2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review

Hydrogen Delivery Infrastructure Analysis

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Argonne NATIONAL LABORATORY

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Overview

Timeline

- Start: FY 2007
- End: Determined by DOE

Barriers/Challenges

- A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis
- Reliability and Costs of Gaseous Hydrogen Compression
- Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Budget

- FY13 Funding: $250K
- Total FY14 Funding: $200K ($75K cost shared with Systems Analysis)
- 100% DOE funding

Partners

- GTI – P&ID
- PNNL – HDSAM updates

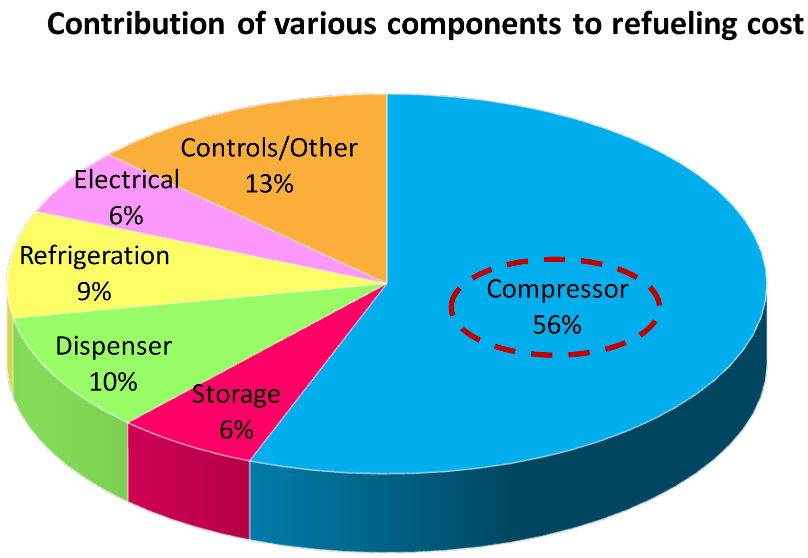
Collaborations

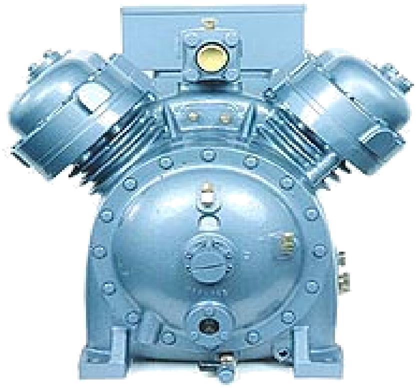
- Hexagon Lincoln – Tube Trailers
- PDC Machines – Compressor

Relevance/Impact

- Provide platform for comparing impacts of alternative delivery and refueling options on the cost of dispensed hydrogen
  - ✓ Identify cost drivers of current technologies for hydrogen delivery and refueling
  - ✓ Evaluate the potential of novel delivery concepts for refueling cost reduction
  - ✓ Evaluate role of high-pressure tube-trailers in reducing compression cost at HRS
  - ✓ Incorporate implications of SAE J2601 refueling protocol in the modeling of hydrogen refueling stations (HRS)
- Assist with FCT Office planning
  - ✓ Investigate delivery pathways with potential to achieve cost goals in MYRD&D
  - ✓ Assist with defining R&D areas for future funding priorities to achieve targeted performance and cost goals
- Support existing DOE-sponsored tools (e.g., H2A Components, H2A production, MSM, JOBS FC, GREET)
  - ✓ Collaborate with model developers and lab partners
  - ✓ Collaborate with industry for input and review

Compression is a major contributor to refueling cost – Relevance





- ✓ Shift the capital of the major components (i.e., compressor) to upstream of the refueling station where:
  - ➢ The capital has better utilization (serves multiple markets)
  - ➢ The capital benefits from economies of scale
  - ➢ The risk is distributed between different market segments

- ✓ High-pressure tube trailers can serve that purpose

Approach

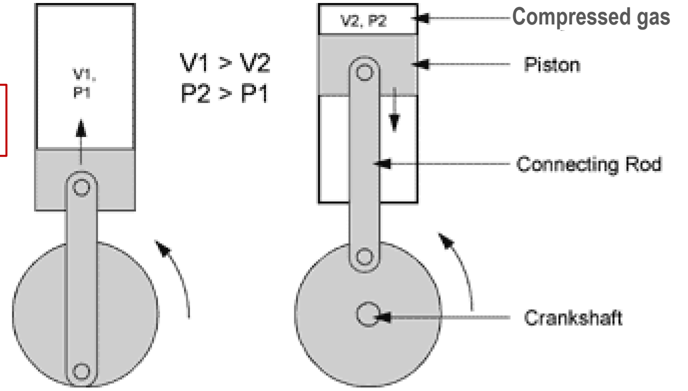
- **Examine** pros and cons of existing and new technology options for hydrogen delivery, including refueling
- **Identify** major cost drivers for hydrogen delivery
- Develop modeling structure to **optimize** delivery pathways and refueling systems
- **Simulate** performance of delivery system by solving physical laws (i.e., mass, momentum, and energy conservation) and implementing appropriate initial and boundary conditions
- **Collaborate** to acquire/review model inputs, analyze delivery and refueling options, and examine/review results
- Provide **thorough QA**
  - Internally via partners
  - Externally, via collaborators and through briefings to Tech Teams, early releases to DOE lab researchers, and industry interaction

Employ high pressure tube trailers to reduce the compressor size – Approach

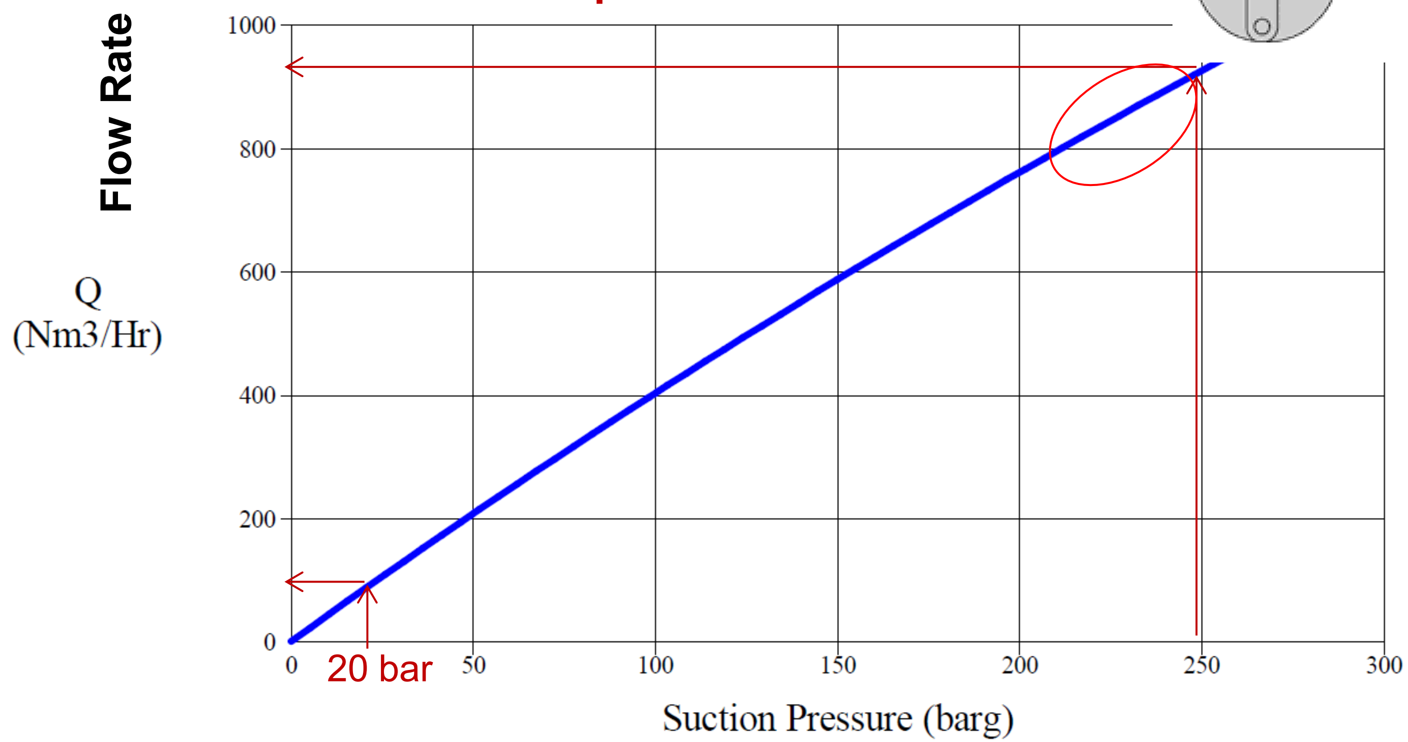
Mass flow rate = volume displacement x r.p.m. x density

Mass flow rate = volume displacement x r.p.m. x $[P/ZRT]_s$

Mass flow rate ~ suction pressure

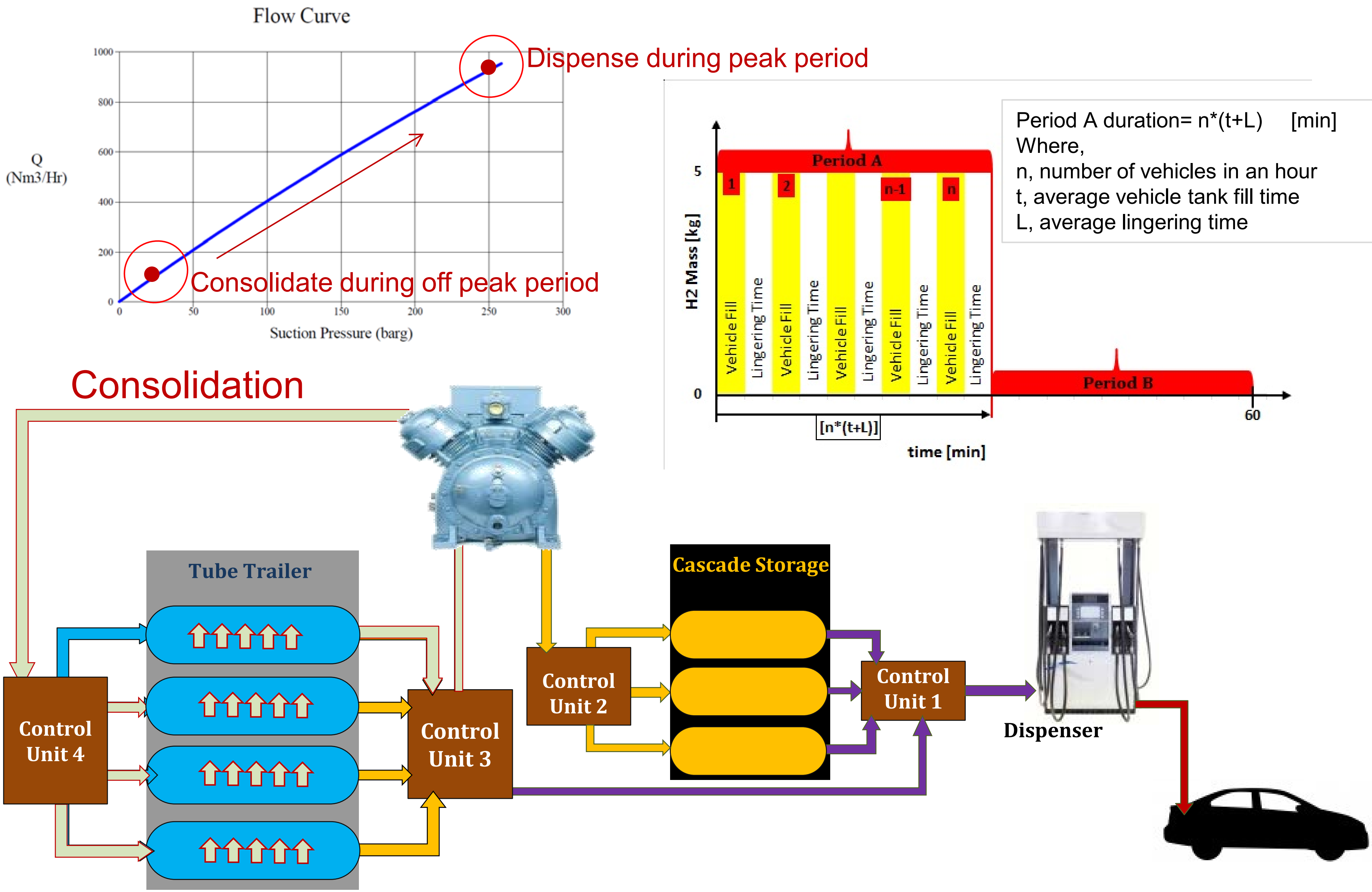


PDC Compressor Flow Curve



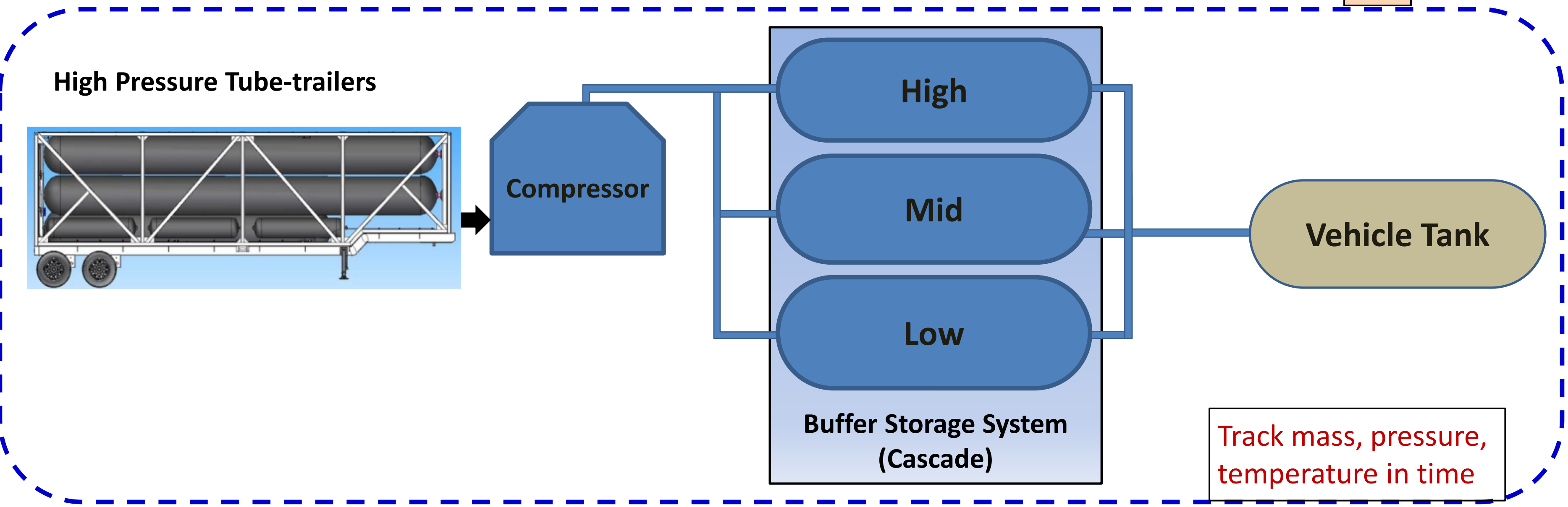
✓Higher pressure provided by the tube trailer to the compressor inlet (suction) produces much higher compression throughput

Tube trailer consolidation concept can reduce HRS compression – Approach



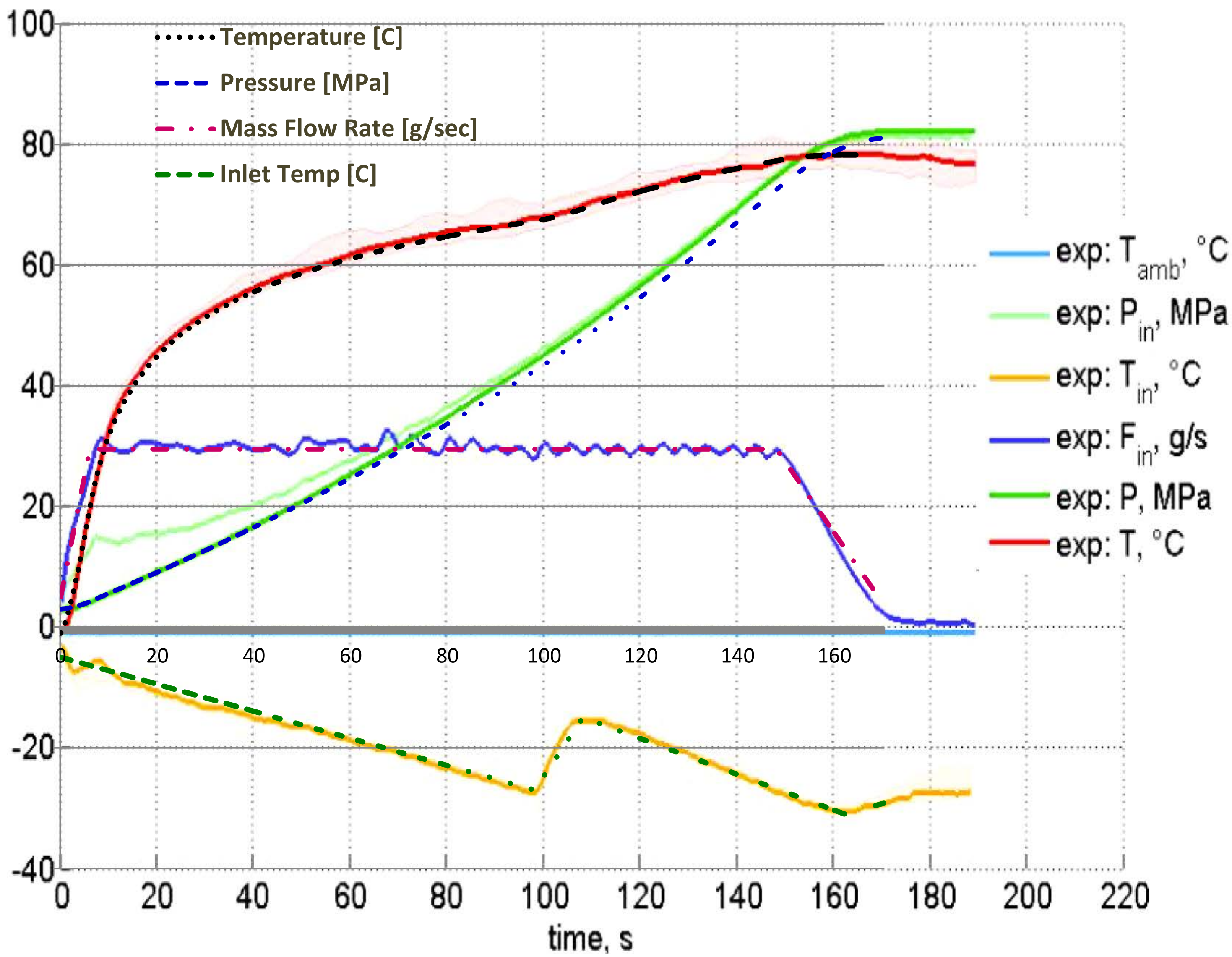
Solving physical laws – Approach/Accomplishment

- ❑ Continuity equation (mass balance)
- ❑ Flow equations (momentum conservation)
- ❑ Energy equation (1st Law of thermodynamics)
- ❑ Equation of state (P-V-T)
- ❑ Thermodynamics relations (internal energy, enthalpy, etc.)
- ❑ Heat transfer equations (at boundary)



✓Developed Hydrogen Station Cost Optimization and Performance Evaluation (H2SCOPE) model to accurately simulate vehicle fills and optimize refueling equipment sizing and selection

Simulation results were validated against published experimental data – Accomplishment

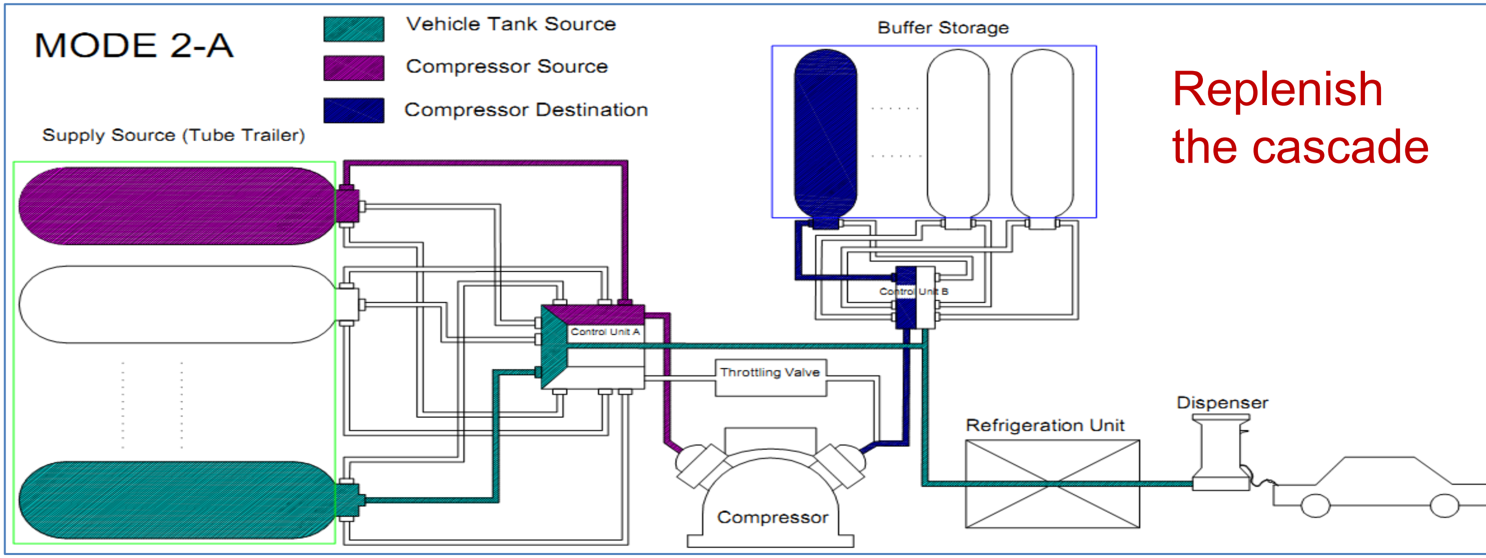


Experimental data source: "Immel 2011. Reprinted with permission from SAE paper 2011-01-1342 Copyright © 2011 SAE International."

Fill strategy – Approach

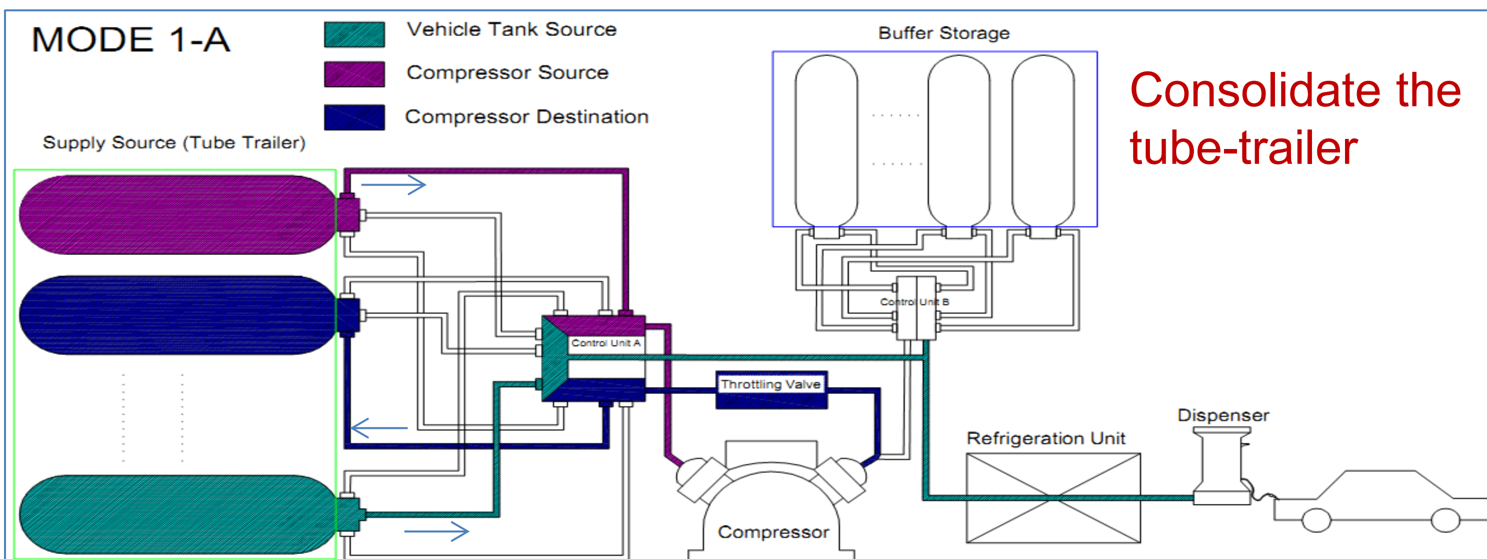
- Initially the vehicle tank is filled directly from the tube trailer
- While filling directly from tube trailer, the compressor can be used to:

Either



Replenish the cascade

OR

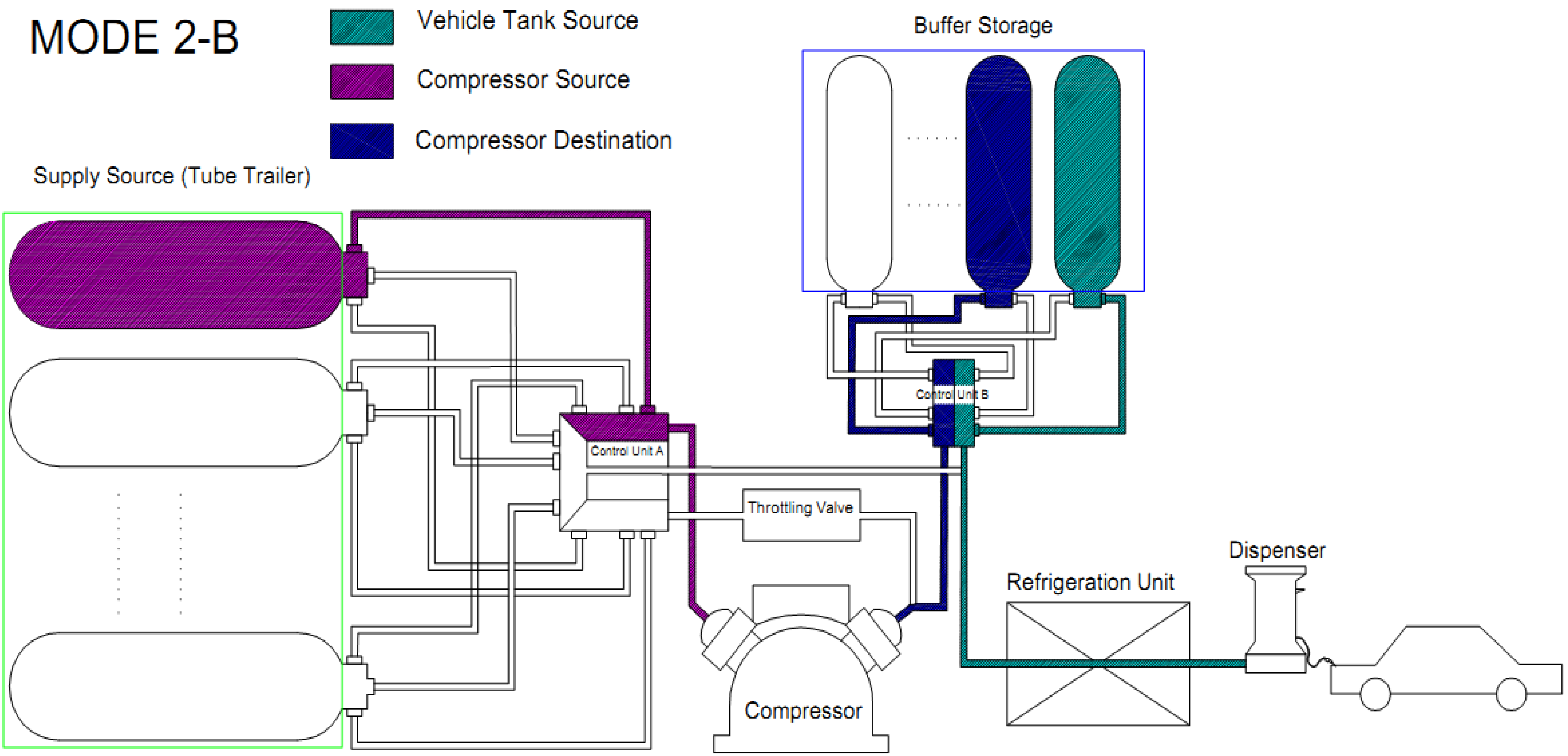


Consolidate the tube-trailer

✓Tube trailer for initial vehicle fill can reduce burden on refueling equipment

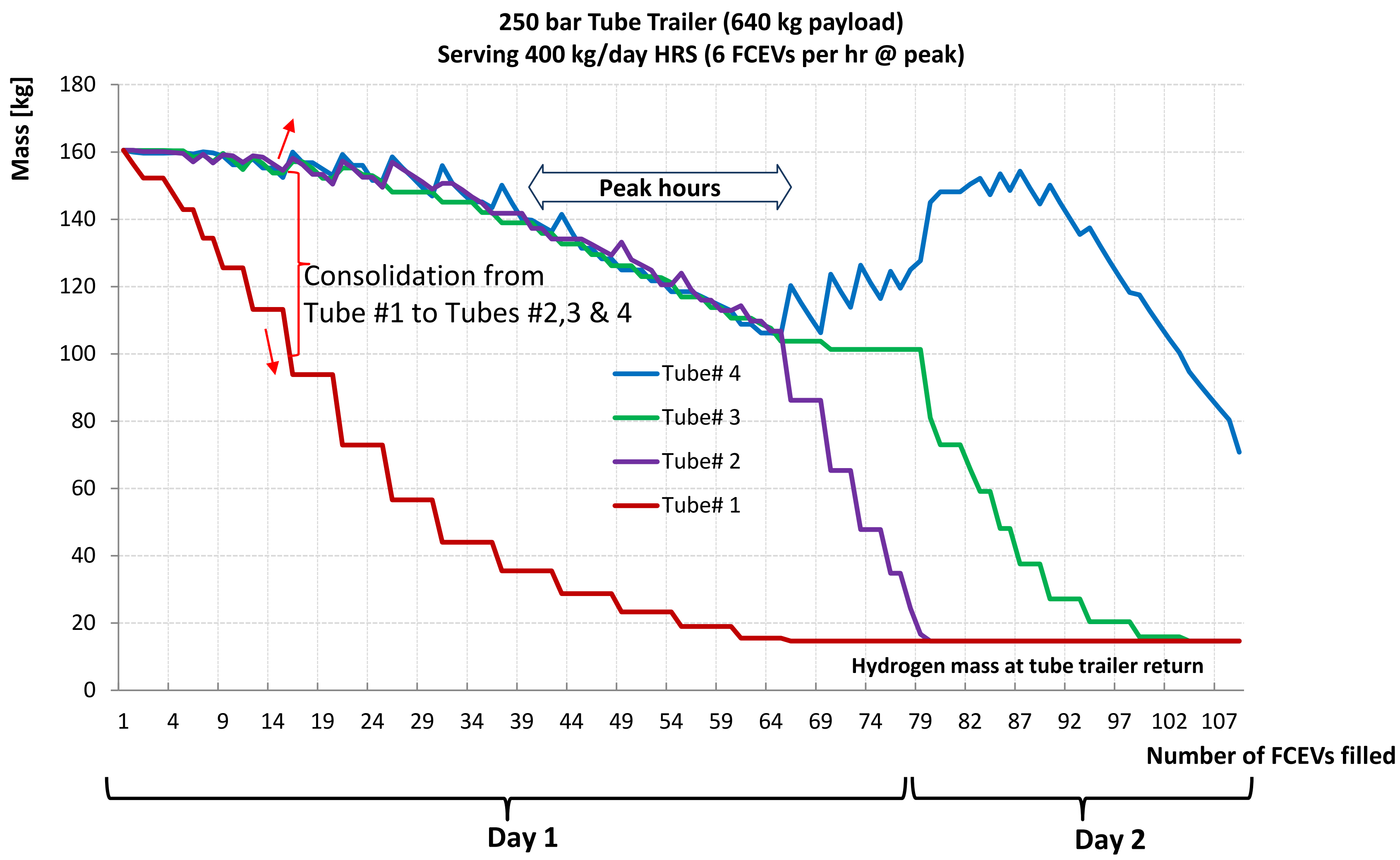
Fill strategy (continued) – Approach

- The vehicle fill is then completed from buffer storage



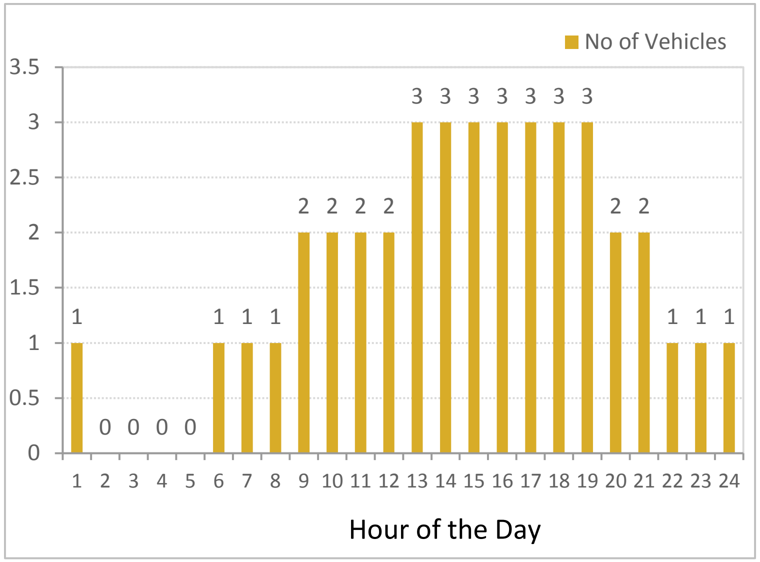
✓ Tube trailer consolidation allows for fast refueling during peak hours

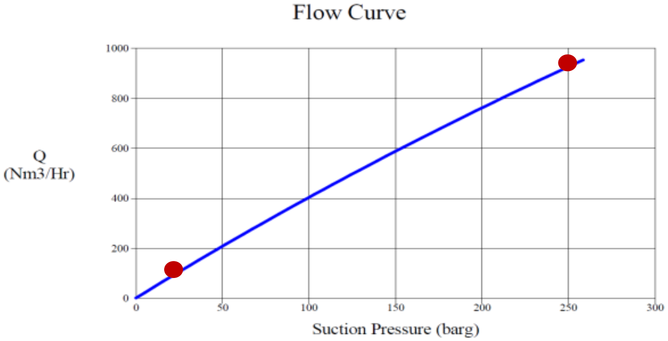
Consolidation strategy visualization – Accomplishment



✓*Tube trailer with consolidation strategy improves payload utilization*

Tube trailer H_2 consolidation strategy can triple the number of vehicle fills per day – Accomplishment





Operation Strategy	# of Vehicles Filled (Payload Utilization)	
Daily Vehicles' H2 Demand [kg/day]	Without Consolidation	With consolidation
100	121 (94%)	
150	121 (94%)	
200	21	110 (86%)
250		110 (86%)
300		110 (86%)
350		109 (85%)
400		109 (85%)
450		109 (85%)

- ✓ Without tube trailer consolidation, compressor satisfies up to <u>150 kg/day HRS</u>
- ✓ With tube trailer consolidation, compressor satisfies up to <u>450 kg/day HRS</u>

Tube trailer design optimization – Accomplishment

	Tube Trailer Configuration 1	Tube Trailer Configuration 2	Tube Trailer Configuration 3
Number of Tubes in Tube Trailer	4	14	24
TT Capacity [H2 in kg]	641	641	641
TT Capacity [vehicles]	128	128	128
Daily Vehicles' H2 Demand [kg/day]	# of Vehicles Filled (Payload Utilization)		
100			
150			
200	110 (86%)	117 (91%)	119 (93%)
250	110 (86%)	117 (91%)	120 (94%)
300	110 (86%)	118 (92%)	121 (94%)
350	109 (85%)	113 (88%)	114 (89%)
400	109 (85%)	113 (88%)	113 (88%)
450	109 (85%)	117 (91%)	117 (91%)

improved payload utilization

→

with increase in number of tubes

Increasing the number of tubes improves the payload utilization with the consolidation concept

Summary – Progress and Accomplishment

- 250 bar tube-trailers can reduce compression capacity at HRS by more than 50%
- Alternatively, 250 bar tube-trailers can satisfy 3x station daily demand using consolidation strategy
- Higher pressure tube-trailers (e.g., 350 bar and 500 bar) can realize greater benefits
- Consolidation strategy improves the utilization of the compressor capacity → more steady compressor operation → improved reliability
- Increasing the number of tubes in the ISO container improves payload utilization
- Need to evaluate cost trade off with upstream components

Response to Reviewers' Comments from 2013 AMR

Question 3: Collaboration and coordination with other institutions

Comment

- Regarding the hydrogen production companies as industry stakeholders, there should be an effort to approach and include their suppliers (and potential suppliers) to get more reliable cost information.

Response

- The project team acted upon the recommendation of the reviewers and collaborated with industry stakeholders on the project from concept, to data acquisition, and finally to soliciting critical input on the project outcomes.

Collaborations and Acknowledgments

Collaborators and Partners:

- Kareem Afzal, PDC Machines: provided valuable critical input, and compressor flow charts for a wide variety of compressor models
- Don Baldwin, Hexagon Lincoln: provided critical input, new ideas, and valuable information on a wide variety of tube-trailer configurations
- Tony Lindsay, Ted Barnes, and Ken Kriha, GTI: provided valuable information on process flow diagram, piping and instrumentation diagram, and control logic
- Daryl Brown, Pacific Northwest National Laboratory: Update refueling components cost estimates and update cost and price indices

Future Work

- Evaluate cost trade off between HRS and upstream components with consolidation concept
- Propose demonstration of consolidation concept
- Evaluate benefits of tube trailers with higher pressures (e.g., 350 and 500 bar, with different tube configurations) to HRS cost
- Evaluate benefits of high-pressure cryo-pumps (as alternative to compressors) to 700 bar HRS served by liquid deliveries
- Update Hydrogen Delivery Scenario Analysis Model (HDSAM) with updated data and cost information for early markets based on accomplishments by Argonne and other DOE laboratories
- Continue to provide technical support to FCT Office, hydrogen community, and interact with industry stakeholders

Planned updates to Hydrogen Delivery Scenario Analysis Model (HDSAM) - Future Work

- Update key statistics for calculating market demand of hydrogen with vehicle penetration scenarios
- Update cost of major refueling equipment (i.e., compression, storage, refrigeration/HX, and dispensing)
- Update station footprint evaluation (size and cost) in collaboration with Codes and Standards Tech Team (CSTT)
- Develop near-term modeling capabilities of HRS
  - Define station daily capacities and peak hourly demand
  - Cost of equipment (e.g., compressor, storage, dispenser) at low production volume
  - Incorporate current knowledge of equipment reliability (e.g., hoses and compressors)
  - Develop ramp up of station utilization with FCEV deployment scenarios
  - Investigate IRR scenarios (hedging against investment risk)
- Update fuel and electricity prices based on latest EIA/AEO data
- Use price and cost indices to allow selection of reference year $ for delivery cost up to [2013$]

Project Summary

- **Relevance:** Identify cost drivers of current technologies for hydrogen delivery and refueling. Evaluate the potential of novel delivery concepts for refueling cost reduction. Evaluate role of high-pressure tube-trailers in reducing compression cost at HRS. Investigate delivery pathways with potential to achieve cost goals in the Hydrogen Delivery MYRD&D plan.
- **Approach:** Develop a new strategy for operating high-pressure tube-trailers to reduce compression cost at HRS. Developed a model (H2SCOPE) that solves the physical laws to ensure sizing of refueling components consistent with the SAE J2601 refueling protocol. The model is capable of sizing components to minimize refueling cost for a given refueling demand.
- **Collaborations**: Collaborated with experts from the industry with knowledge and experience on delivery and refueling components relevant to this project. Acquired information needed for the simulations and received valuable input and suggestions to complete our project.
- **Technical accomplishments and progress:**
  - Identified a new tube-trailer consolidation strategy to reduce compression cost and increase the number of vehicle fills at HRS
  - Quantified the benefits of high-pressure tube-trailers to the cost reduction of hydrogen refueling
- **Future Research**: Evaluate cost trade off between HRS and upstream components with consolidation concept. Evaluate benefits of tube trailers with higher pressures (e.g., 350 and 500 bar, with different tube configurations) to HRS cost. Evaluate benefits of high-pressure cryo-pumps (as alternative to compressors) to 700 bar HRS served by liquid deliveries.

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Project PD14