2014 DOE Hydrogen and Fuel Cells Program Annual Merit Review

Analysis of Incremental Fueling Pressure Cost

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AN045

Overview

Timeline

- ☐ Start: October 2013
- ☐ End: September 2014

Barriers/Challenges

- ☐ A. Lack of hydrogen/carrier and infrastructure options analysis
- ☐ Cost and efficiency of delivery components
- ☐ Reliability and costs of gaseous hydrogen compression
- ☐ Lack of appropriate models and tools/stove-piped analytical capability

Budget

- ☐ FY13 Funding: N/A
- ☐ Total FY14 Funding: $150K ($75K cost shared with Delivery Program)
- ☐ 100% DOE funding

Partners

- ☐ Pacific Northwest National Lab

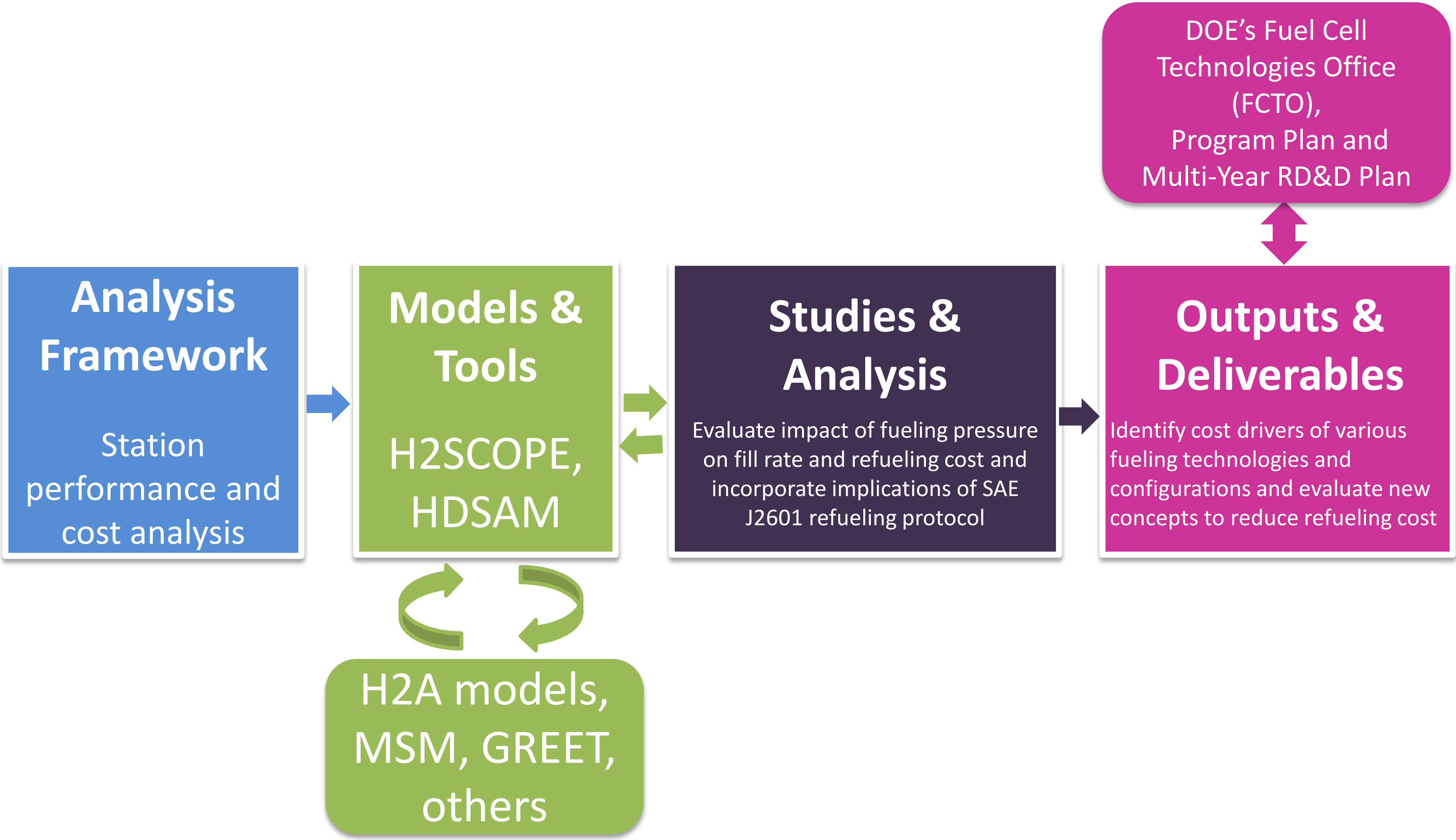
Collaborations

- ☐ ORNL
- ☐ Industry stakeholders

Relevance/Impact

- ☐ Provide a platform for comparing impact of alternative refueling methods and fueling pressures on the cost of dispensed hydrogen
  - ✓ Evaluate impact of fueling pressure on fill rate and refueling cost
  - ✓ Incorporate implications of SAE J2601 refueling protocol in the modeling of hydrogen refueling stations (HRS)
  - ✓ Identify cost drivers of various fueling technologies and configurations
  - ✓ Evaluate the potential of novel concepts to reduce refueling cost
- ☐ Assist in FCTO planning
  - ✓ Investigate delivery and refueling options with potential to achieve cost goals in MYRD&D
  - ✓ Assist with defining R&D areas for future funding priorities to achieve performance targets 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

Modeling impact of incremental fueling pressure on refueling cost – Approach



DOE's Fuel Cell Technologies Office (FCTO),
Program Plan and Multi-Year RD&D Plan

Analysis Framework

Station performance and cost analysis

Models & Tools

H2SCOPE, HDSAM

H2A models, MSM, GREET, others

Studies & Analysis

Evaluate impact of fueling pressure on fill rate and refueling cost and incorporate implications of SAE J2601 refueling protocol

Outputs & Deliverables

Identify cost drivers of various fueling technologies and configurations and evaluate new concepts to reduce refueling cost

Approach

- ☐ Develop modeling structure to **optimize** delivery pathways and refueling systems
- ☐ **Simulate** performance of refueling system by solving physical laws (i.e., mass, momentum, and energy conservation) and implementing appropriate initial and boundary conditions
- ☐ **Examine** pros and cons of existing and new refueling options
- ☐ **Identify** major cost drivers for hydrogen fueling
- ☐ **Collaborate** to acquire/review model inputs, analyze 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

Evaluate various fueling pressures: 350, 500 and 700 bar – Relevance/Approach

I. Determine precooling requirement for various fill rates and capacities

- ❑ Key issues on the vehicle side
  - ➢ Tank characteristics:
    - ❖ Type III or IV
    - ❖ Tank configuration (number, diameter, length, thickness)
    - ❖ Thermal properties (thermal conductivity, specific heat, density)
  - ➢ Boundary conditions:
    - ❖ Ambient (and pre-soaking) temperature
    - ❖ Convective heat transfer (H.T. coefficient)
    - ❖ Inlet temperature and flow rate (interface with supply side)
    - ❖ Maximum mass, pressure and temperature at end of fill

II. Determine size and cost of refueling equipment, and $/kg$_{H2}$

- ❑ Key issues on the fueling (supply) side
  - ➢ Precooling requirement, and cost
  - ➢ Cost of storage
  - ➢ Cost of compression
  - ➢ Cost of dispensing

Define vehicle tank characteristics: Dimensions – Relevance/Approach

- Tank dimensions (single tank):
  - 700 bar (5 kg) from GM SAE paper, Immel 2011 (Type IV)
  - Fueling pressure of 350 and 500 bar in same tank as 700 bar (3 and 4 kg, respectively)

Vehicle Tank			
Fueling Pressure	700 bar	500 bar	350 bar
Capacity	5 kg_{H2}	4 kg_{H2}	3 kg_{H2}
Outer Diameter [inch]	19.5		
Thickness [inch]	1.83		
Tank Length [inch]	49.2		
Liner Thickness [inch]	0.20		
Volume [L]	129		

Define vehicle tank characteristics: Thermal properties – Relevance/Approach

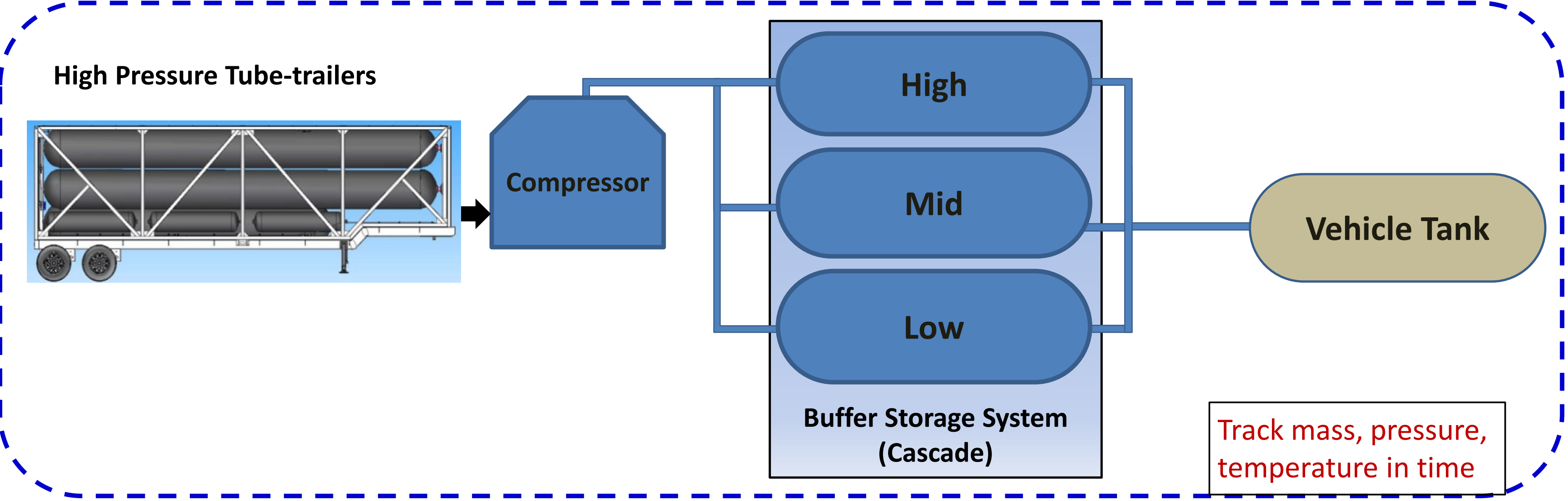
Vehicle Tank		
	Composite	Liner
	Temperature Range (-100°C to 140°C)	Type IV (PE, -100°C to 140°C)
Density [kg/m^3]	1550	975
Specific Heat [J/kg-K]	500 – 1500	1000 – 3000
Thermal Conductivity [W/m-K]	0.3 – 0.8	
Thermal Diffusivity [cm^2/sec]	0.001 – 0.009	

Define vehicle tank initial and boundary conditions – Relevance/Approach

Vehicle Tank	
Initial Pressure	2 [MPa] Other initial pressures are modeled (5 and 10 MPa)
Initial (= Ambient) Temperature	298 [K] Hot soak condition (+15°C) is also modeled
Maximum Pressure	1.25 x Service Pressure (700 bar)
Maximum Temperature	358 K [85°C]
Convective H.T. Coefficient [W/m^2K]	325 (inside), 5 (outside)
Inlet Temperature	Precooled to 0, -10, -20, -30, and -40°C
Fill Strategy	Constant Pressure Ramp Rate (Other filling methods are being considered)

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)



High Pressure Tube-trailers

Compressor

High

Mid

Low

Buffer Storage System (Cascade)

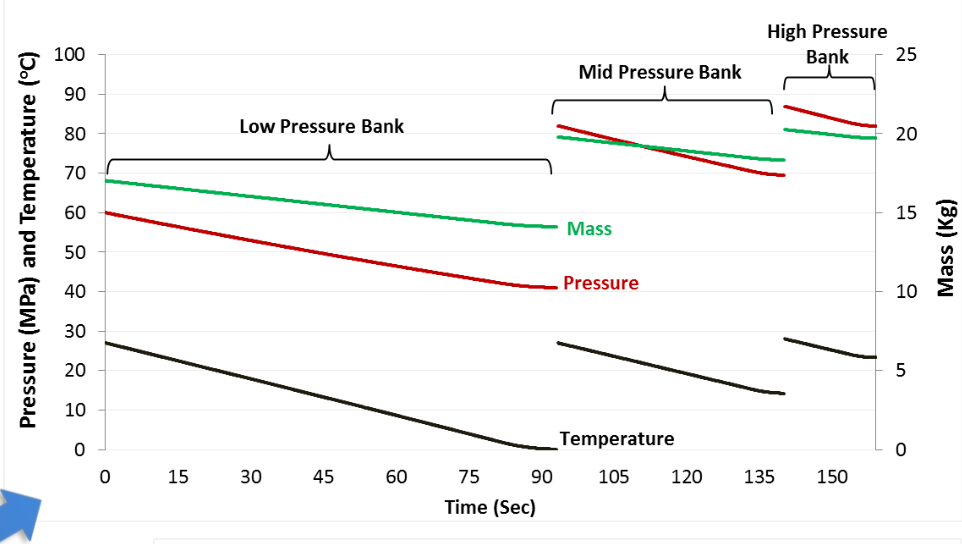
Vehicle Tank

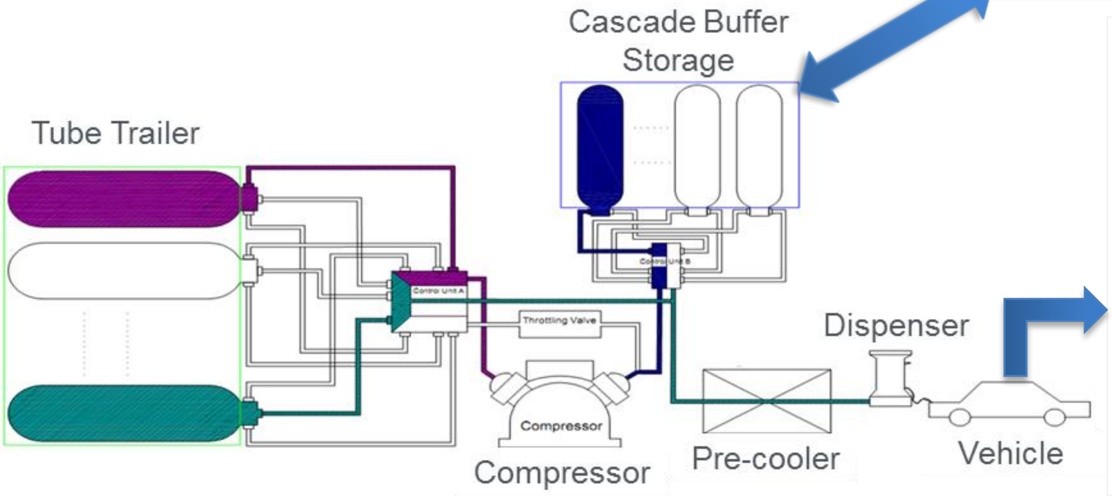
Track mass, pressure, temperature in time

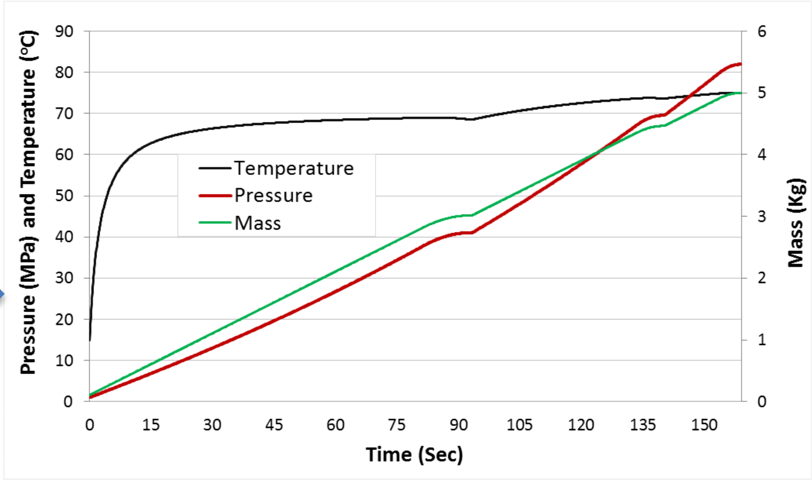
✓Developed Hydrogen Station Cost Optimization and Performance Evaluation (H2SCOPE) model to accurately simulate vehicle fills and optimize refueling equipment sizing and selection

H2SCOPE tracks mass, temperature, and pressure between refueling components and within vehicle's tank – Approach

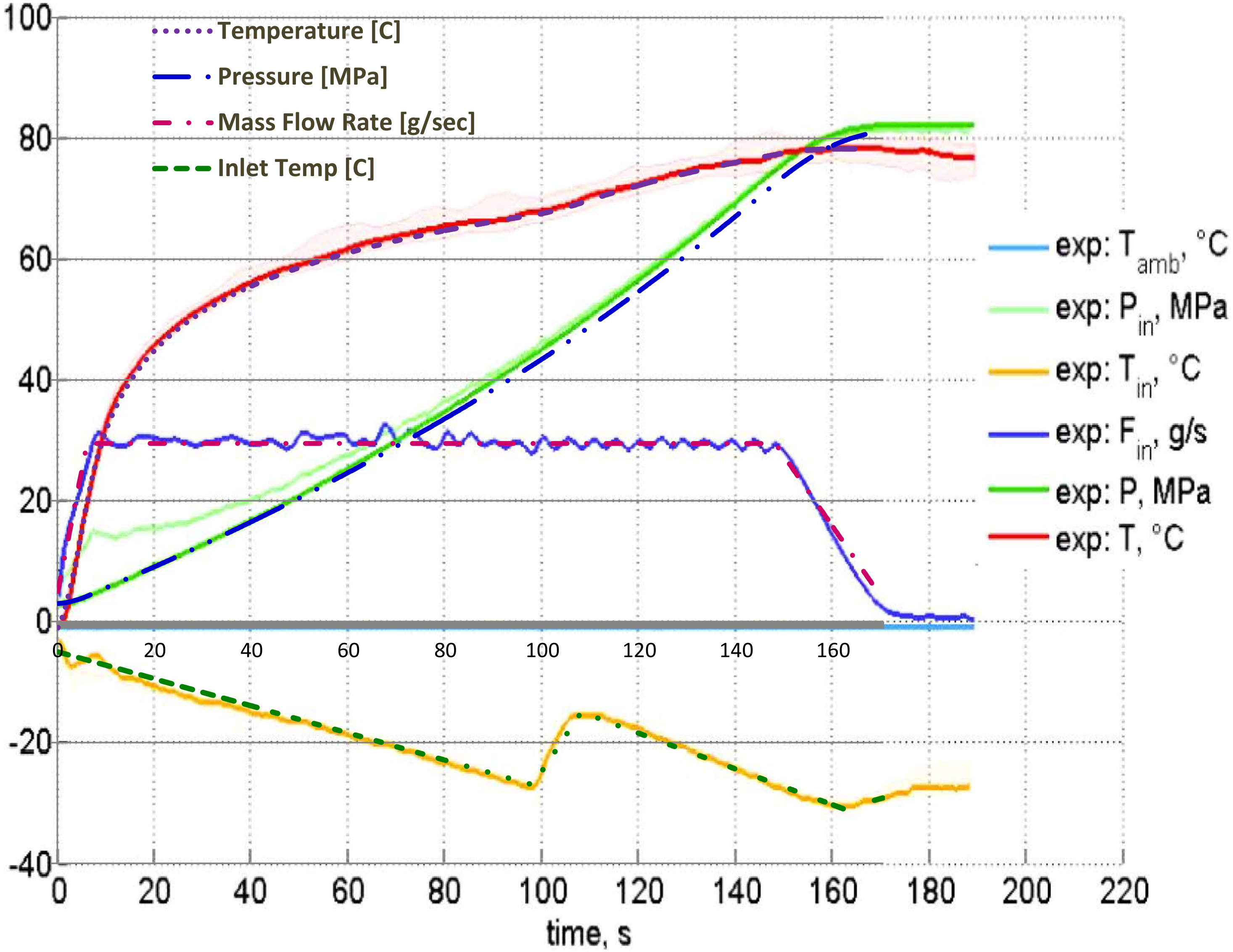
- Solve physical laws (conservation of mass, momentum and energy)
- Simulate various refueling methods (e.g., SAE J2601, MC method, etc.)







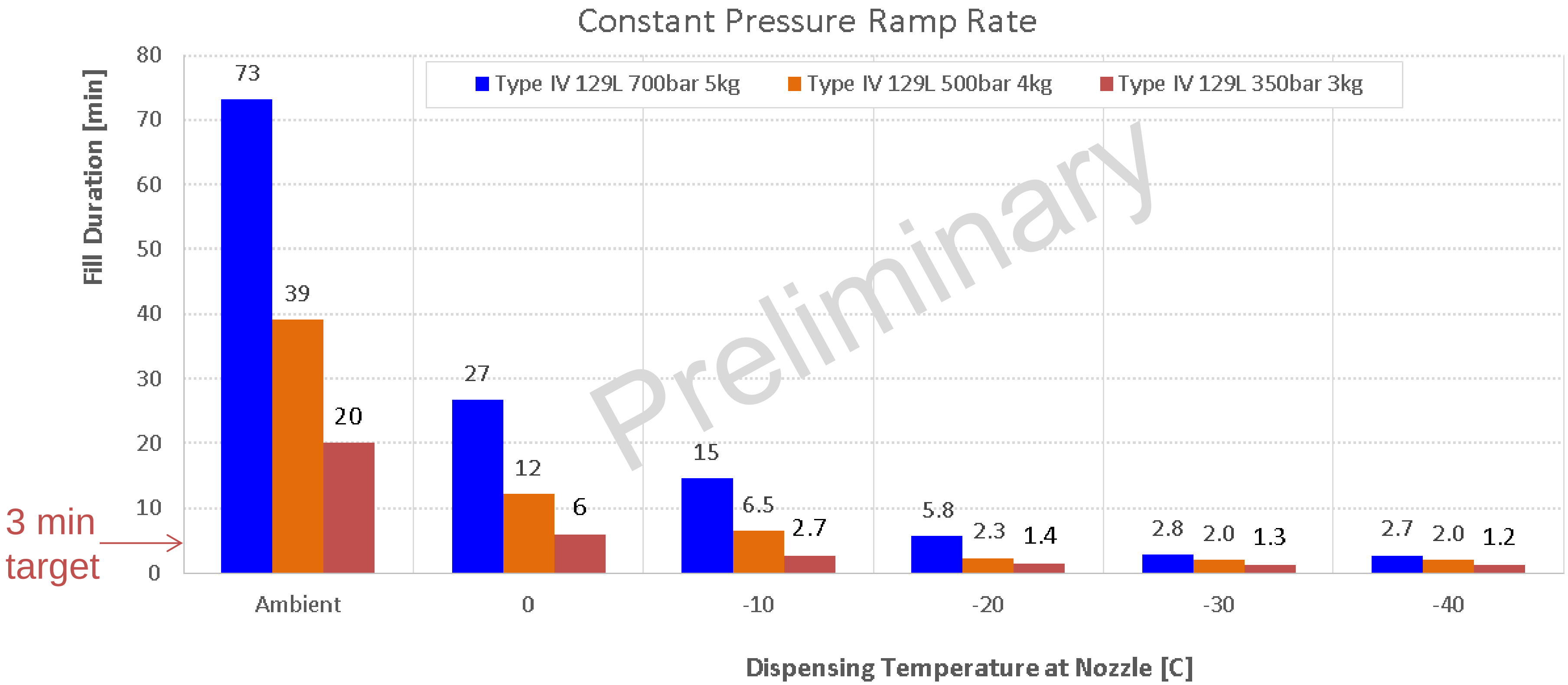
Simulation results were validated against published experimental data – Accomplishment



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

Impact of fueling pressure on fill duration

Fueling pressure greatly impacts fill duration at elevated precooling temperature – Accomplishment

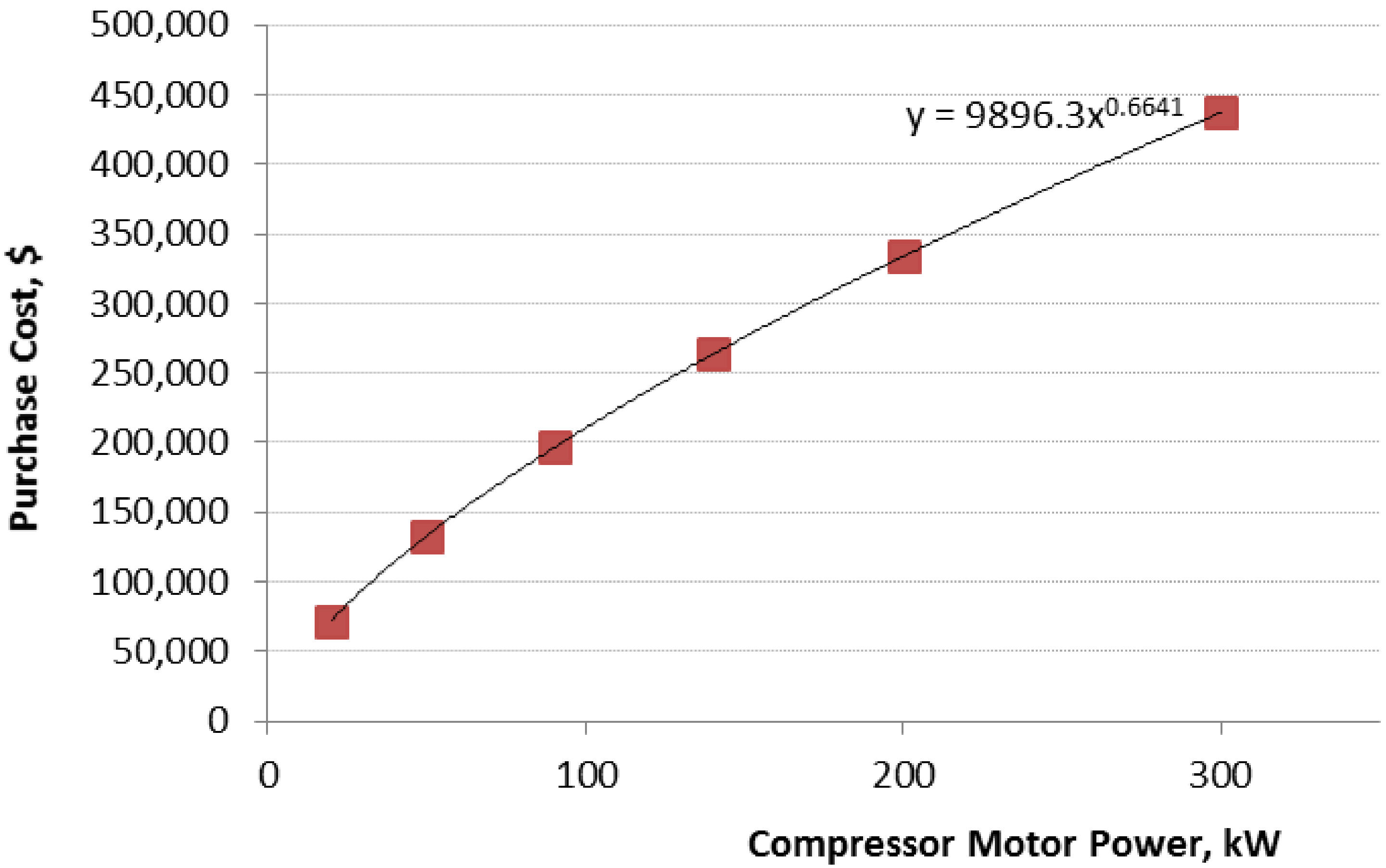


- *Vehicle's tank presoaked in (ambient + 15°C)*

Cost of Major Refueling Equipment

(compression, storage, refrigeration and dispenser)

Cost of compressor is a major investment in HRS (volume production) – Accomplishment



- ➢ 500 bar compressor is only 10% less costly than 700 bar compressor
- ➢ 350 bar compressor assumed 20% less costly than 700 bar compressor

Cost of cascade buffer storage is another major expense (volume production) – Accomplishment

950 bar (for 700 bar fueling)

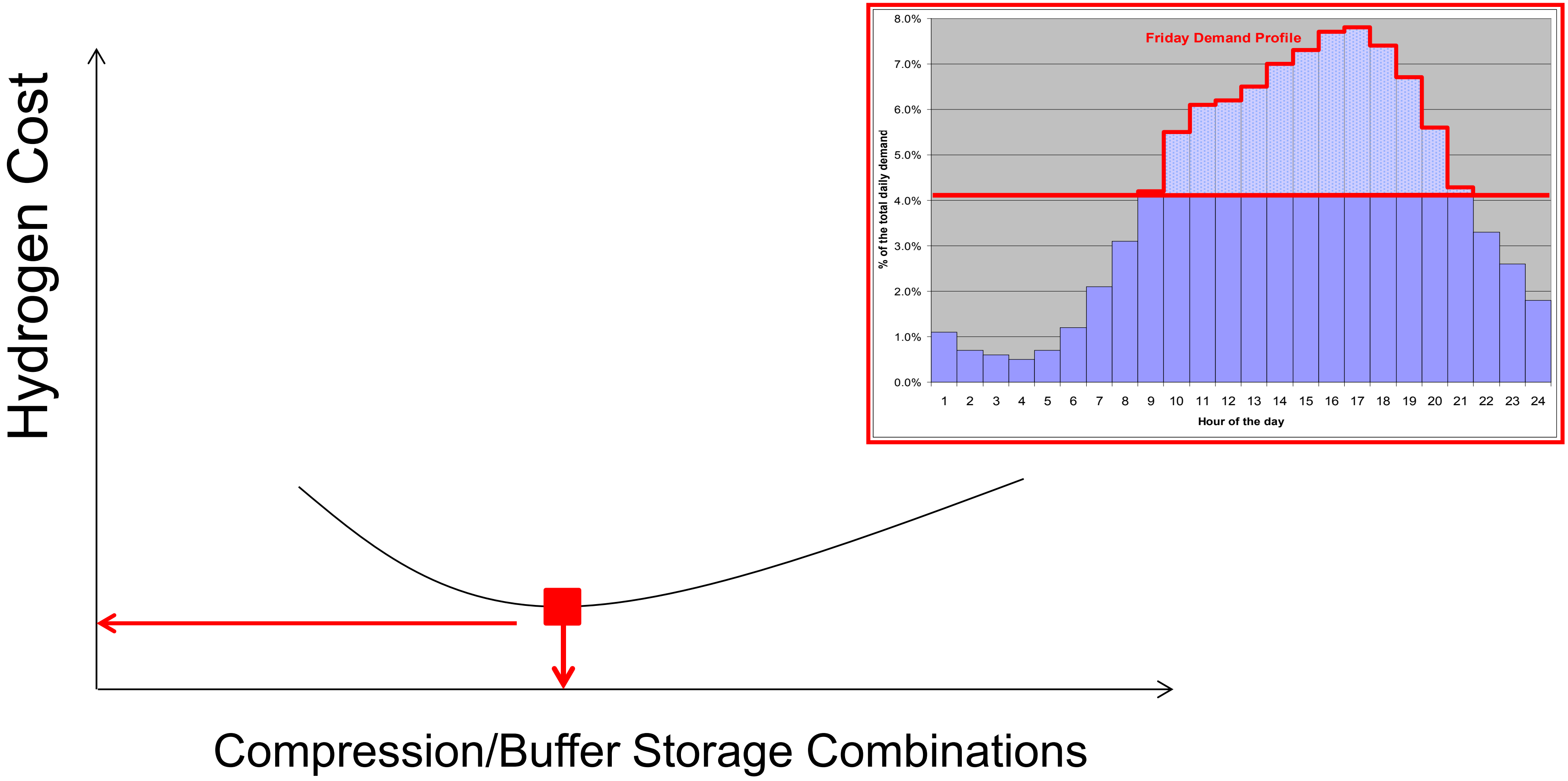
- Type II tank : $1200-$1800/kg
  - Tank length 14.5-29 ft
- Type IV Tank: $1500/kg (used in this analysis)

700 bar (for 500 bar fueling)

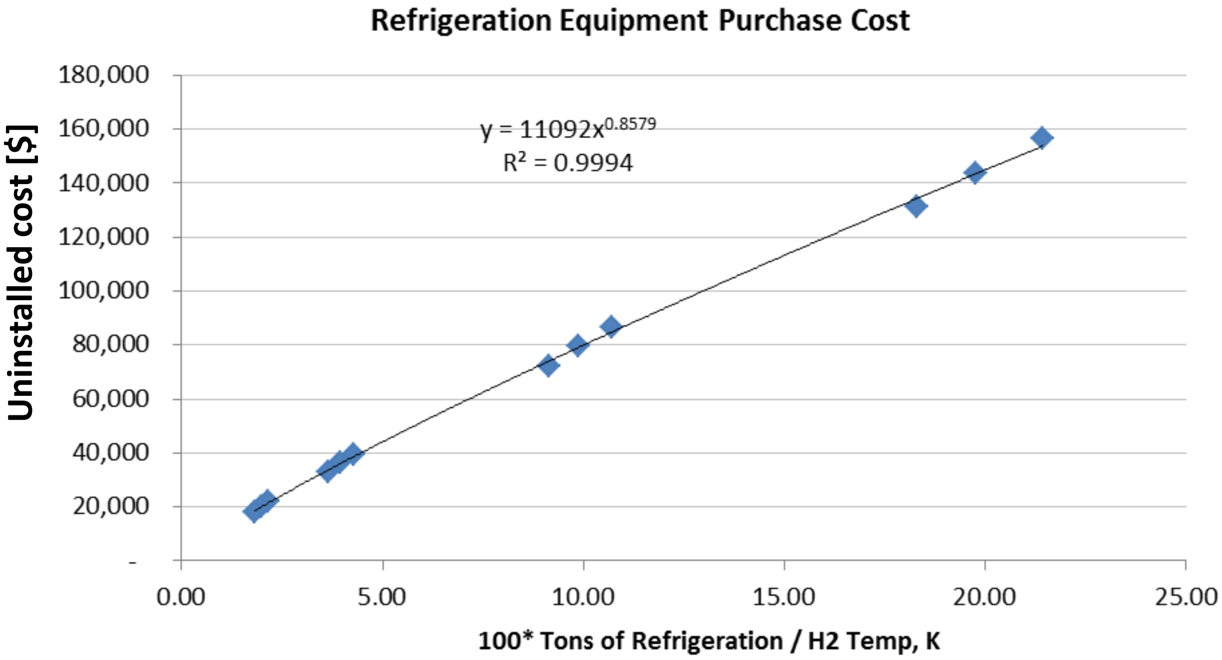
- Type II tank : $800-$1600/kg
  - Tank length 14.5-29 ft
- Type IV Tank: $1000/kg (used in this analysis)

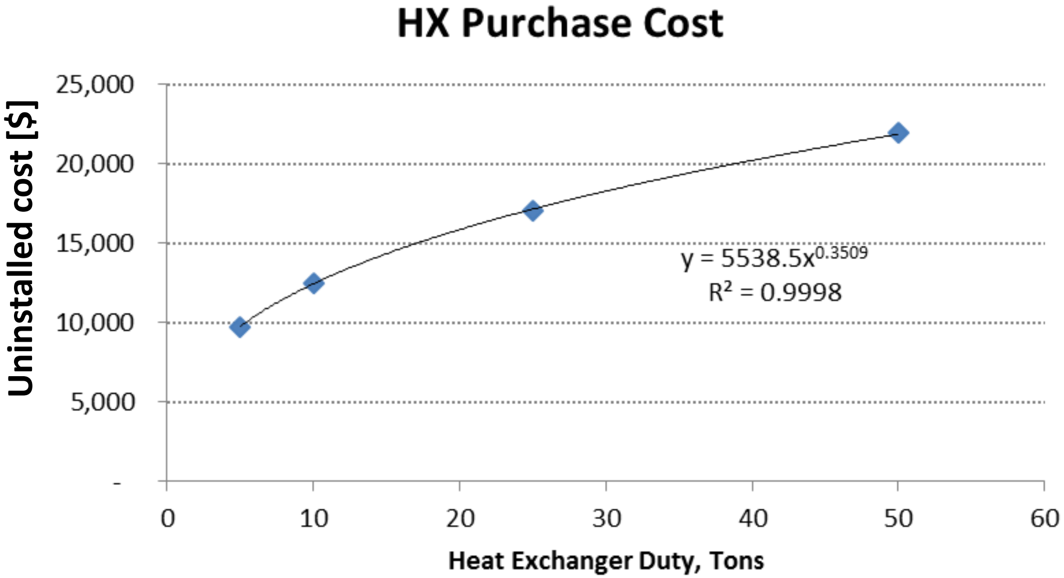
Model optimizes station configuration by minimizing cost of compression/ buffer storage combination — Approach/Accomplishment

- ✓ *Peak demand can be satisfied by either more storage or more compression throughput → optimization is needed*



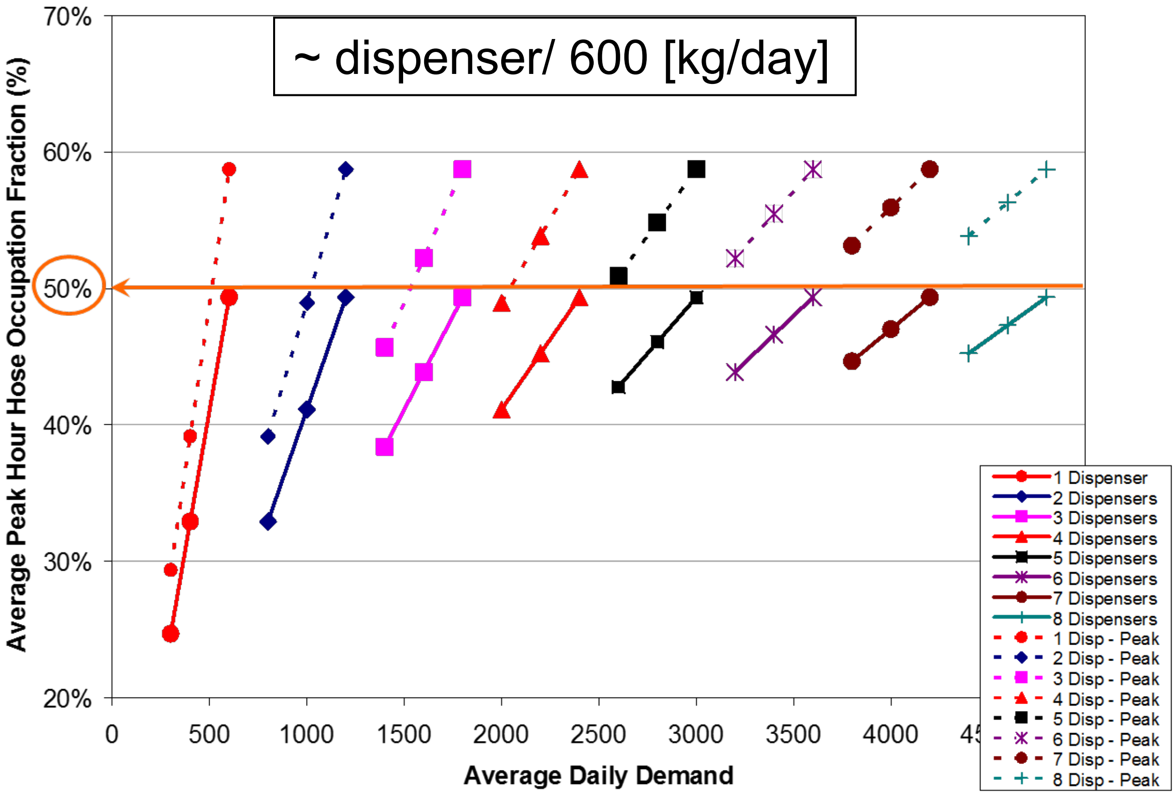
Refrigeration cost is a strong function of precooling temperature (volume production) – Accomplishment



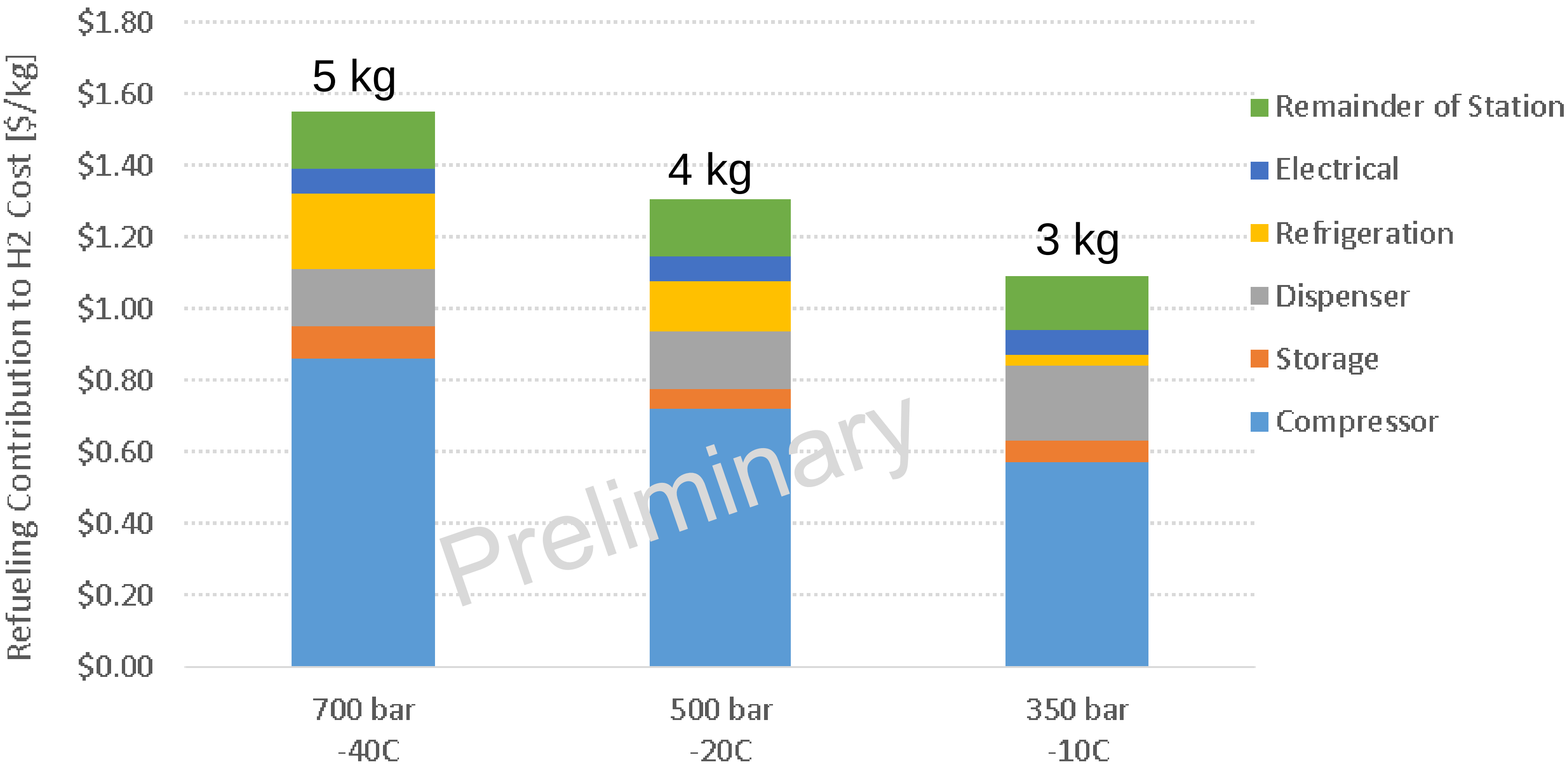


Dispenser cost and number can increase with slower or partial fills (volume production) – Approach/Accomplishment

- One hose per dispenser
- Dispenser cost: $50K
- Fill time: 5kg in 3 min
- Lingering time at dispenser: 2 min
- Hose occupied fraction (HOF) during peak hour: 50%

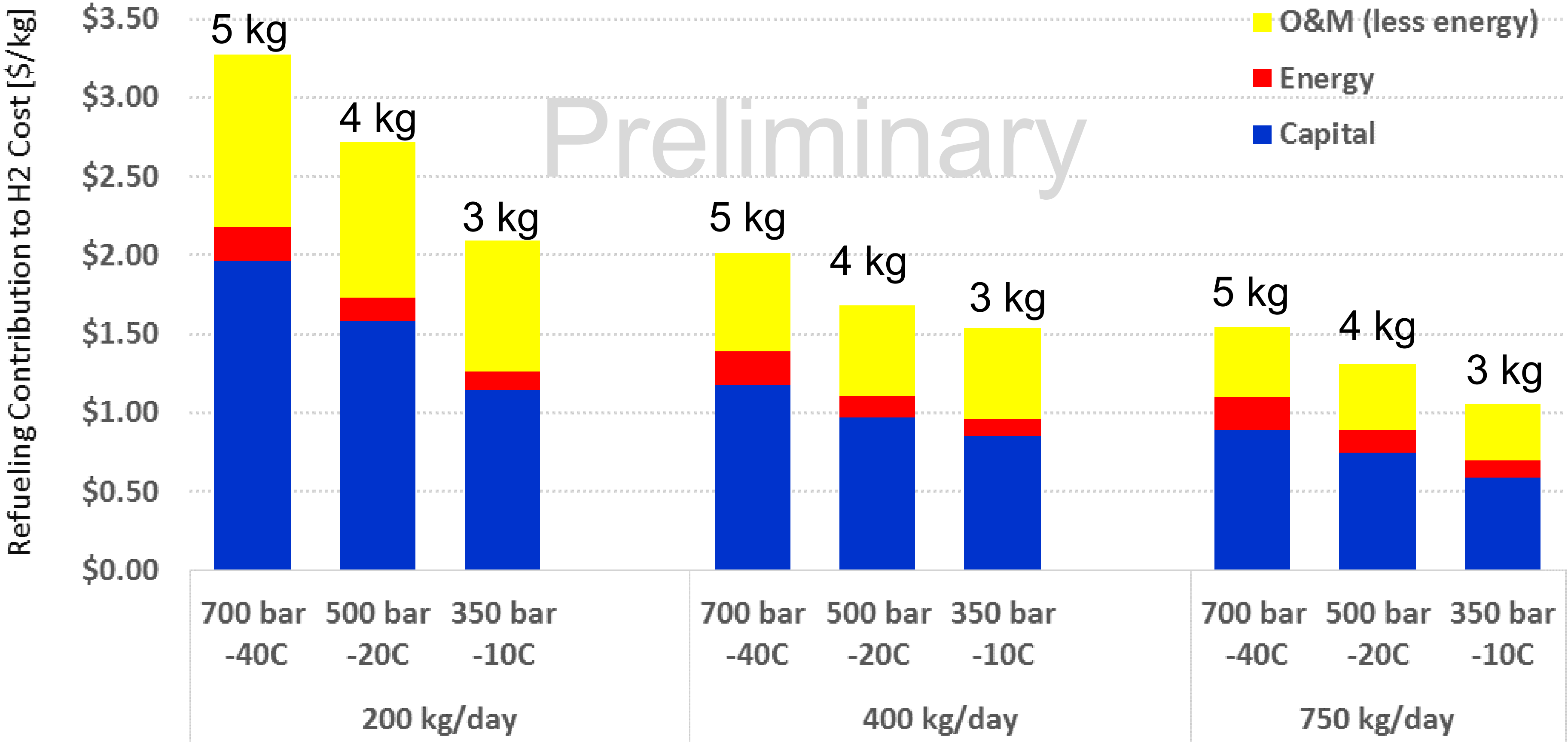


Partial vehicle fills (with lower fueling pressures) reduces refueling cost – Accomplishment



750 kg/day station

Impact of fueling pressure on refueling cost is greater for small refueling station sizes – Accomplishment



Summary – *Progress and Accomplishment*

- A modeling framework (H2SCOPE) was developed to accurately evaluate various fueling pressures and precooling temperatures
- Fueling pressure greatly impacts fill duration at elevated precooling temperature
- Cost of major refueling equipment (e.g., compression, storage, refrigeration and dispenser) was updated
- Partial vehicle fills (with lower fueling pressures) reduce refueling cost
- Impact of fueling pressure on refueling cost is greater for small refueling station sizes

Collaborations and Acknowledgments

Collaborators:

- Daryl Brown, Pacific Northwest National Laboratory: Update fueling components cost estimates and update cost and price indices
- PDC Machines: provided valuable critical input, and compressor flow charts for a wide variety of compressor models
- Industry stakeholders: provided estimates for cost of dispensers
- Vehicle OEMs: provided information to understand the importance of vehicle driving range and valuable input to improve the objective of the analysis
- USDRIVE Tech Teams: provided critical input that improved the outcome of this analysis (e.g., need to consider important factors such as HOF as a function of partial fills)

Future Work

- ☐ Evaluate cost trade off between refrigeration capacity and sizing of heat exchanger
- ☐ Update analysis based on final release of SAE J2601 protocol
- ☐ Evaluate impact of MC refueling method on HRS cost (compared to SAE J2601)
- ☐ Evaluate cost 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 technical 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

Project Summary

- **Relevance:** Evaluate impact of fueling pressure on fill rate and refueling cost. Incorporate implications of SAE J2601 refueling protocol in the modeling of hydrogen refueling stations (HRS). Identify cost drivers of various fueling technologies and configurations.
- **Approach:** Identify key vehicle tank geometric and thermal characteristics. Solve physical laws subject to initial and boundary conditions to track mass transfer, pressure and temperature between refueling components and within vehicle tank. Determine size and cost of refueling equipment. Calculate fill duration and refueling cost for various fueling pressures.
- **Collaborations**: Collaborated with experts from the industry with knowledge and experience on fueling equipment and vehicle tanks. Acquired information needed for the simulations and received valuable input and suggestions to complete the analysis.
- **Technical accomplishments and progress:**
  - A modeling framework (H2SCOPE) was developed to accurately evaluate various fueling pressures and precooling temperatures.
  - Evaluated fill duration at various precooling temperature
  - Updated the cost of major refueling equipment (e.g., compression, storage, refrigeration and dispenser)
  - Determined that partial vehicle fills (with lower fueling pressures) reduce refueling cost, and that impact of fueling pressure on refueling cost is greater for small refueling station sizes
- **Future Research**: Evaluate cost trade off between refrigeration capacity and sizing of heat exchanger. Evaluate impact of MC refueling method on HRS cost (compared to SAE J2601 refueling protocol). Update Hydrogen Delivery Scenario Analysis Model (HDSAM) with new technical data and cost information.

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Project AN45

Acronyms

- ANL: Argonne National Laboratory
- DOE: Department of Energy
- FC: Fuel Cell
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- GREET: Greenhouse gas, Regulated Emissions, and Energy in Transportation
- H2: Hydrogen
- H2A: Hydrogen Analysis
- H2SCOPE: Hydrogen Station Cost Optimization and Performance Evaluation
- HDSAM: Hydrogen Delivery Scenario Analysis Model
- HRS: Hydrogen Refueling Station
- H.T.: Heat Transfer
- MSM: Macro-System Model
- MYRD&D: Multi-Year Research, Development, and Demonstration
- ORNL: Oak Ridge National Laboratory
- SAE: Society of Automotive Engineers