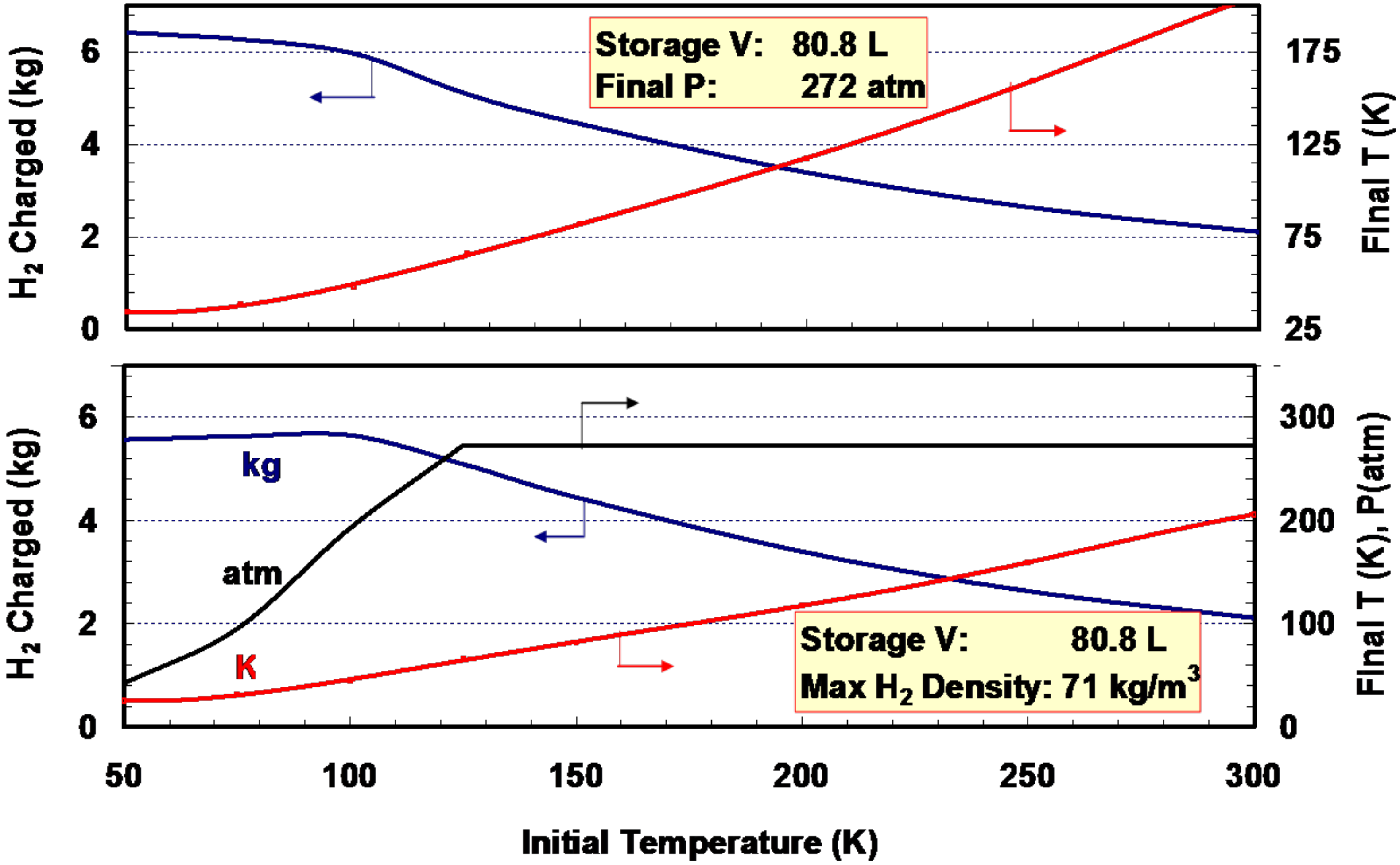
- Refueling with high-pressure LH_2 pump at 25% above tank pressure
- Storage capacity function of final pressure, 5.7 kg for P = 37.7 atm
- Depending on initial T and H_2 charged, final P may be less than 4 atm



- **Initial conditions**
  P=4 atm, T=50 K
- **Gas**
  m < 0.4 kg
- **2-Phase**
  0.4 < m < 5.4 kg
- **Sub-cooled Liquid**
  5.4 < m < 6.5 kg
- **Supercritical Fluid**
  m > 6.5 kg

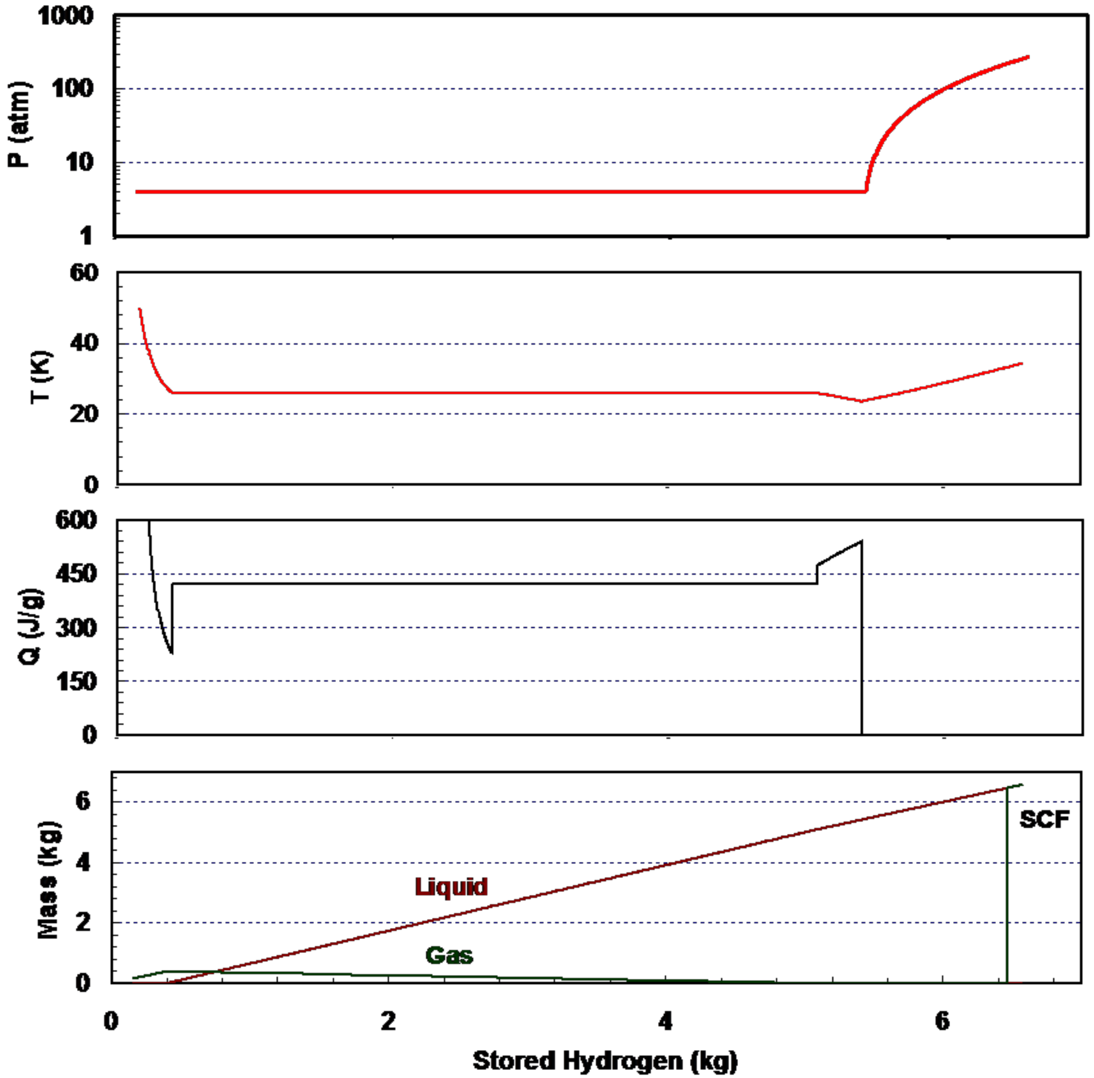
Storage Capacity: Cryo-compressed Option

- Storage capacity is a function of initial temperature
  - 6.4 kg recoverable for initial T = 50 K, P = 4 atm



Discharge Dynamics: Cryo-compressed Option

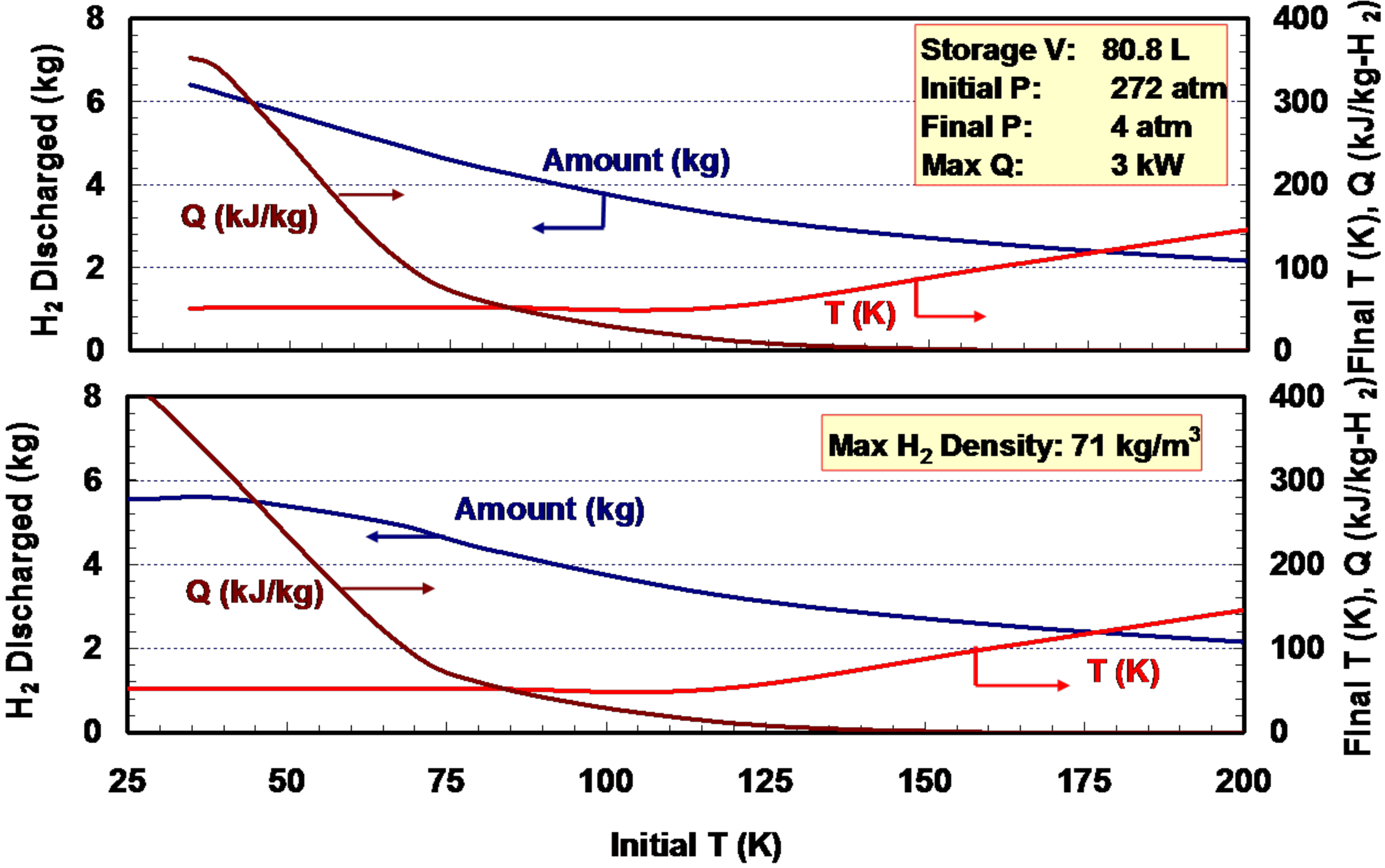
- Heat supplied to maintain 4-atm minimum delivery pressure



- Initial conditions:
  P = 272 atm
  T = 34.3 K
  m = 6.6 kg
- 1.6 g/s full flow rate of H_2
- Max Q = 3 kW

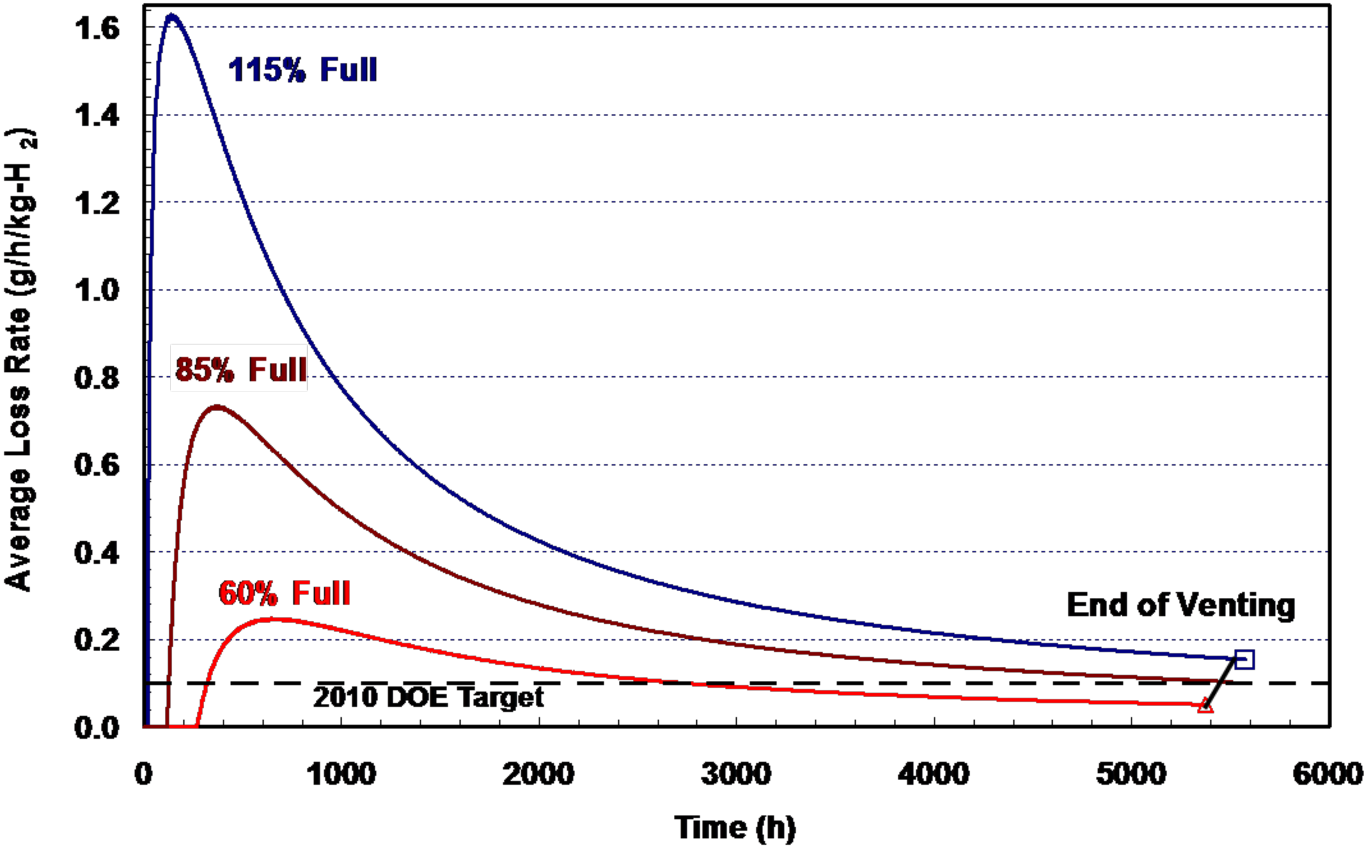
Discharge Behavior: Cryo-compressed Option

- Total heat load is a function of initial temperature
  - 2.3 MJ for 34.3 K initial T, 6.4 kg stored H_2



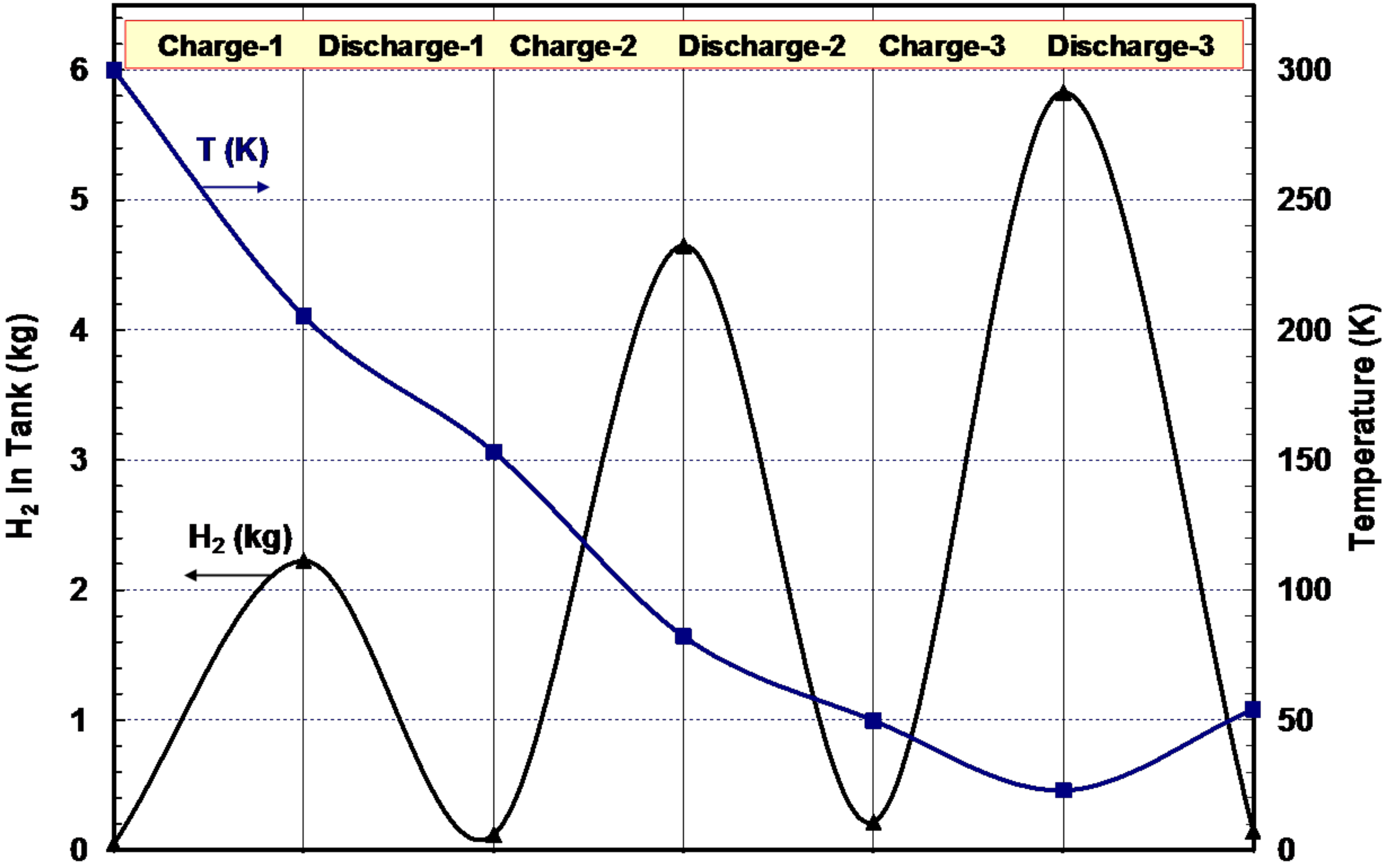
Dormancy and Hydrogen Loss Rate

- No loss of hydrogen after tank reaches 323 K, tank 30% full
- Difficult to always meet the targets of 0.1/0.05 g/h/kg-H_2 with 5 W reference heat in-leakage rate
- No H_2 loss with minimal daily driving (LLNL paper)



CH_2 to cCH_2 Transition

- Three complete charge-discharge cycles needed to reach 71 kg/m^3 hydrogen density



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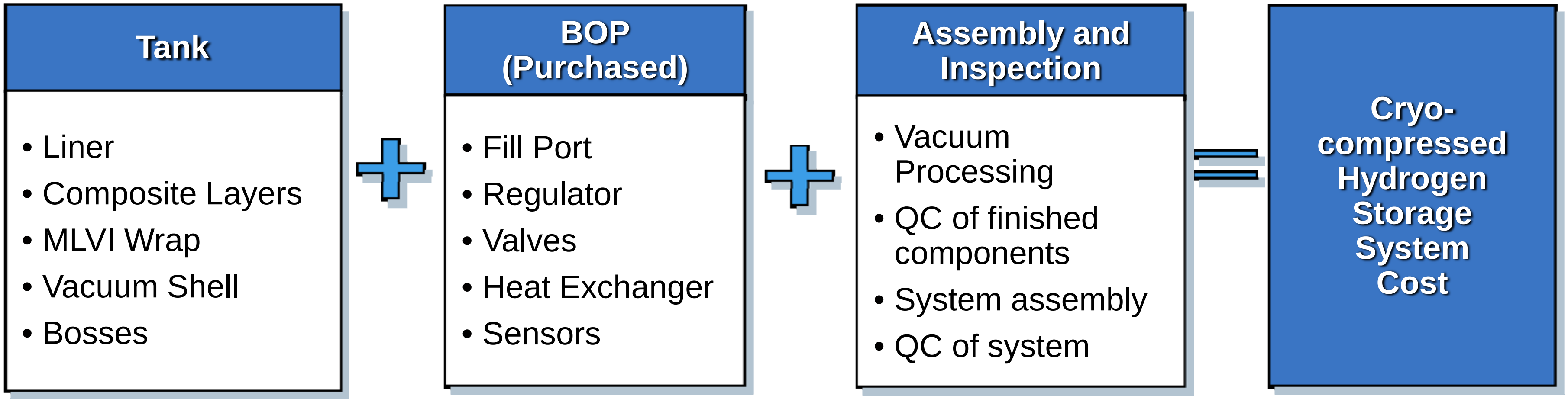
The high volume (500,000 units/year) manufactured cost for all H_2 storage systems is estimated from raw material prices, capital equipment, labor, and other operating costs.

BOP Bottom-up Costing Methodology

- Develop Bill of Materials (BOM)
- Obtain raw material prices from potential suppliers
- Develop production process flow chart for key subsystems and components
- Estimate manufacturing costs using TIAX cost models (capital equipment, raw material price, labor rates)



Tank

- Liner
- Composite Layers
- MLVI Wrap
- Vacuum Shell
- Bosses

+

BOP (Purchased)

- Fill Port
- Regulator
- Valves
- Heat Exchanger
- Sensors

+

Assembly and Inspection

- Vacuum Processing
- QC of finished components
- System assembly
- QC of system

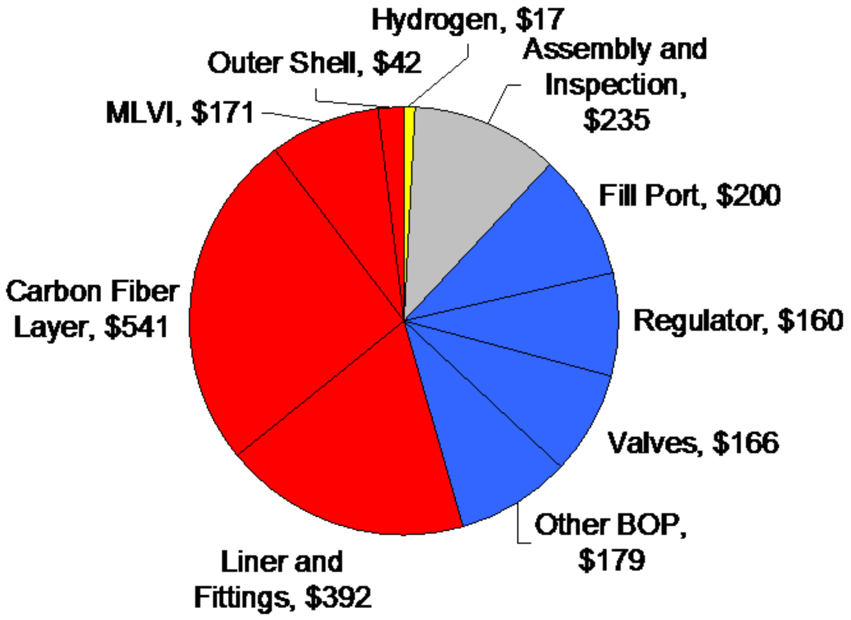
=

Cryo-compressed Hydrogen Storage System Cost

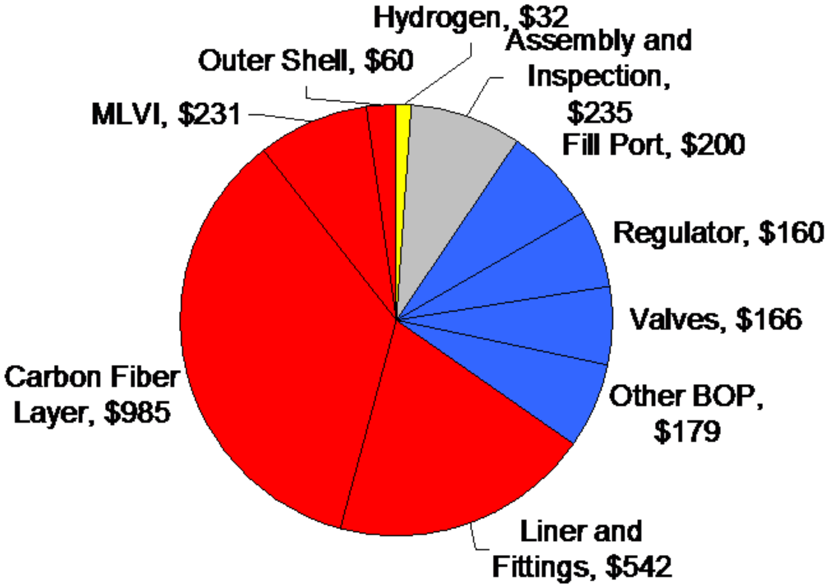
We modeled material and manufacturing process costs for the cryo-compressed tank, while the BOP is assumed to be purchased.

The carbon fiber layer is the most expensive single component and accounts for about 25% and 35% of the base case 5.6 and 10.4 kg systems costs.

5.6 kg Base Case Factory Cost[1] = $2,200
\$12/kWh based on 5.6 kg usable LH_2



10.4 kg Base Case Factory Cost[1] = $2,900
\$8/kWh based on 10.4 kg usable LH_2



[1] Cost estimate in 2005 USD. Includes processing costs.

The BOP components account for about 30% and 25% of the base case 5.6 and 10.4 kg system costs, respectively.

WTT Efficiency

- WTT efficiency = 41.1% (LH_2 refueling)
- Assumptions

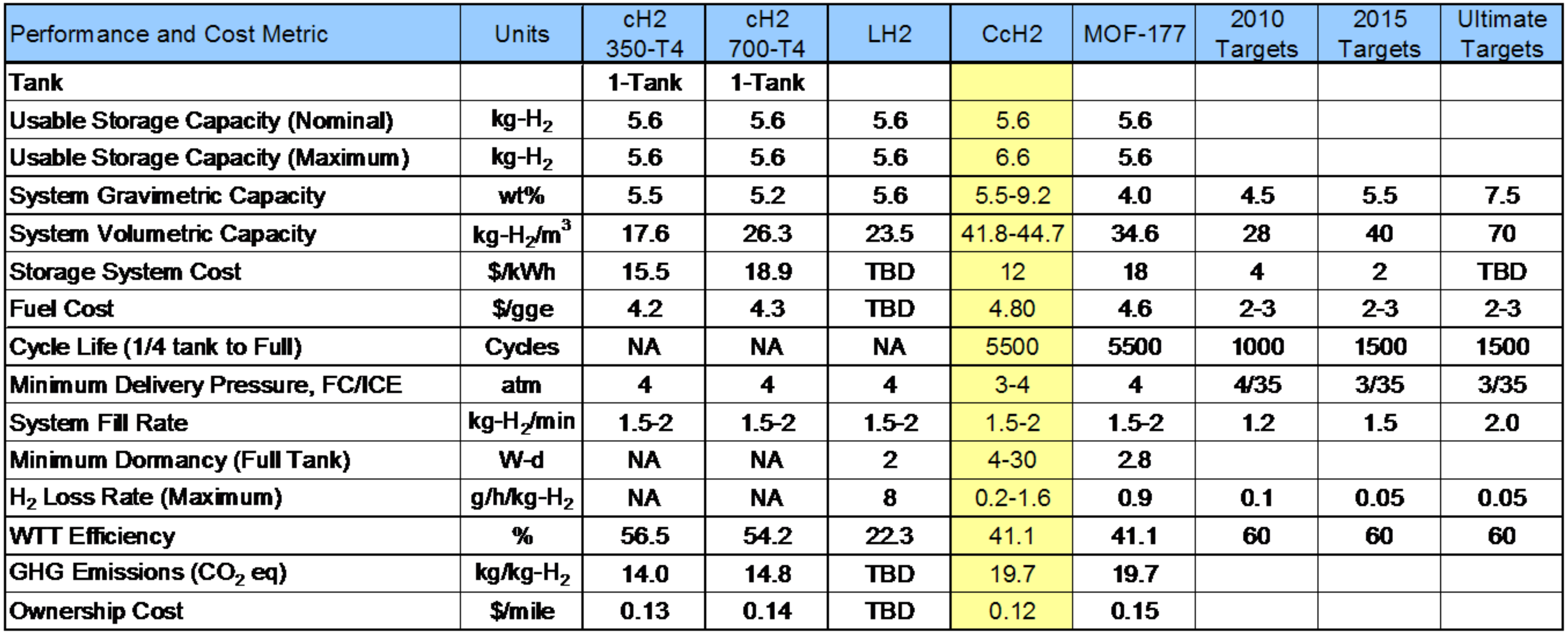
Process/Process Fuels	Nominal Value	Source/Comment
Electricity production	32.2% thermal efficiency	EIA projected U.S. grid for 2015, inclusive of 8% transmission loss from power plant to user site
North American natural gas production	93.5% efficiency	GREET data
H_2 production by SMR	73% efficiency	H2A
H_2 Liquefaction	8.2 kWh/kg	HDSAM, 150 tons/day liquefier
Liquid H_2 (LH_2) delivery by truck	284 km round trip	HDSAM
Truck capacity	4300 kg	HDSAM
Boil-off losses	9.5%	HDSAM: liquefaction 0.5%, storage 0.25%/day, loading 0.5 %, unloading 2%, cryopump 3%
Vehicle refueling with LH_2	2 kg/min; 80% isentropic efficiency	BMW LH_2 pump data
Greenhouse gas emissions	range	Emission factors data from GREET

Off-Board Cost and Performance Summary

- Hydrogen production cost is dominated by fuel cost
  - Central SMR ~ $1.6/kg (77% fuel, 14% capital)
  - Central electrolysis ~ $3.8/kg (6 cents/kWh, 80% fuel, 15% capital)
- Hydrogen delivery cost is dominated by capital cost
  - ~ $6.1/kg for 2% market (60% capital, 10% fuel)
  - ~ $3.2/kg for > 15% market (55% capital, 18% fuel)
- Ownership cost
  - ~12 - 17 cents/mile (15%/2% market) for NG/standard grid scenario
  - ~16 - 21 cents/mile (15%/2% market) for electrolysis/renewable
  - ~10 cents/mile for conventional gasoline ICEV ($3/gal untaxed)
- WTT efficiency: 36 - 41%
- GHG emissions
  - ~ 0.31 - 0.37 kg/mile for NG/standard grid scenario
  - ~ 0 kg/mile for electrolysis/renewable scenario
  - ~ 0.35 kg/mile for gasoline ICEV (31 mpg fuel economy)

Summary and Conclusions

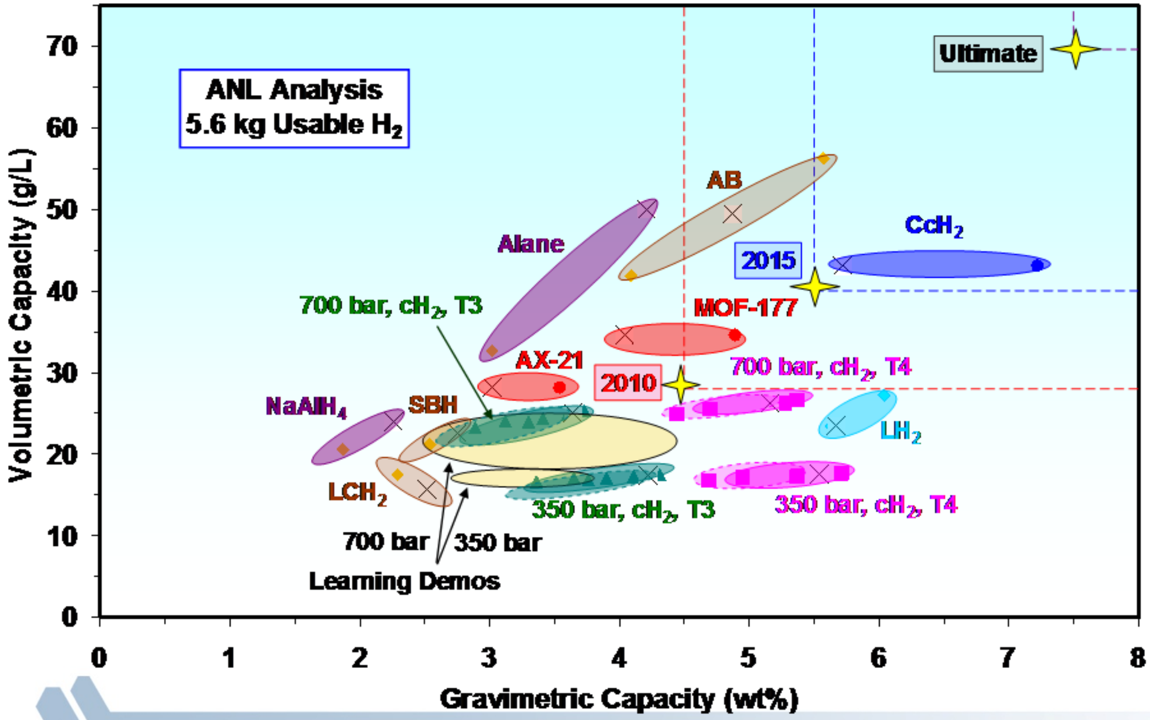
- Cryo-compressed: 71 kg/m^3 max density or 272 atm max pressure
- Results given as single data points, consult references for range, sensitivity and background
- Metrics cover all DOE targets for on-board and off-board storage
- Some results vetted, others for developmental materials and processes



Performance and Cost Metric	Units	cH2 350-T4	cH2 700-T4	LH2	CcH2	MOF-177	2010 Targets	2015 Targets	Ultimate Targets
Tank		1-Tank	1-Tank						
Usable Storage Capacity (Nominal)	kg-H_2	5.6	5.6	5.6	5.6	5.6			
Usable Storage Capacity (Maximum)	kg-H_2	5.6	5.6	5.6	6.6	5.6			
System Gravimetric Capacity	wt%	5.5	5.2	5.6	5.5-9.2	4.0	4.5	5.5	7.5
System Volumetric Capacity	kg-H_2/m^3	17.6	26.3	23.5	41.8-44.7	34.6	28	40	70
Storage System Cost	$/kWh	15.5	18.9	TBD	12	18	4	2	TBD
Fuel Cost	$/gge	4.2	4.3	TBD	4.80	4.6	2-3	2-3	2-3
Cycle Life (1/4 tank to Full)	Cycles	NA	NA	NA	5500	5500	1000	1500	1500
Minimum Delivery Pressure, FC/ICE	atm	4	4	4	3-4	4	4/35	3/35	3/35
System Fill Rate	kg-H_2/min	1.5-2	1.5-2	1.5-2	1.5-2	1.5-2	1.2	1.5	2.0
Minimum Dormancy (Full Tank)	W-d	NA	NA	2	4-30	2.8			
H_2 Loss Rate (Maximum)	g/h/kg-H_2	NA	NA	8	0.2-1.6	0.9	0.1	0.05	0.05
WTT Efficiency	%	56.5	54.2	22.3	41.1	41.1	60	60	60
GHG Emissions (CO_2 eq)	kg/kg-H_2	14.0	14.8	TBD	19.7	19.7			
Ownership Cost	$/mile	0.13	0.14	TBD	0.12	0.15			

Storage Capacity

- Of all the systems built, Gen3 CcH_2 has the highest demonstrated gravimetric and volumetric capacity
- Alane slurry shows high volumetric capacity but stable 70-wt% slurry not formulated, volume-exchange tank not developed
- On-going studies to find AB/IL formulations that remain liquid under all conditions, volume-exchange tank not developed
- cH_2 model capacities in agreement with Tech Val data



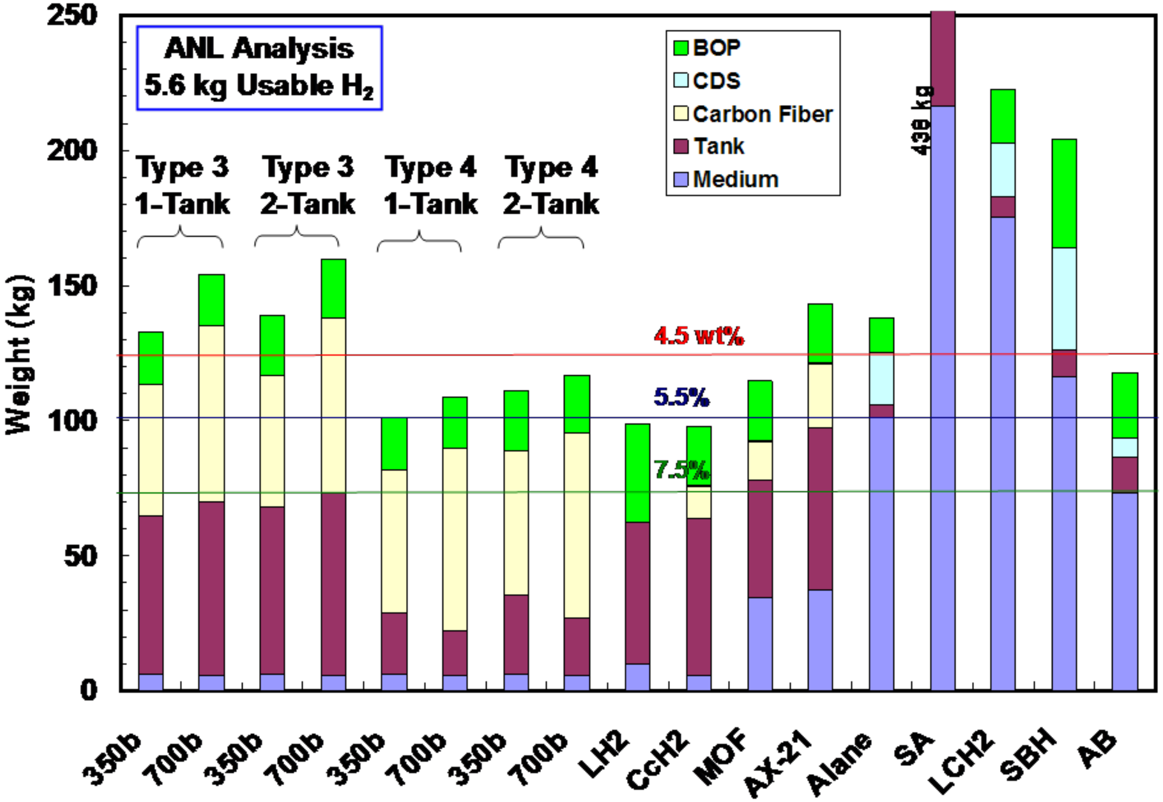
- Diagram to be regarded as a snapshot in time
- Different systems not analyzed to same level of sophistication
- Advanced materials not ready for deployment
- Some component concepts require further development

Consult ANL reports for complete details, assumptions and background

Weight Distribution

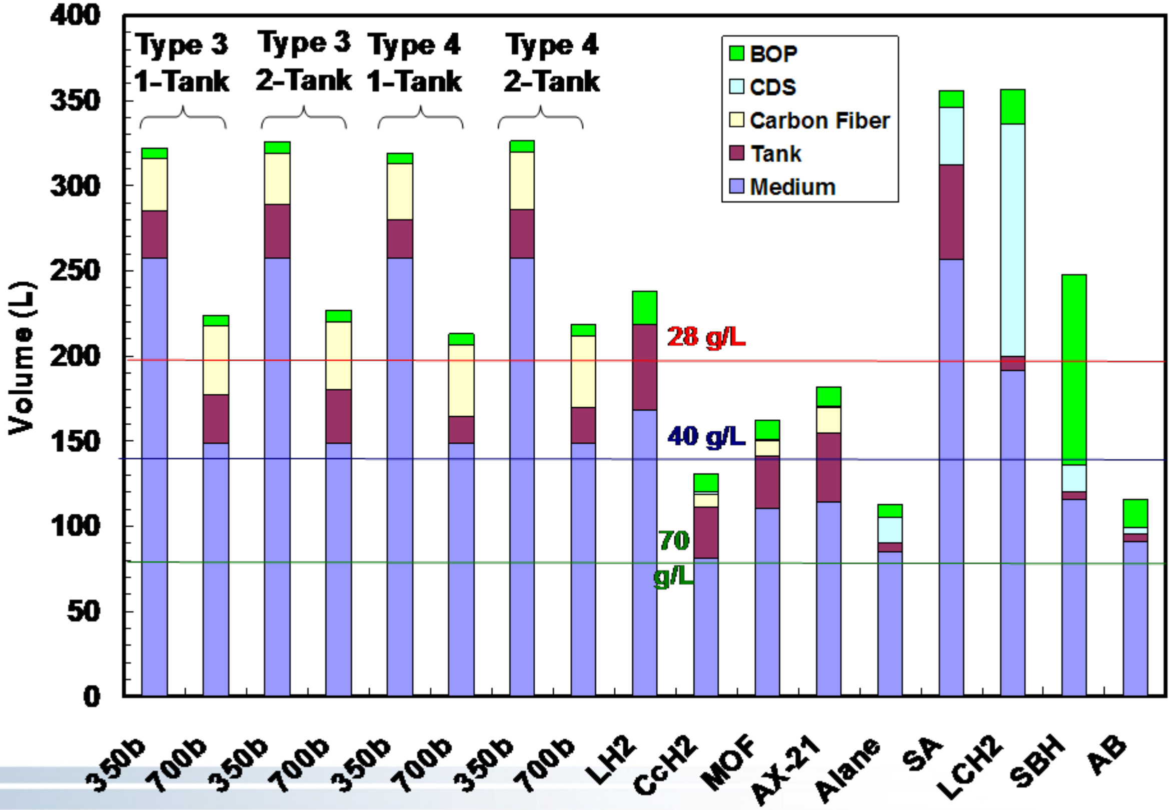
- 350-bar cH_2, LH_2 & CcH_2 systems may meet 2015 gravimetric target
- CcH2 system with Al shell approaches the ultimate gravimetric target
- CF is the main contributor to the overall weight in cH_2 systems
- Metal liner is a heavy component in all Type-3 pressure vessels
- Medium weight dominates in metal hydride and chemical H_2 systems

cH_2: Compressed H_2
350b: 350 bar
700b: 700 bar
LH_2: Liquid H_2
CcH2: Cryo-compressed H_2
MOF: MOF-177
SA: $TiCl_3$ catalyzed $NaAlH_4$
LCH2: Organic liquid carrier
SBH: Alkaline $NaBH_4$ solution
AB: Ammonia borane



Volume Distribution

- CcH_2 system meets 2015 volumetric target but not ultimate target
- Medium volume significant in all options and, by itself, exceeds the 2015 system target in cH_2 systems
- Insulation volume important in cryogenic systems
- CDS in LCH2 is bulky because of highly endothermic reaction
- BOP in SBH (adiabatic reactor, exothermic release) is bulky because of condensers

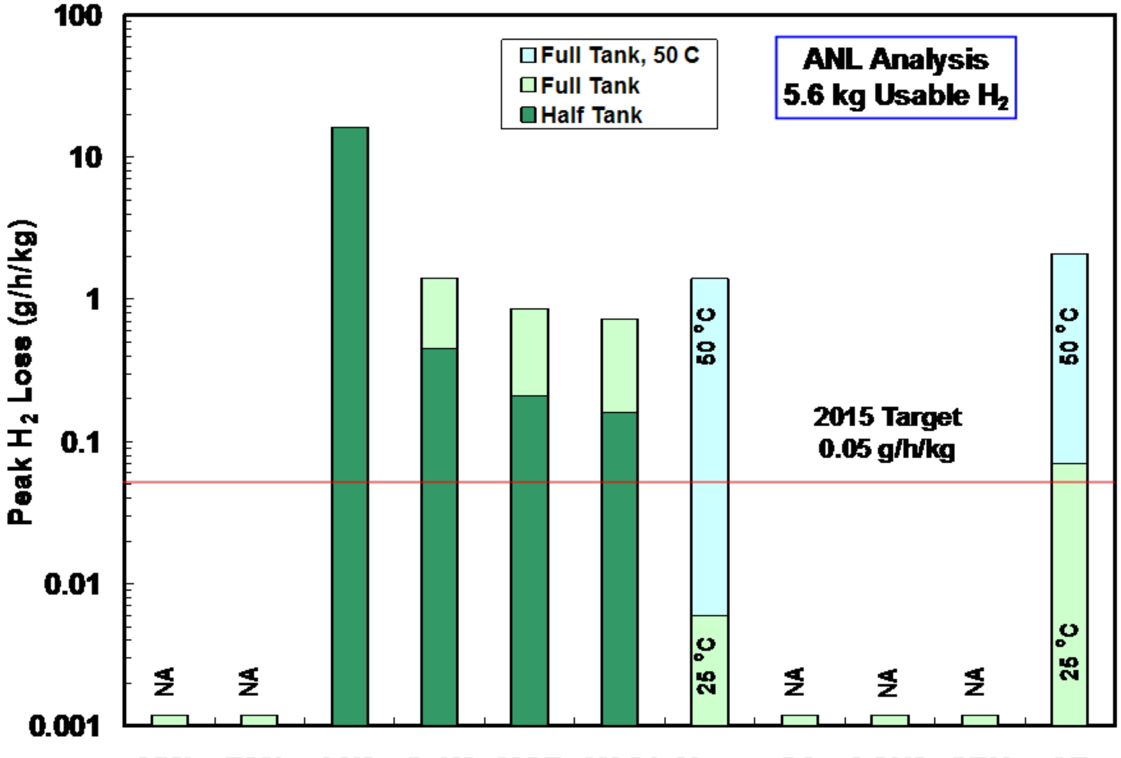


BOP: Balance of Plant

CDS: Charge-Discharge System

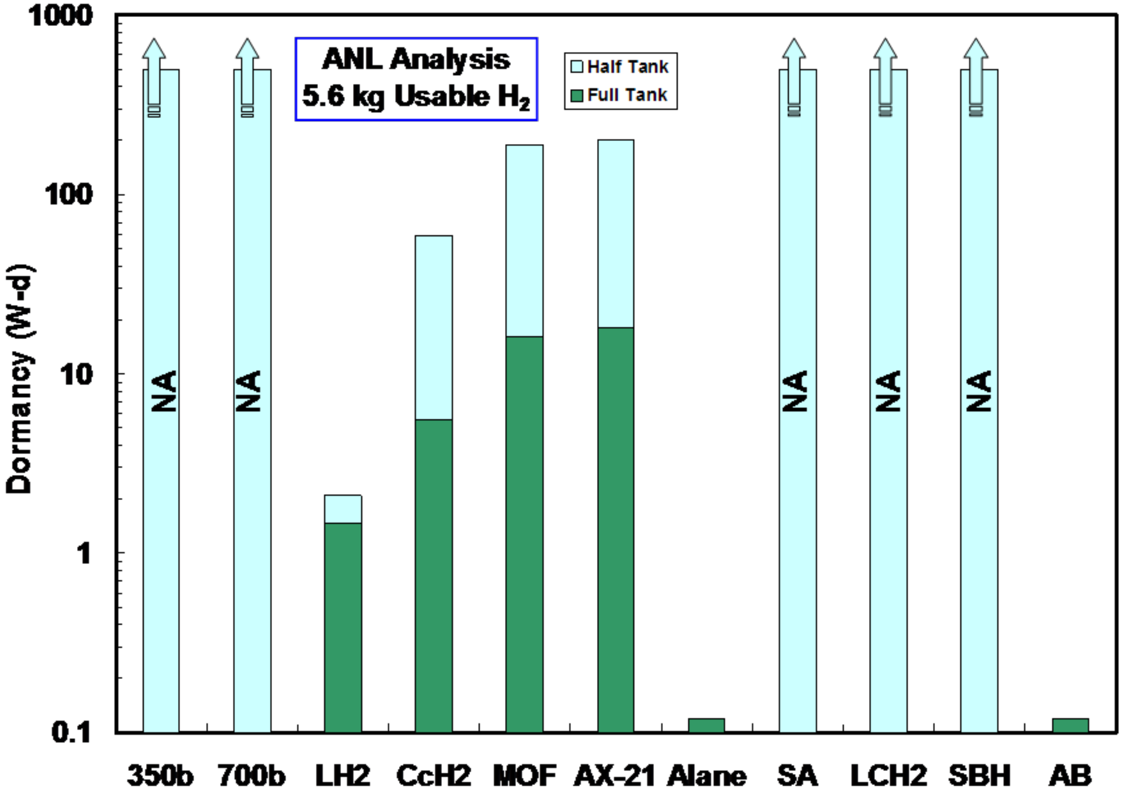
Hydrogen Loss During Extended Parking

- 40% of H_2 stored in LH_2 tank vented to ambient in a typical use cycle
- Negligible H_2 loss from insulated cryogenic pressure vessels with some daily driving
- H_2 loss from alane determined by kinetics and ambient temperature, not by heat transfer
- H_2 loss from AB/IL determined by kinetics, ambient temperature, and heat transfer coefficient



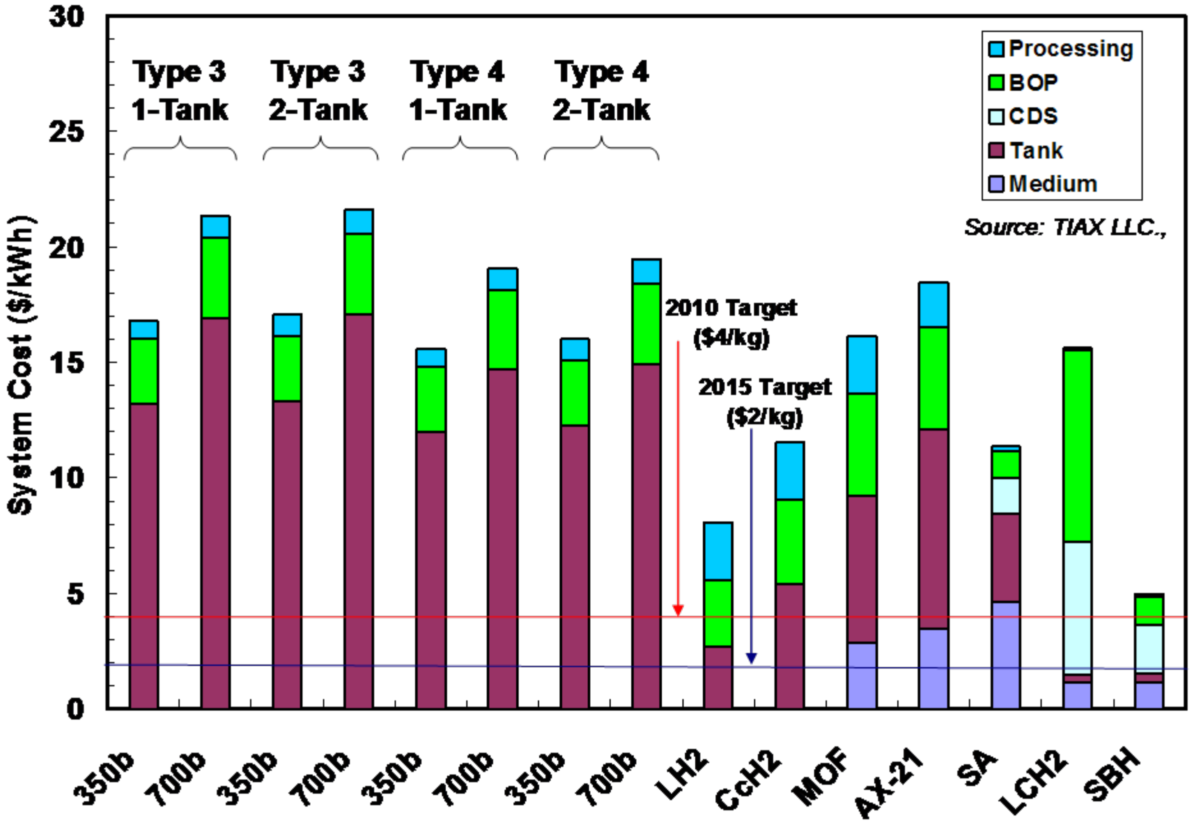
Dormancy

- Shorter dormancy in LH_2 system if the fuel tank is partially full
- Longer dormancy in CcH_2 system with partially-full tank, no stranded driver syndrome
- Longer dormancy in cryogenic sorbent systems than CcH_2 because of heat of desorption
- Dormancy definition not meaningful for alane and AB storage



Cost of On-Board Systems at High-Volume Manufacturing

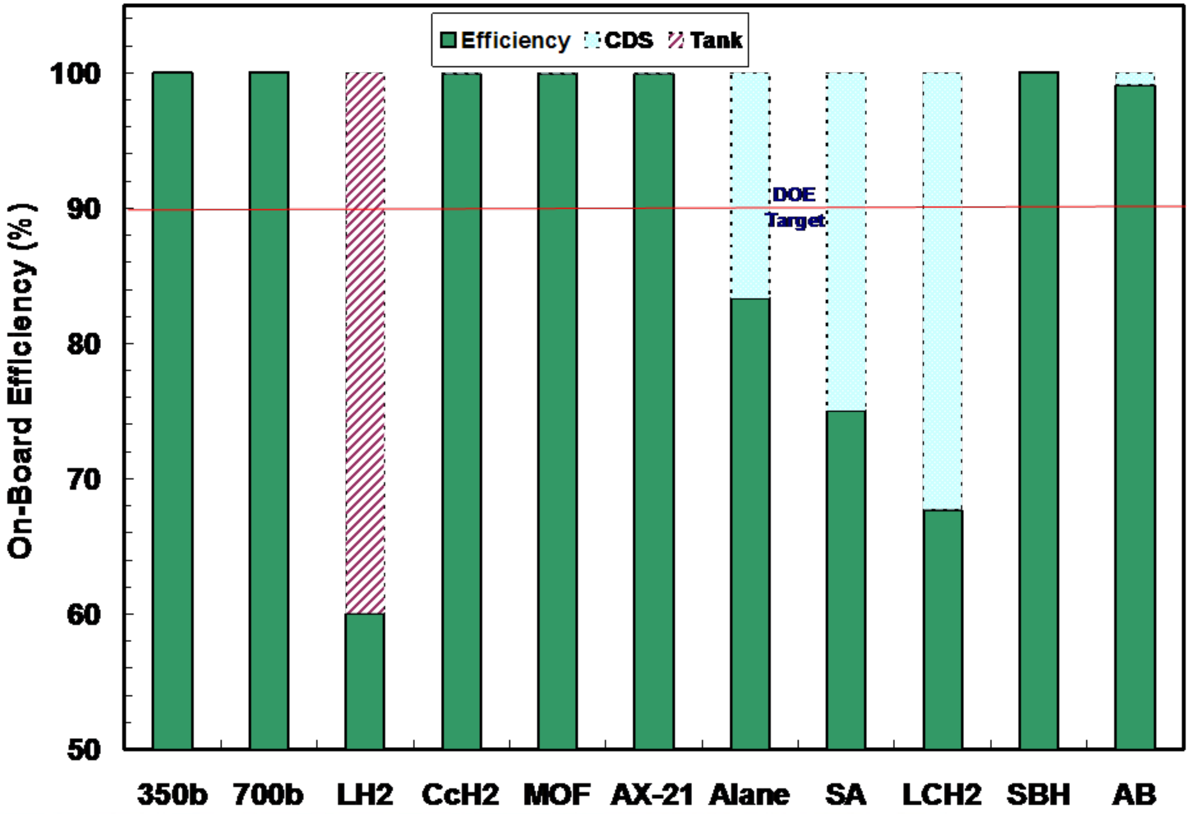
- Cost data from TIAX studies with ANL inputs, 500,000 units/year
- Fiber cost dominates in cH_2 systems, less expensive in cryogenic sorption systems
- Material cost important in sorption systems and in SA system
- Dehydrogenation catalyst cost important in LCH2 system



Consult TIAX reports for complete details, assumptions and background

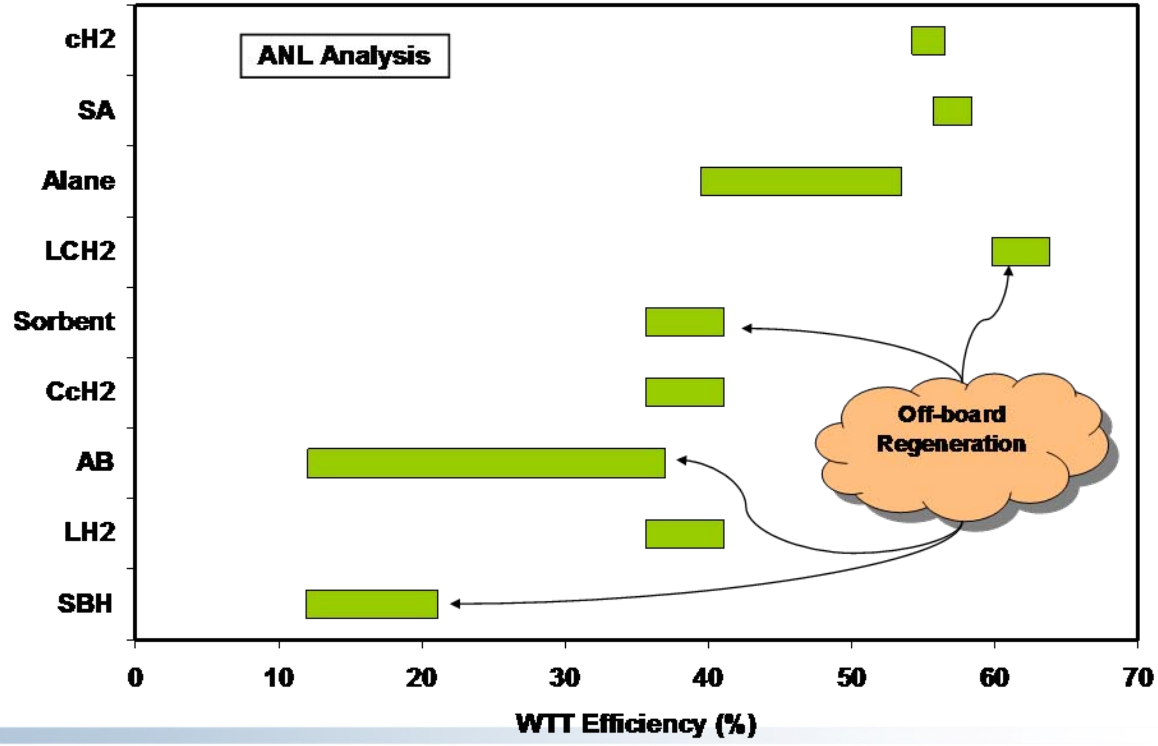
Efficiency of On-Board Systems

- Venting loss accounts for inefficiency of LH_2 system
- 10-30% H_2 consumed in alane, SA and LCH2 systems to sustain high-temperature endothermic reactions
- ~1% loss in AB system efficiency because of fuel pump, additional FCS coolant and radiator fan power
- DOE target for on-board system efficiency is 90%



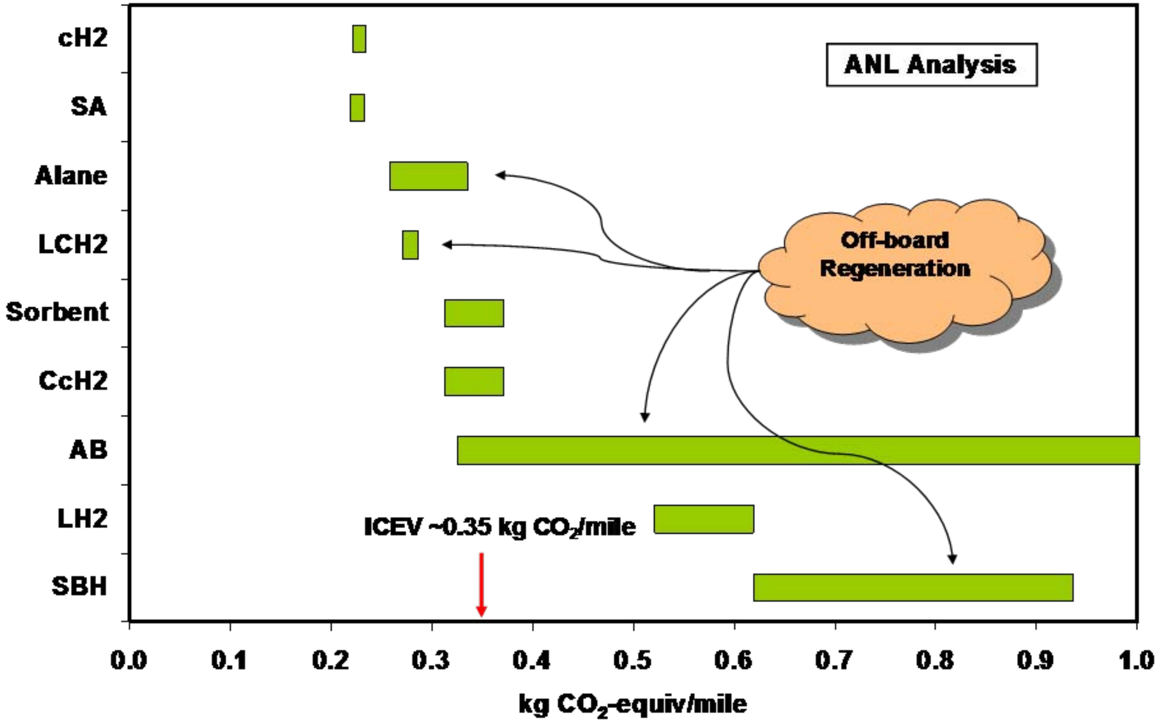
Well-to-Tank Efficiency

- 350- and 700-bar cH_2 options have <60% WTT efficiency
- Reversible metal hydrides may have higher WTT efficiency than cH_2
- LCH2 regeneration is exothermic and can reach 60% efficiency
- High uncertainty in alane regeneration efficiency because of vacuum distillation steps and low-grade waste heat requirement
- Options involving cryogenic H_2 have < 41% WTT efficiencies
- Low efficiencies for AB and SBH regeneration



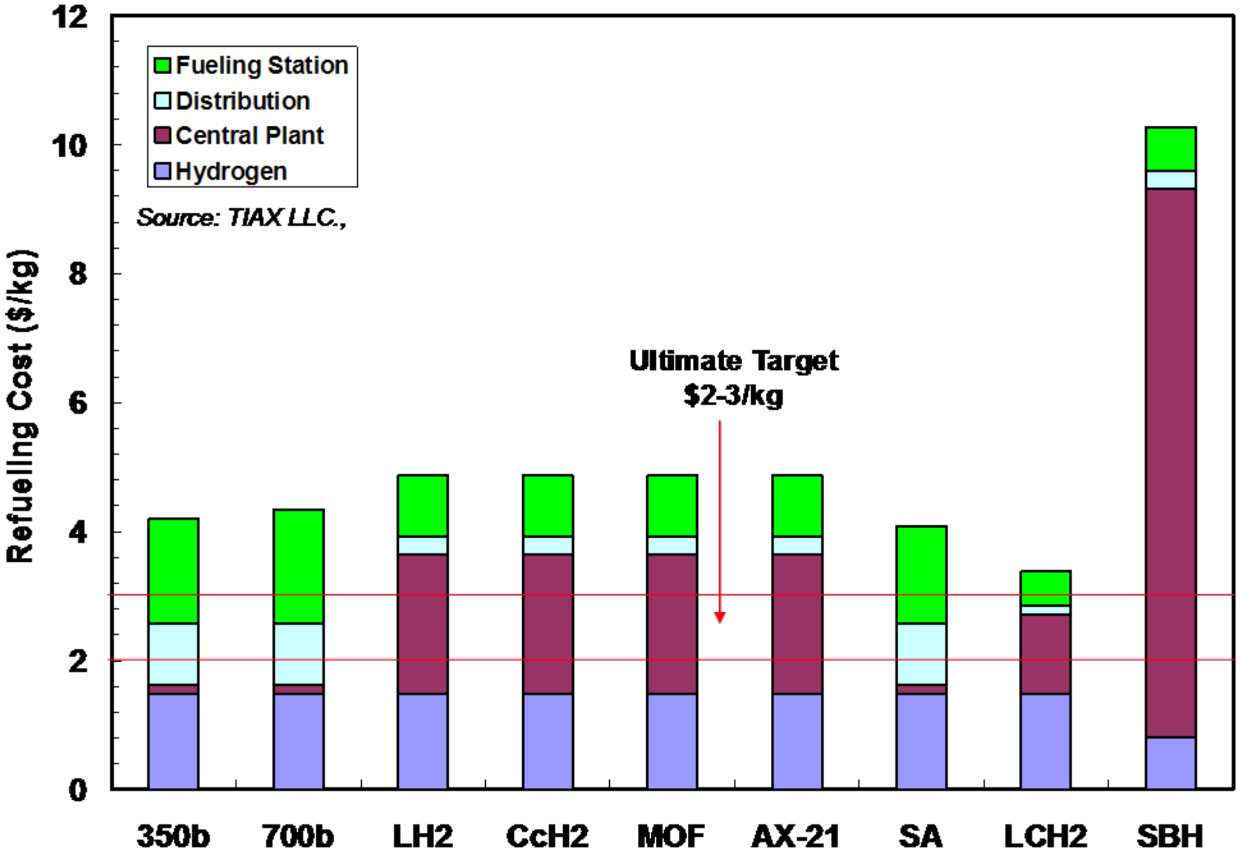
Greenhouse Gas Emissions

- Values given in kg of CO_2 equivalent per kg of H_2 delivered to the vehicle or per mile driven
  - 63.4 mpgge assumed fuel economy for 2015 advanced FC vehicle
- As reference, GHG emissions for 2015 mid-size ICE vehicle with 31 mpgge fuel economy is 0.35 kg-CO_2/mile



Refueling Cost

- H2A data for cost of unit operations, natural gas at \$0.22/Nm^3
- Liquefaction contributes significantly to the fuel cost in options requiring LH_2
- Regeneration is the main component of fuel cost in SBH option
- No storage option can meet the \$2-3/kg cost target (untaxed)



Source: TIAX LLC.,

Ultimate Target \$2-3/kg

Consult ANL and TIAX reports for complete details, assumptions and background