Modeling Hydrogen Dispensing Options for Advanced Storage

2010 DOE Hydrogen Program Review

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This document does not contain proprietary information

Overview

Timeline

- 7/20/2009
- 6/30/2010
- 95% complete

Barriers

- Barriers addressed
  - Dispensing rate: 1.6 kg/min
  - Delivery cost: $2-3/kg
  - Fueling station requirements for advanced vehicle storage options

Budget

- $99,882 total
  - DOE share: $99,882
- Funding received in FY09
  - $9,842
- Funding for FY10
  - $90,040

Partners

- Interactions/ collaborations
  - St. Croix Research
  - Argonne National Lab
  - H2 Delivery Tech Team
  - BMW
  - Dispenser manufacturers
- Project lead
  - TIAX

Technical Approach

The primary objective of this Phase I SBIR is to determine the incremental fueling station costs for advanced vehicle storage options relative to the baseline 350 bar compressed pathway.

Technical Tasks:

- Storage technology down-select
- Energy and mass flow modeling
- Baseline fueling station requirements
- Technology gap identification and concept definition
- Fueling station configuration
- Cost assessment

Our goal is to enable the integration of baseline station costs and configurations into HDSAM.

Approach: Advanced Vehicle Storage Technologies

We are analyzing five refueling station scenarios categorized by the vehicle storage technology.

Advanced Vehicle Storage Categories:

- 700 bar compressed gas – 875 bar H_2 fill
- Cryo-compressed gas – 272 bar LH_2 fill
- Sorbent – MOF 177 with adiabatic 350 LH_2 filling
- Off-board regenerable – ammonia borane (AB) ionic liquid
- On-board regenerable – sodium alanate, 100 bar H_2 gaseous filling with heat recovery

Advanced storage technologies aim to improve the feasibility (i.e., cost and performance) of delivering and storing hydrogen.

Relevance: Refueling Station Requirements

We will use baseline fueling station requirements consistent with HDSAM v2.2.

Baseline Refueling Station Assumptions:

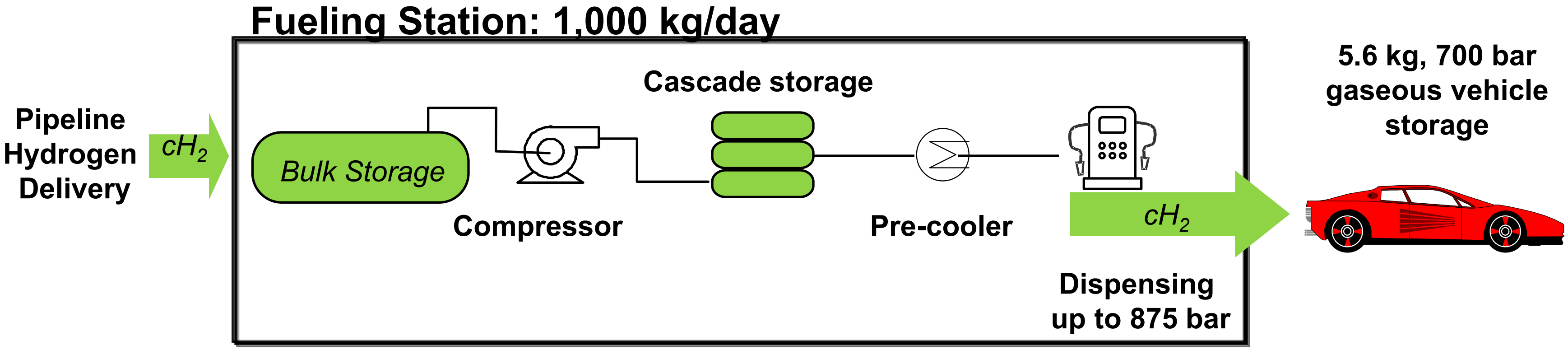
- 1,000 kg/day average
- 4.6 kg H2 in 2.8 minutes (vehicles assumed to start with 1 kg)
- 2 dispensers, 4 nozzles per station, simultaneous filling
- Baseline land, labor, and other general capital and operating costs from HDSAM

Other Baseline Delivery Assumptions:

- Urban
- Sacramento, CA
- 40% market penetration
- Liquid hydrogen storage to meet plant outages and summer peak

Other fueling station requirements will be specific to the assumed vehicle storage technology.

For the 700 bar compressed gas option, the heat of compression and the Joule-Thomson effect need to be offset to meet fast fill requirements.



700 bar Refueling Station Notes:

- High pressure compression is the most demonstrated advanced storage technology to enable longer range and/or improved volumetric capacity for hydrogen vehicles
- Fueling station configuration is similar to baseline 350 bar stations (i.e., bulk storage, compression, cascade storage, and dispenser)
- Pre-cooling to -20 to -40°C is required to offset the heat of compression and the Joule-Thomson (JT) effects

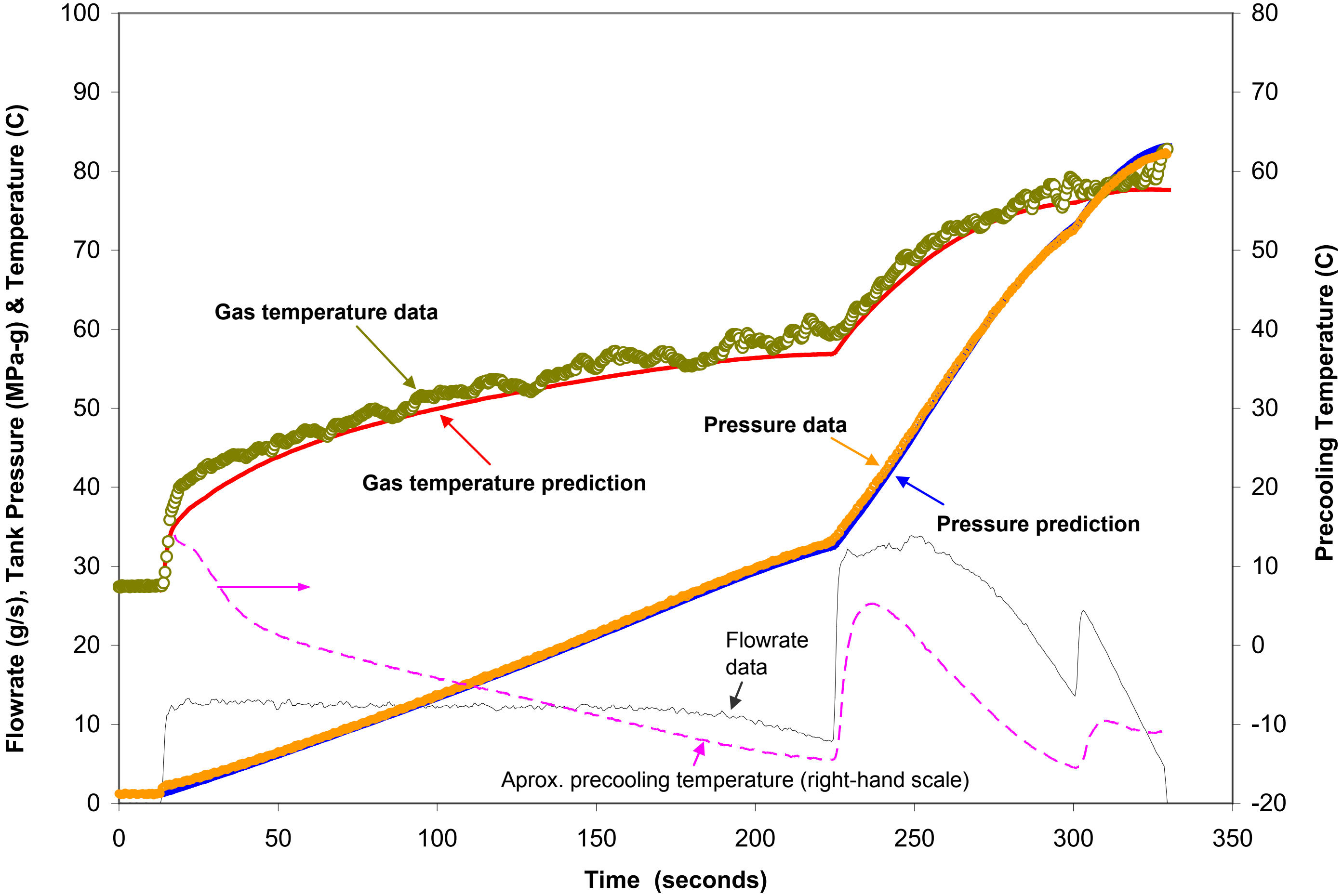
The following assumptions were used to analyze 700 bar (~70 MPa) vehicle filling.

- 5.6 kg, type III vehicle tanks assumed (~54.7 cm OD X ~97 cm OL),
  - Note that a type IV tank will require more pre-cooling due to heat transfer effects of plastic liner
- A typical vehicle tank receives 4.6 kg (i.e., starts with 1 kg)
- Final SOC = 100% with the specific P (<87.5 MPa) and T (<85^{o}C) determined by iteration to enable near-optimum utilization of the storage cascade
- All vessels and hydrogen start at 15^{o}C (ambient temp.)
- The vehicle tank is filled with a constant pressure ramp rate (CPRR), per SAE draft J2601 and the interim OEM specification
- A cascade storage vessel is not being recharged by the station compressors while it is being discharged to take advantage of the vessel cooling
- The cascade vessel discharge model simulates heat-of-expansion effects, but heat transfer to/from the gas is neglected (cascade vessels are relatively large and the pressure change is less than the vehicle tank)

700 bar vehicle filling assumptions continued…

- The heat that must be extracted from the flowing hydrogen in the pre-cooler is calculated as that which is required to maintain a constant “nozzle” (i.e., vehicle tank inlet) temperature, per SAE daft J2601 and the OEM interim spec
  - This requirement adds a large amount of initial pre-cooling to meet the target nozzle temperature
  - Changing this requirement would greatly reduce the peak refrigeration needed
- Pre-cooling refrigeration occurs downstream of the flow control valve (FCV)
- The total pressure drop between the cascade and vehicle tank is equal to the pressure drop in the plumbing plus the pressure drop across the FCV
- The cascade sequencing criterion is 20 psi (i.e., when dP declines to 20 psi, it’s time to switch to the next cascade vessel or stop vehicle tank filling)

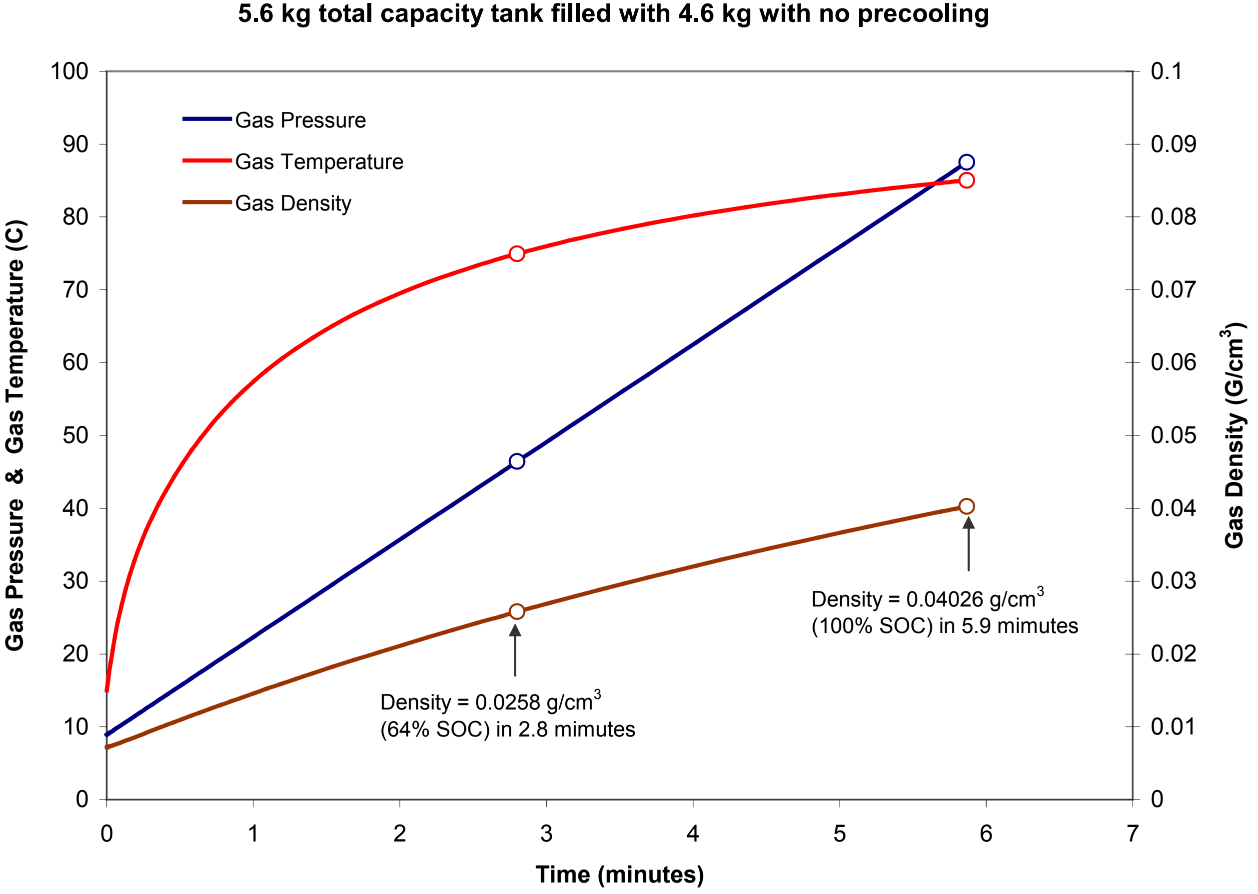
Our vehicle fill models and the methodology compares very well with actual test data.



Test data from:

Schneider, J., et al., “Evaluation of Fueling Performance Targets for Onboard 70 MPa Gaseous Hydrogen Storage Containers,” 17th Annual NHA Conference, Long Beach, California, March 12-16, 2006.

We modeled the vehicle filling process (heat-of-compression and J-T effects) to estimate the pre-cooling refrigeration requirement.

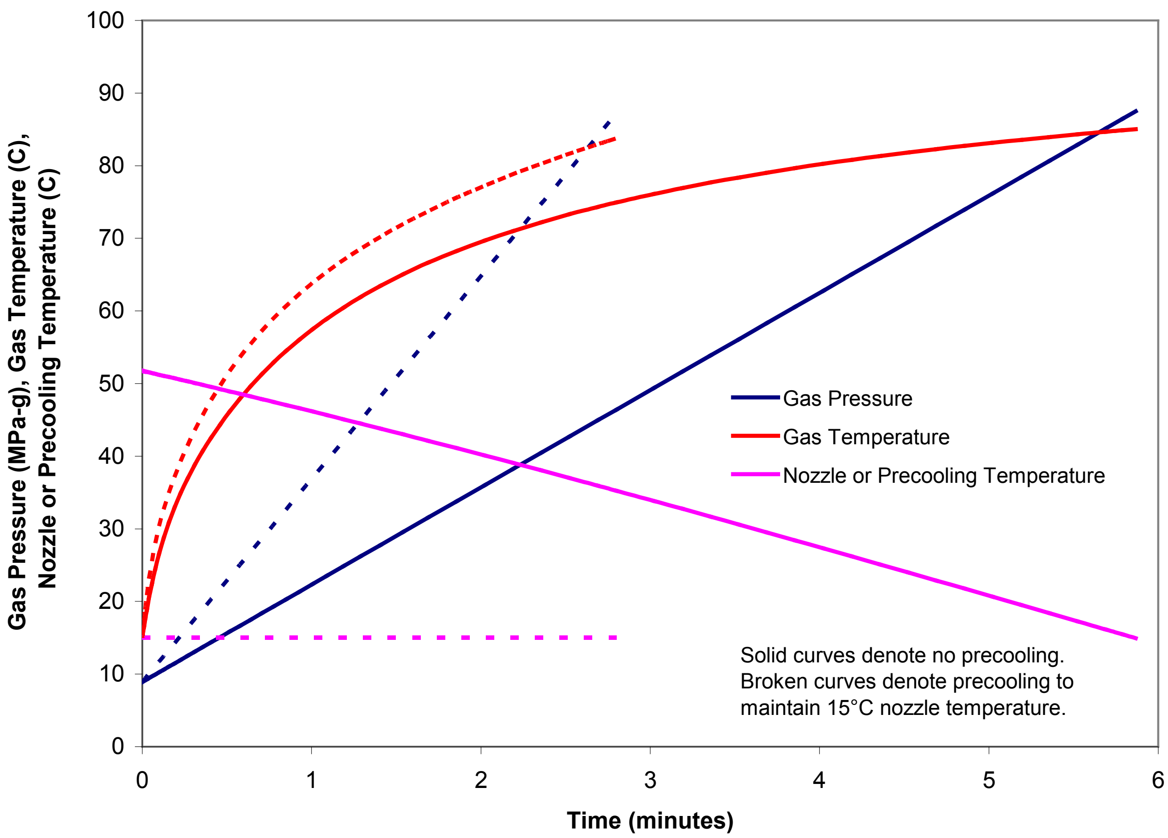


- **1 vehicle**
- **1 kg H_2 initially in tank**
- **4.6 kg H_2 added**
- **no pre-cooling**

To fill 1 vehicle initially with 1 kg without pre-cooling would take ~6 minutes, and over 10 minutes for vehicles starting nearly empty.

To fill a vehicle in 2.8 minutes, pre-cooling to 15°C is needed for a single vehicle with 1 kg initially.

5.6 kg total capacity tank filled with 4.6 kg to 100% SOC (density = 0.04026 g/cm^3)



Solid curves denote no precooling. Broken curves denote precooling to maintain 15°C nozzle temperature.

- 1 vehicle
- 1 kg H_2 initially in tank
- 4.6 kg H_2 added
- Pre-cooling to 15°C vs no pre-cooling

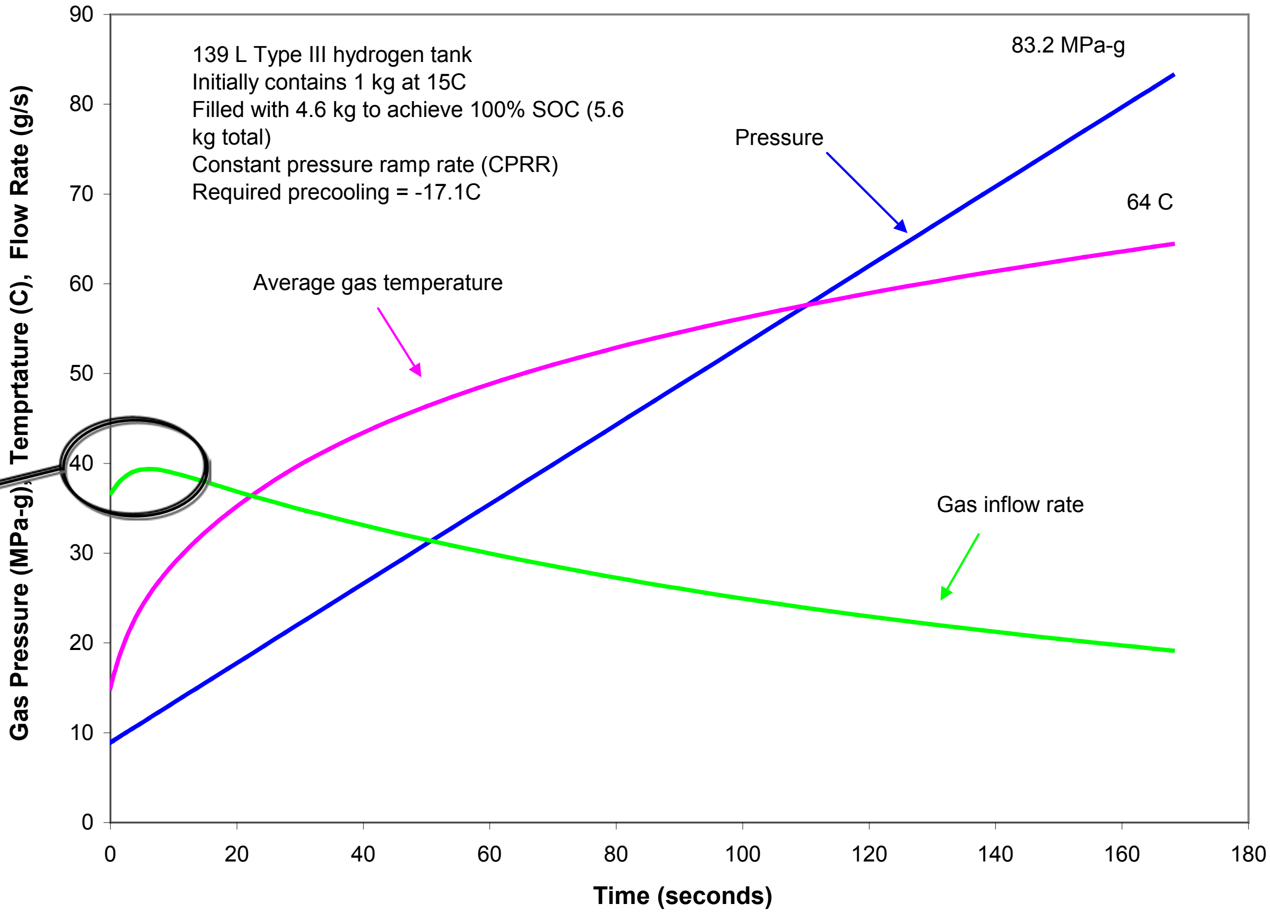
- Throttling initially warms the hydrogen from 15°C to 52°C.
- Pre-cooling is needed to offset the JT effect of the throttled gas, less throttling and pre-cooling is needed as the tank pressure increases.

However, a vehicle that is nearly empty will require pre-cooling to approximately -20°C.

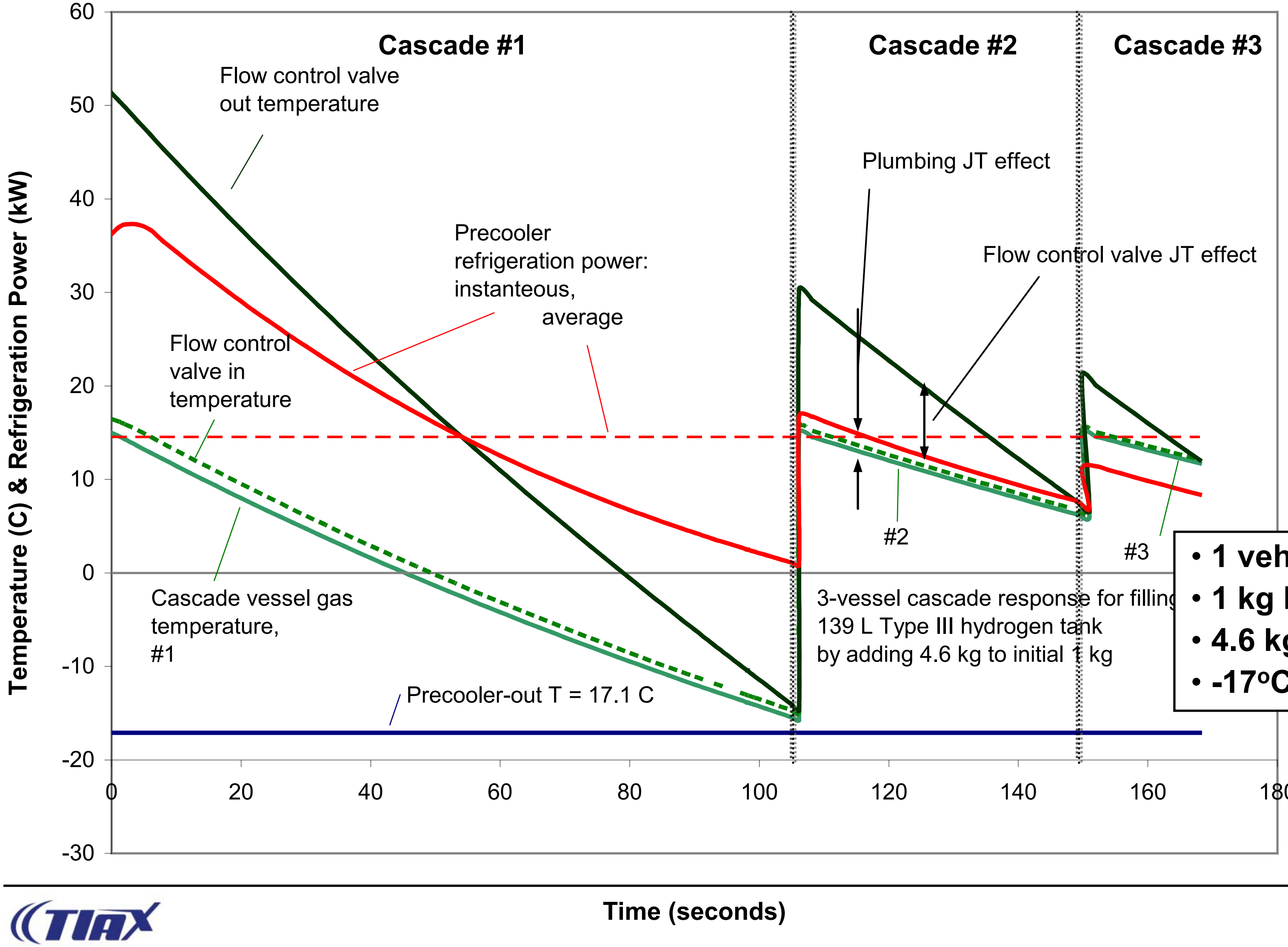
Additional fill dynamics modeling:

- **1 vehicle**
- **1 kg H_2 initially in tank**
- **4.6 kg H_2 added**
- **~-20°C pre-cooling**

The Initial flow rate has a spike to meet the constant pressure flow rate as the cold hydrogen enters and cools the initially ambient temperature tank



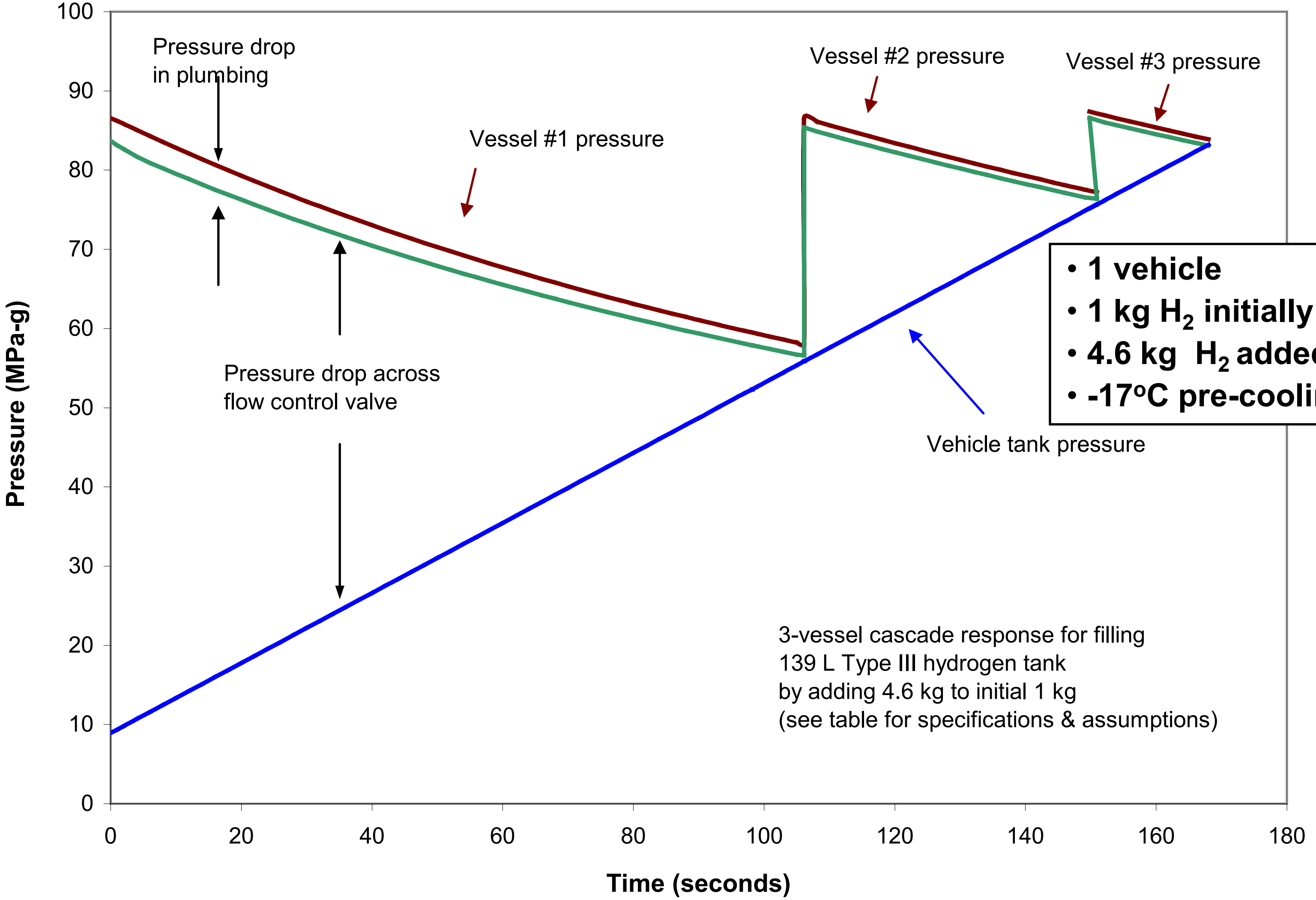
The temperature rise across the FCV due the J-T effect highlights the need for pre-cooling, particularly in the 1st cascade vessel.



3-vessel cascade response for filling 139 L Type III hydrogen tank by adding 4.6 kg to initial 1 kg

- **1 vehicle**
- **1 kg H_2 initially in tank**
- **4.6 kg H_2 added**
- **-17°C pre-cooling**

The temperature rise corresponds to the large pressure drop between the cascade and vehicle tanks.



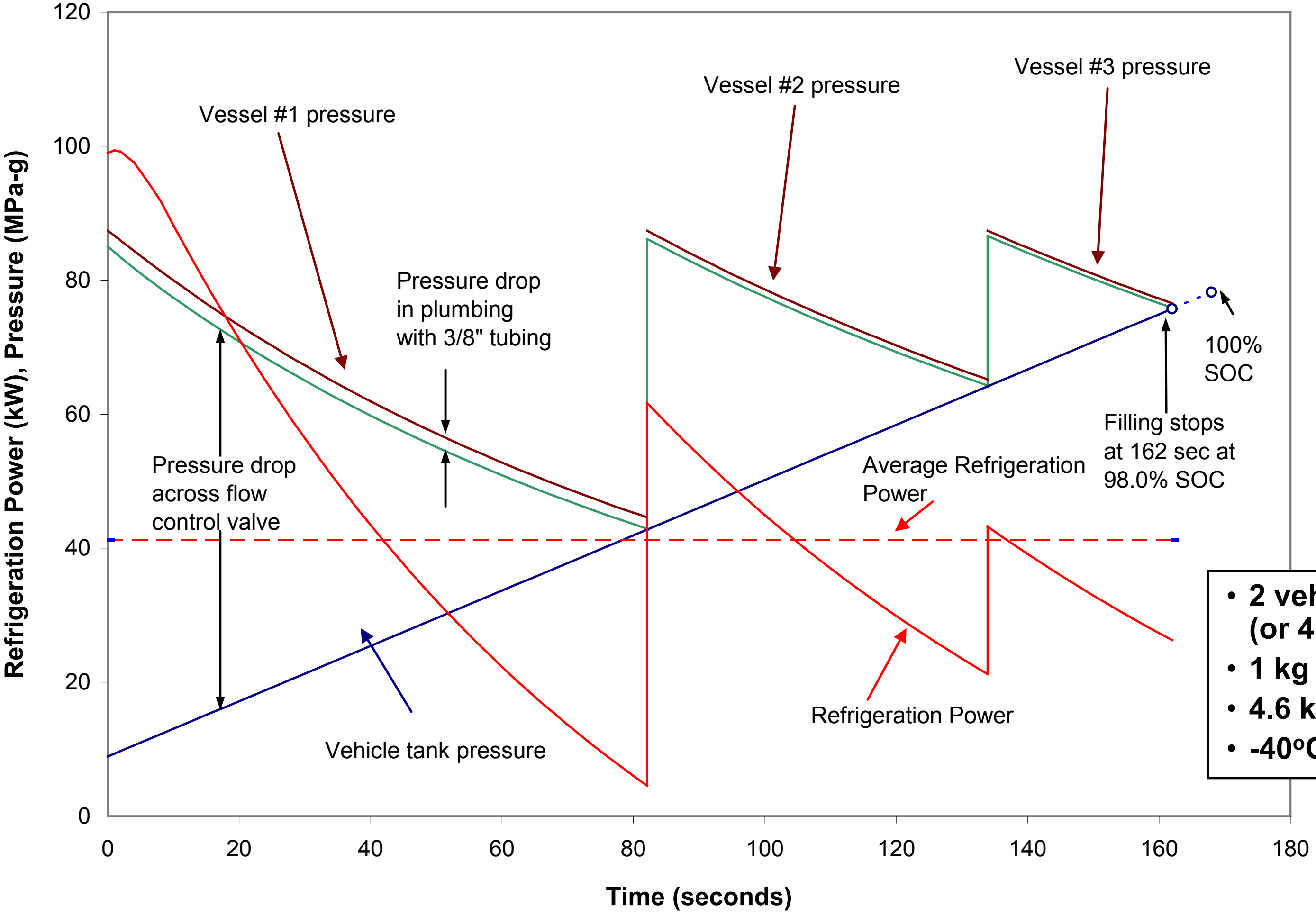
- **1 vehicle**
- **1 kg H_2 initially in tank**
- **4.6 kg H_2 added**
- **-17°C pre-cooling**

3-vessel cascade response for filling
139 L Type III hydrogen tank
by adding 4.6 kg to initial 1 kg
(see table for specifications & assumptions)

To summarize the need for pre-cooling for different scenarios….

- More pre-cooling enables the vehicle tank to be full at a lower pressure
- This means that the vehicle tank can get fuller for a given decline in cascade bank pressure, e.g.:
  - To refuel 1 vehicle (1 kg to 5.6 kg) in 2.8 minutes, pre-cooling to 15°C is needed
  - To refuel 1 vehicle which is nearly empty in 2.8 minutes, pre-cooling to approximately -20°C is needed
- To refuel 4 vehicles at the same time with 2 cascade systems (all 1 kg to 5.6 kg), pre-cooling to -40°C is needed
  - This is necessary to keep enough pressure differential from the cascade to the vehicle to drive the fueling process
  - The refrigeration requirement can be reduced by adding additional cascade storage and/or increasing the cascade storage pressure
- The refrigeration requirement needs to be incorporated into the HDSAM compressor/cascade storage optimization

The peak refrigeration power needed for four vehicles is 198 kW (56 tons), which is driven by the constant nozzle temperature requirement.



- **2 vehicles filled simultaneously (or 4 vehicles from 2 cascades**
- **1 kg H2 initially in each tank**
- **4.6 kg H2 added to each tank**
- **-40°C pre-cooling**

Major station components and specifications:

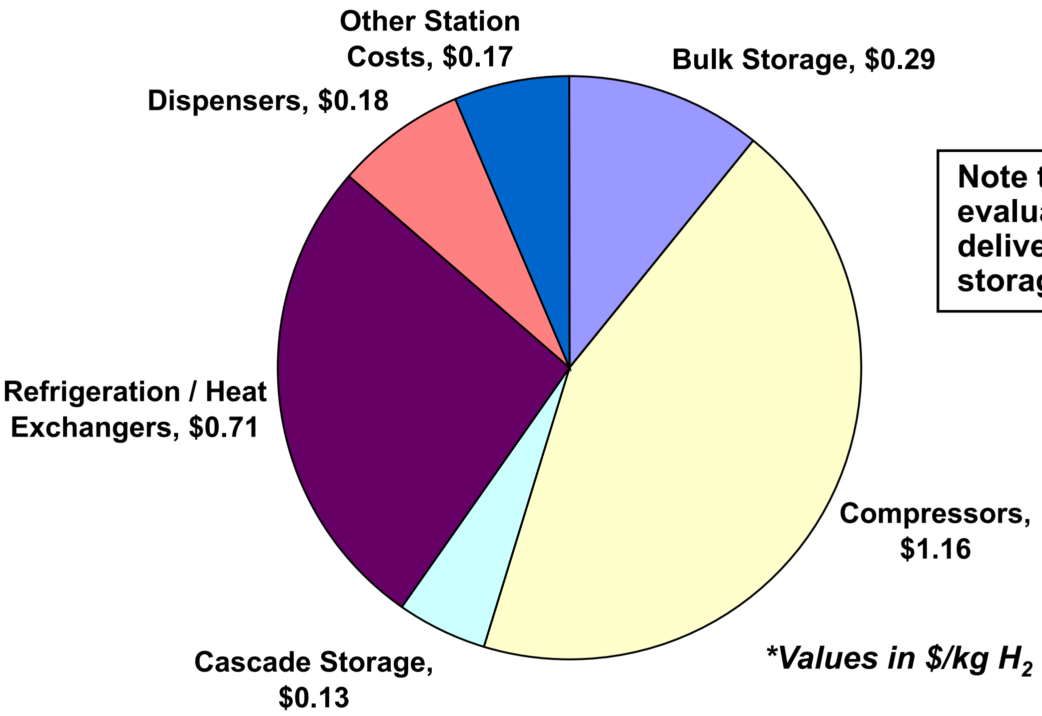
700 Bar Fueling Station Components	Uninstalled Cost ($)	Specifications
Bulk storage	$400,000	5 units, 89 kg each
Compressors	$813,000	3 units, 49 kg/hr each, 875 bar peak
Cascade Storage	$180,000	2 sets, 62 kg each, 875 bar
Pre-cool Refrigeration	$700,000	56 tons, -40°C, 100 kW peak cooling requirement
Dispensers	$215,000	2 units, dual-hose, 875 bar

700 bar Refueling Station Notes:

- Bulk storage and compressor costs and specifications are from HDSAM
- Cascade storage is twice that of HDSAM to avoid running compressors while filling 4 vehicles simultaneously
- Pre-cool refrigeration and dispenser costs are substantially higher than those produced by HDSAM

700 bar fueling station costs are still dominated by compression costs, but refrigeration costs can be significant if four vehicle filling is required.

700 bar fueling station costs ($2.65/kg H_2)



**Values in $/kg H_2*

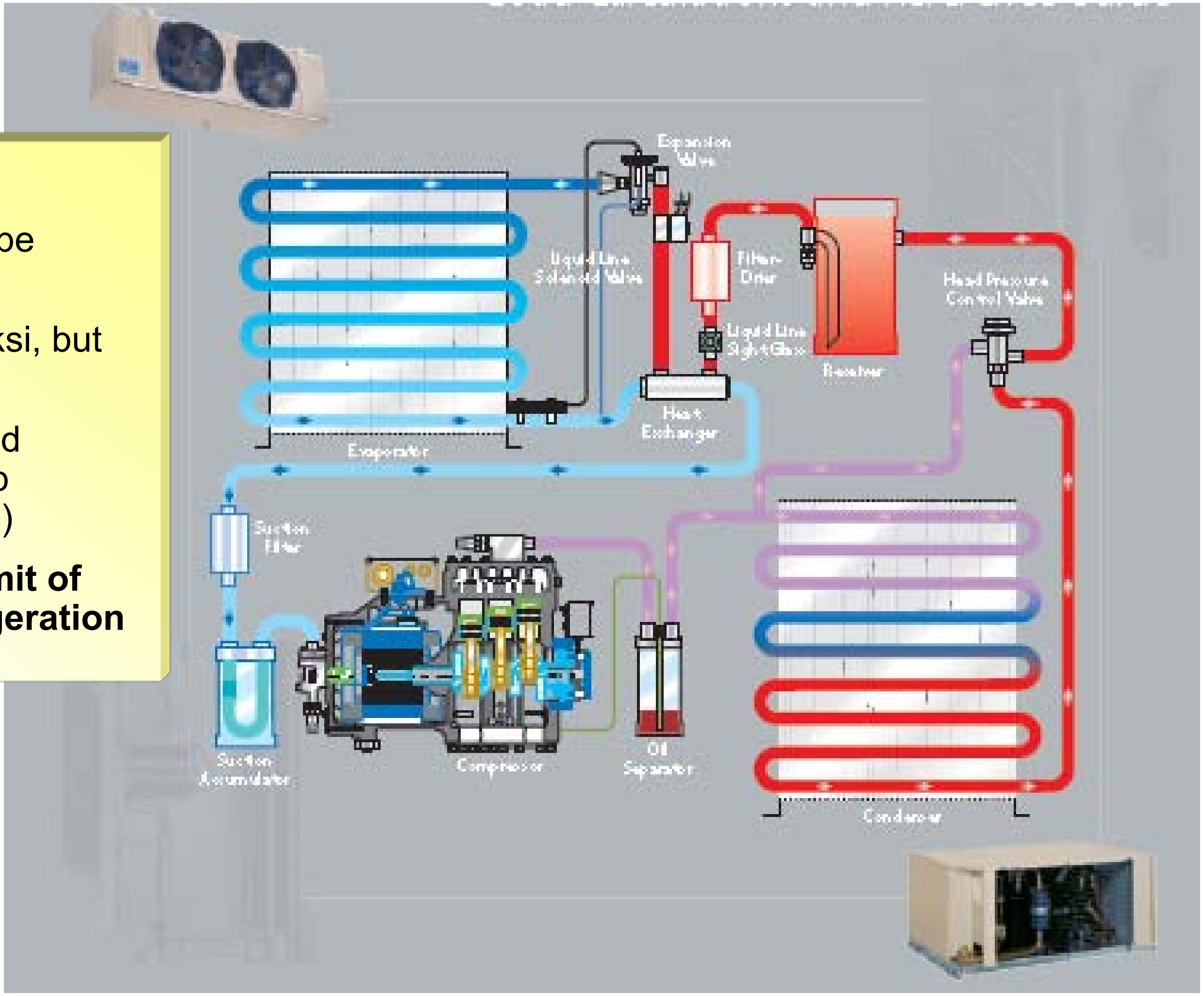
Note that these results should be evaluated in context with other delivery costs as well as vehicle storage costs.

Furthermore, 700 dispenser costs will likely be higher than the baseline dispensers modeled in HDSAM.

Pre-cooling pricing and approach is based on standard industrial refrigeration equipment.

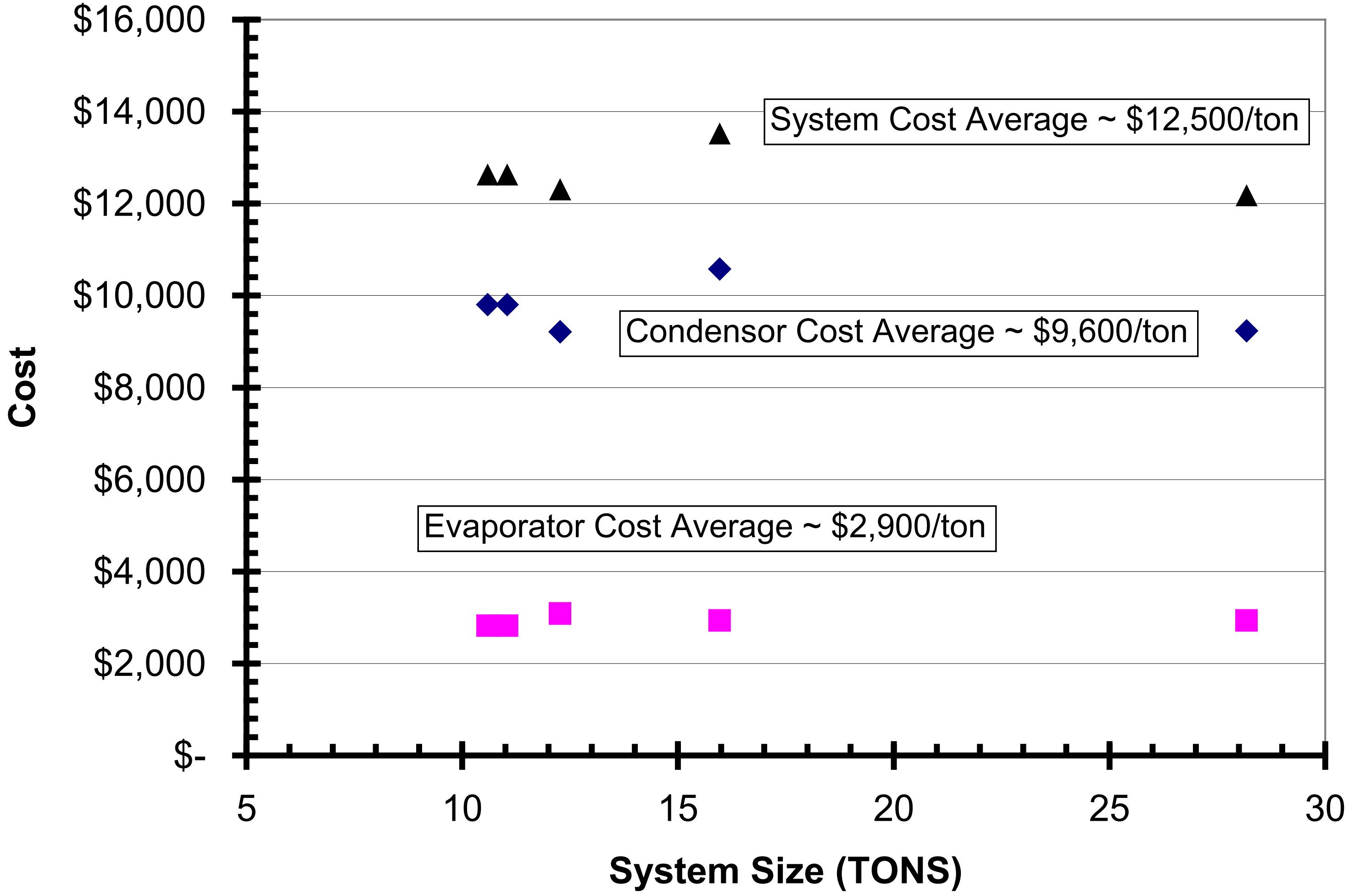
Notes:

- The evaporator is assumed to be mounted in the H2 flow path
- Tubing needs to withstand 12 ksi, but fans are not needed
- Fin enhancements may be used (generally not used in low-temp evaporators due to frost issues)
- **-40°C pre-cooling is at the limit of conventional industrial refrigeration equipment**

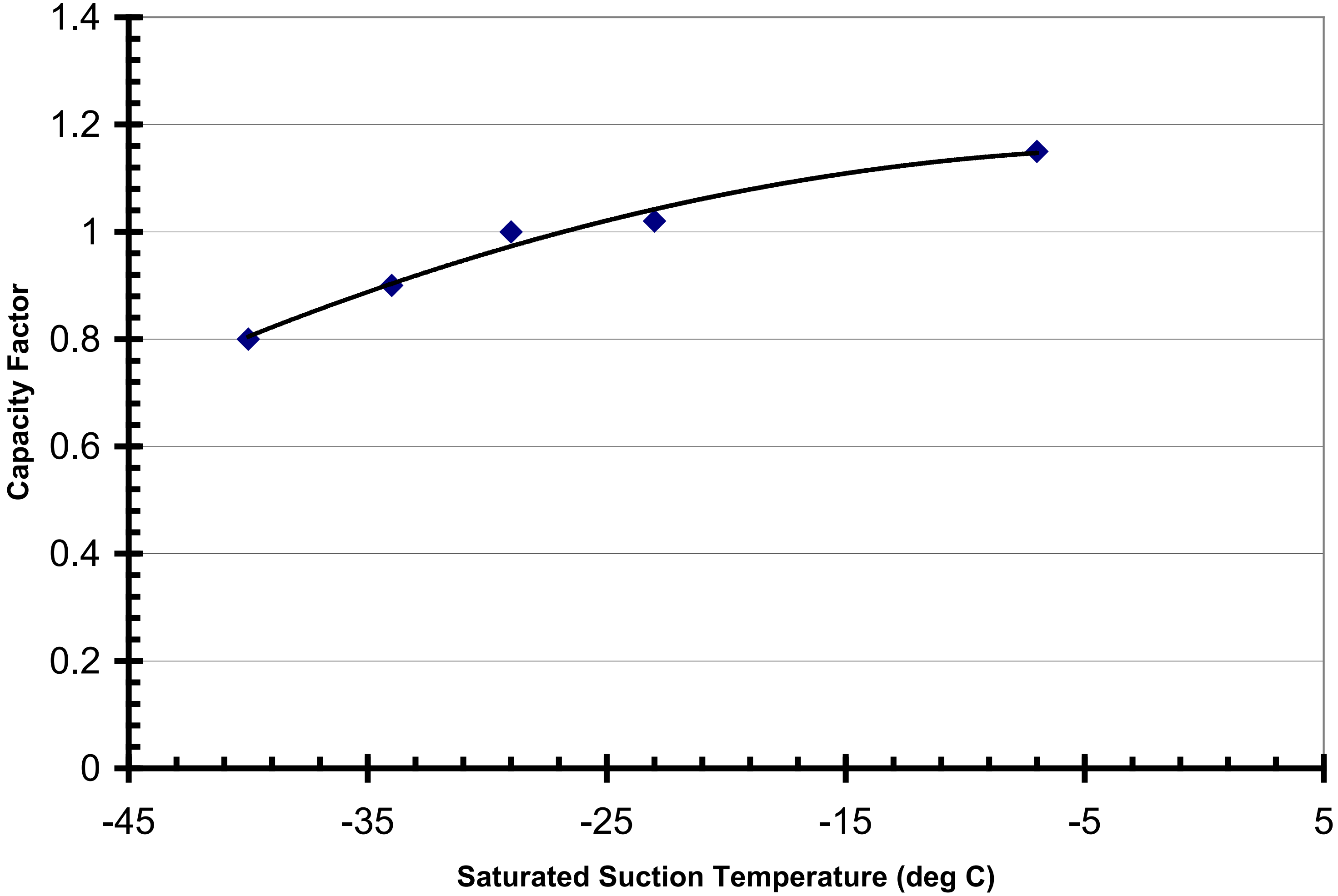


Schematic from Larkin Engineering Manual

The per refrigeration ton cost of pre-cooling is fairly constant across a variety of system sizes.



The available capacity of a given pre-cooling system diminishes as the pre-cooler temperature decreases, increasing the cost of the system.



We have modeled a range of scenarios to determine the pre-cooler refrigeration requirements and their respective cost.

Scenario	Peak Refrigeration (kW) [tons]	Average Refrigeration (kW) [tons]	Pre-cooler Temperature Needed (°C) [°F]	Installation Cost*
1 vehicle, 1 kg H_2 initially in tank, 4.6 kg H_2 added	37 [11]	15 [4]	-17 [1]	$169,000
4 vehicles sequentially, no compressor, 0.2 kg H_2 initially in tank, 4.6 kg H_2 added	56 [16]	24 [7]	-40 [-40]	$279,000
4 vehicles sequentially, compressor running, 0.2 kg H_2 initially in tank, 4.6 kg H_2 added	43 [12]	15 [4]	-17 [1]	$189,000
4 vehicles simultaneously, 1 kg H_2 initially in tank, 4.6 kg H_2 added	198 [56]	82 [24]	-40 [-40]	$886,000

*Cost estimates based on published list prices (Larkin equipment), assuming competitively priced production and an installation factor of 1.2.

We received feedback from several dispenser manufacturers to understand how dispenser cost might vary with gas type, T, and P.

Dispensers	Cost ($)	Comments
Gaseous H_2, 100 bar (for sodium alanate)	$40,000	Based on extrapolation of 350 bar and 700 bar estimates)
Gaseous H_2, 350 bar	$67,500	Based on feedback from manufacturers[1]
Gaseous H_2, 700 bar	$107,500	Based on feedback from manufacturers[1]
Liquid AB	$20,000	Based on estimates from Northwest Pump for E85 retail dispenser[2]
Cryogenic H_2, -250°C, 250 bar	$199,800	Based on the estimate for 350 Bar and the average relationship between LNG/CNG (1.8 – 4.1 range; 3 average)
CNG, 250 bar	$26,000 - $40,000	Based on feedback from manufacturers ($50k for premium dispensers)[1,3,4]
LNG, -160°C	$60,000 - $109,000	Based on feedback from manufacturers[1,3]

*Note that HDSAM uses a baseline assumption of $22,400 for dispensers

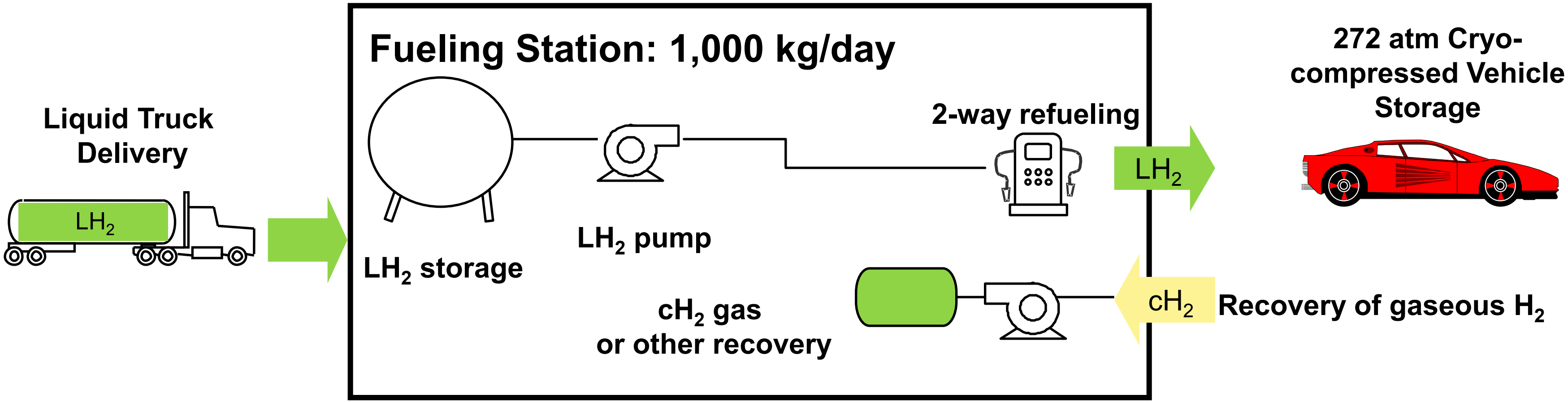
1 – Email communication with a major H2, CNG, LNG, and LPG dispenser manufacturer

2 – Phone communication with Northwest Pump & Equipment Co.

3 – Phone and email communication with Cryostar

4 – Phone communication with FTI international

Cryo-compressed H_2 storage uses high pressure and low temperature to increase the gravimetric and volumetric energy densities.

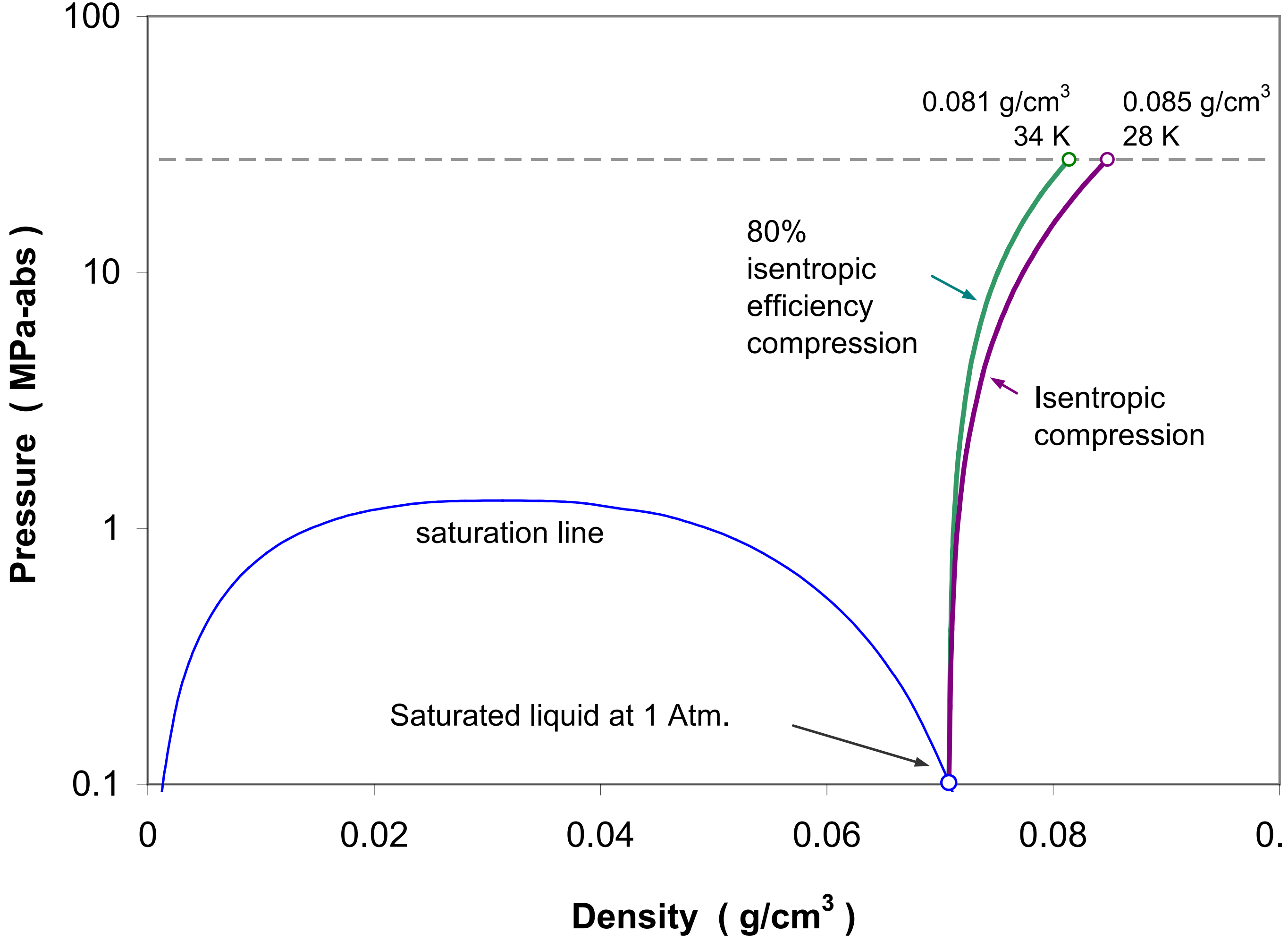


Cryo-compressed Refueling Station Notes:

- Boil-off of the hydrogen from the station storage and the vehicle refueling must be captured and reused for maximum efficiency
- Flexible in terms of refueling options, since it can be filled with pressurized gaseous, liquid, or supercritical hydrogen
- For a vehicle tank to reach a full fill, the heat from compression and from transfer from the tank needs to be managed

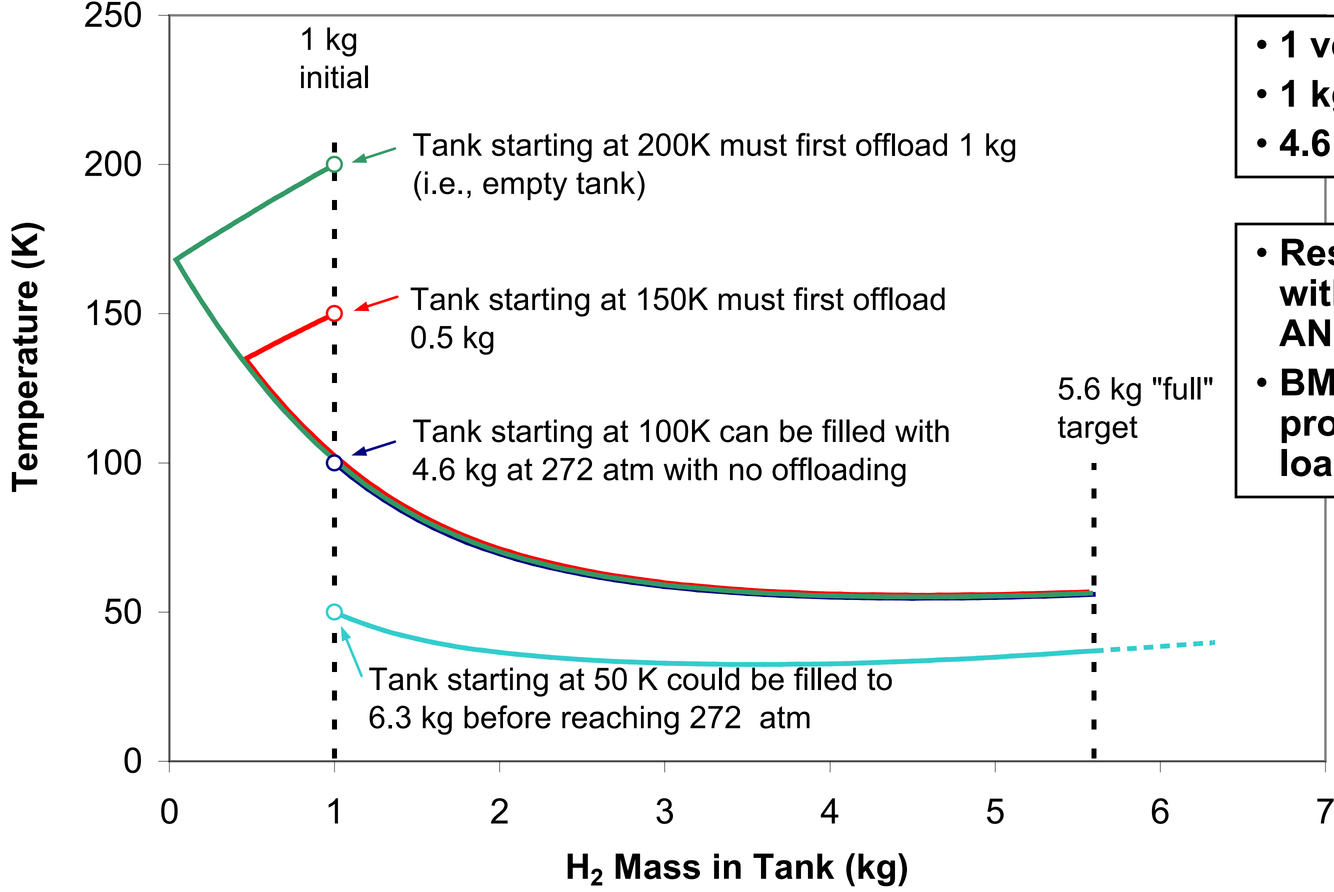
Cryo-compressed vehicles are filled by compressing liquid hydrogen.

LH2 pumped/compressed from 1 to 272 atm



Cryo-compressed refueling modeling shows the off-loading requirements for a complete fill for varied initial tank temperatures.

81 L cryo-compressed tank initially containing 1 kg



Tank starting at 200K must first offload 1 kg (i.e., empty tank)

Tank starting at 150K must first offload 0.5 kg

Tank starting at 100K can be filled with 4.6 kg at 272 atm with no offloading

Tank starting at 50 K could be filled to 6.3 kg before reaching 272 atm

- **1 vehicle**
- **1 kg H_2 initially in tank**
- **4.6 kg H_2 added**

- **Results are consistent with modeling done by ANL[1]**
- **BMW has also proposed an H_2 off-loading strategy[2]**

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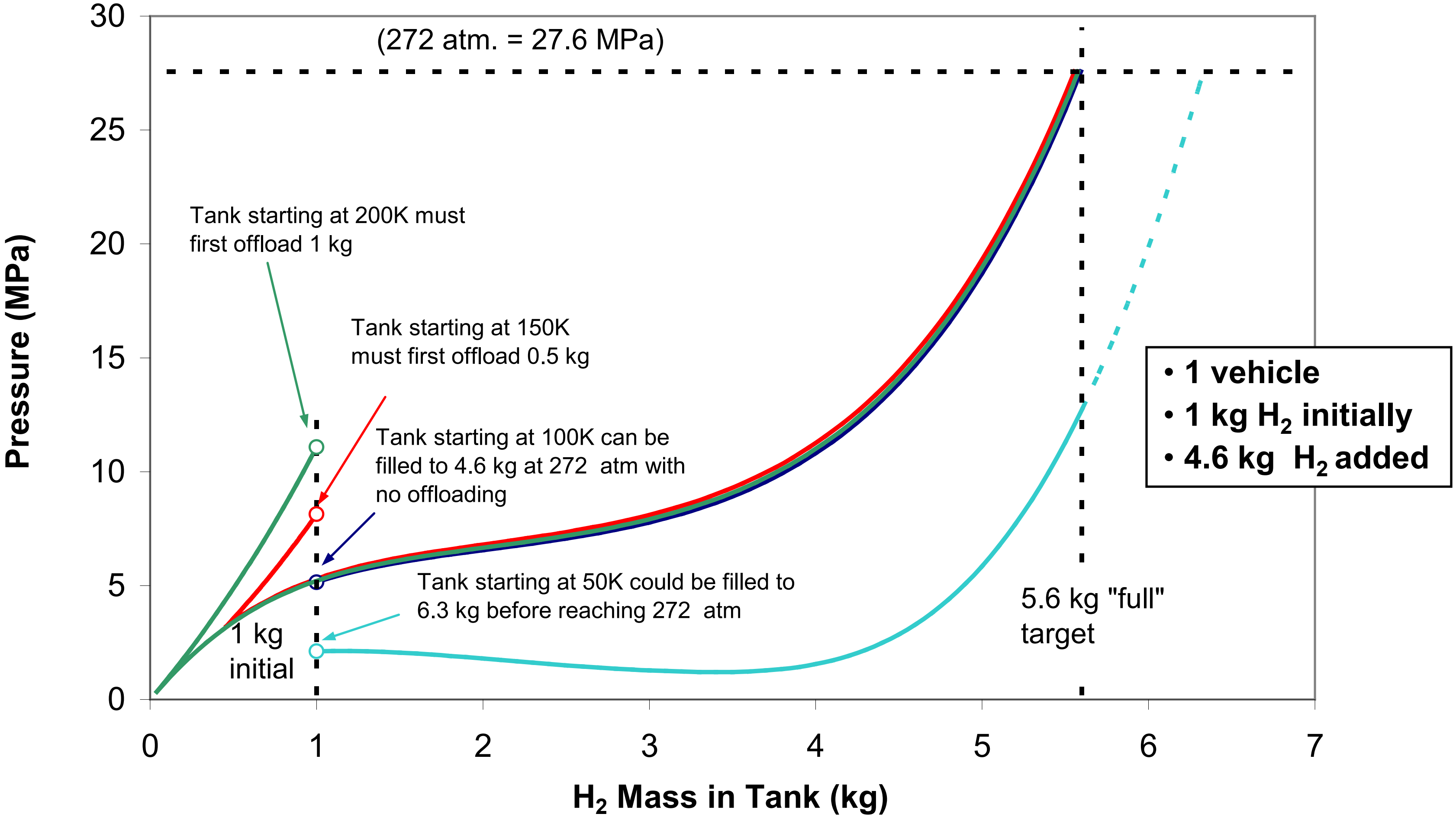
[1] - ANL, 2009, “Technical Assessment of Cryo-compressed Hydrogen Storage Tank Systems for Automotive Applications,” ANL/09-33, December.

[2] – BMW, 2007, “Cryo-compressed Hydrogen Vehicle Storage,” Hydrogen Tech Team Meeting, December.

Cryo-compressed refueling dynamics continued…

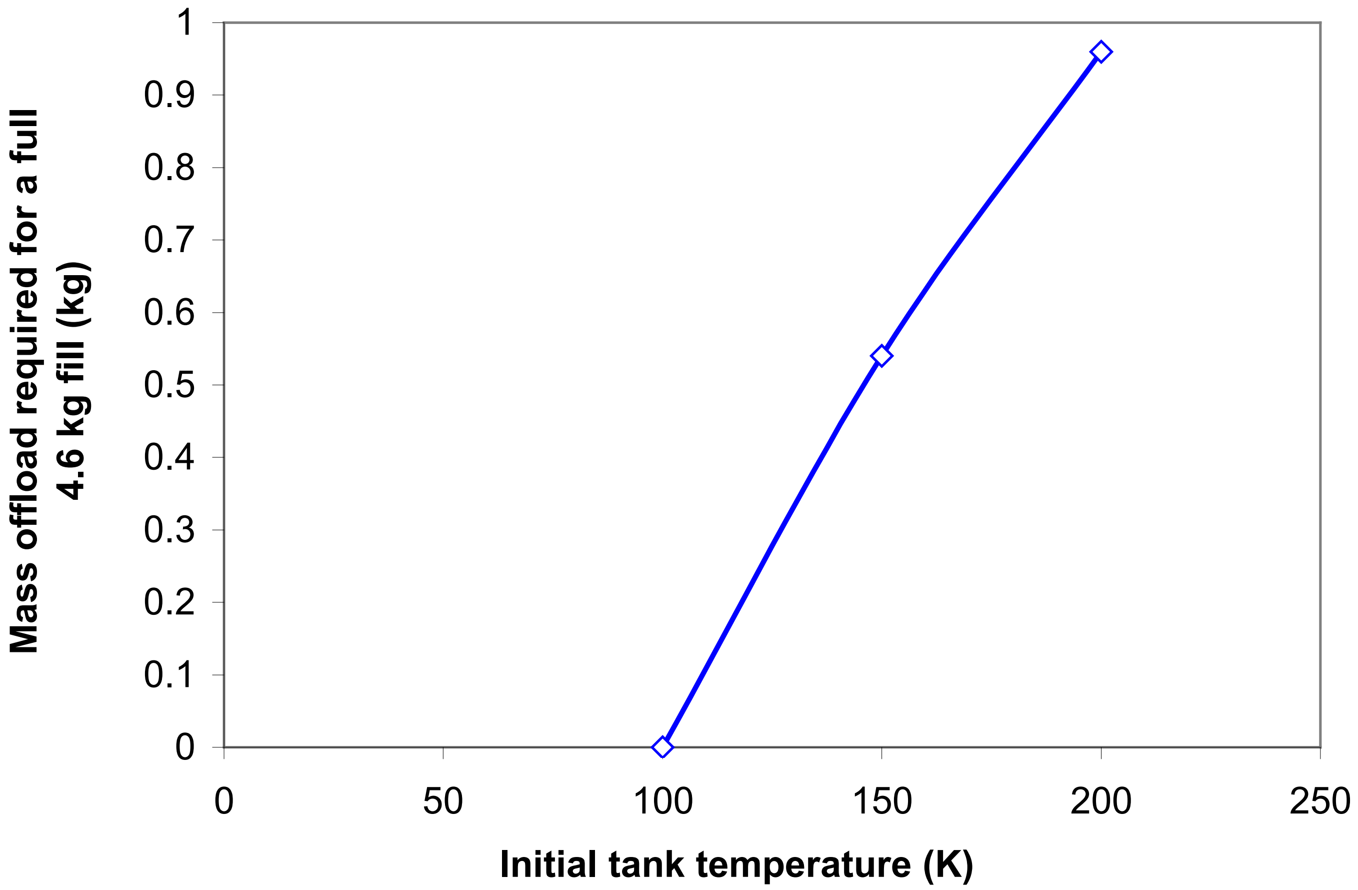
81 L cryo-compressed tank filling dynamics
(filled from 1kg to 272 atm)



- **1 vehicle**
- **1 kg H_2 initially**
- **4.6 kg H_2 added**

Tanks beginning with 1 kg will not require H_2 offloading if they arrive at <100 K, and will need to offload all their H_2 if >200 K.

81 L cryo-compressed tank initially with 1 kg, filled to 272 atm



To ensure full-fills and minimize vent losses, 350 bar, ambient temp dispensing components are added to the cryo-comp station.

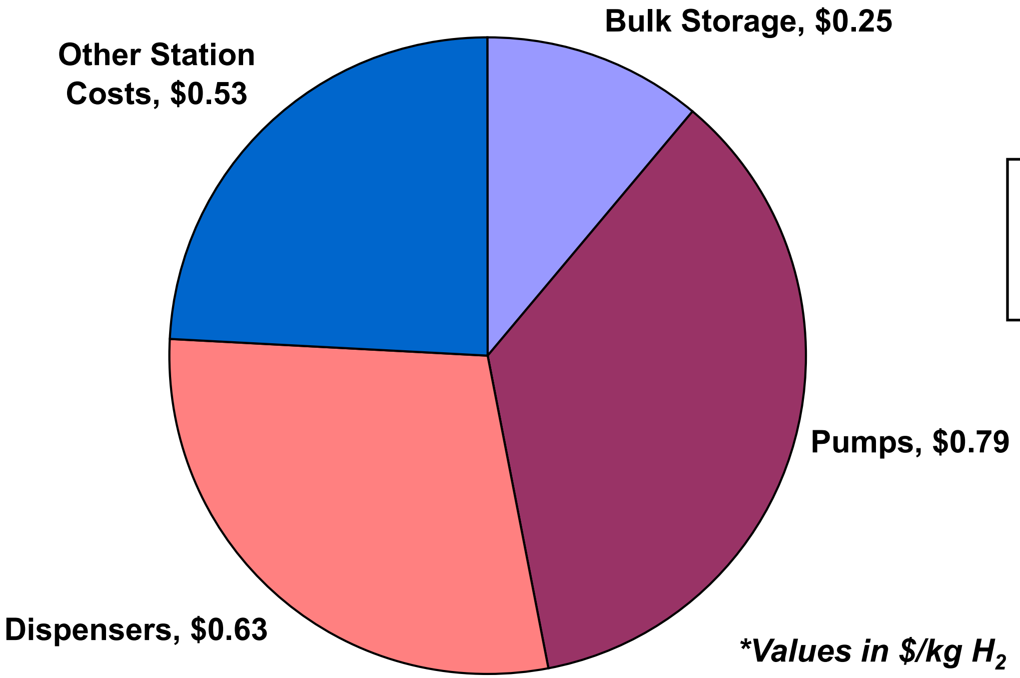
Cryo-comp Fueling Station Components	Uninstalled Cost ($)	Specifications
Bulk storage	$323,000	4,613 kg H2, $70/kg LH_2 storage
Pump	$792,000	2 pumps, 200 kg/hr capacity, 250 bar
Cryo dispenser	$673,000	2 dispensers, dual hose, 272 atm, supercritical H_2
Dispensing requirements for off-loaded hydrogen gas		
Compressor	$127,000	2 units, 11 kg/hr, 440 bar peak
Cascade storage	$63,000	68 kg storage
350 bar dispenser	$67,500	1 unit, dual hose, ambient temp, 350 bar

Cryo-comp Refueling Station Notes:

- Bulk storage and pump costs and specifications are from HDSAM
- The cryo-dispenser is estimated to be significantly higher cost than baseline gas dispensers
- Added cost for lower capacity 350 bar gas dispensing (to handle off-loaded hydrogen) is currently not included in HDSAM

Cryo-compressed fueling station costs are dominated by pumping and dispenser costs.

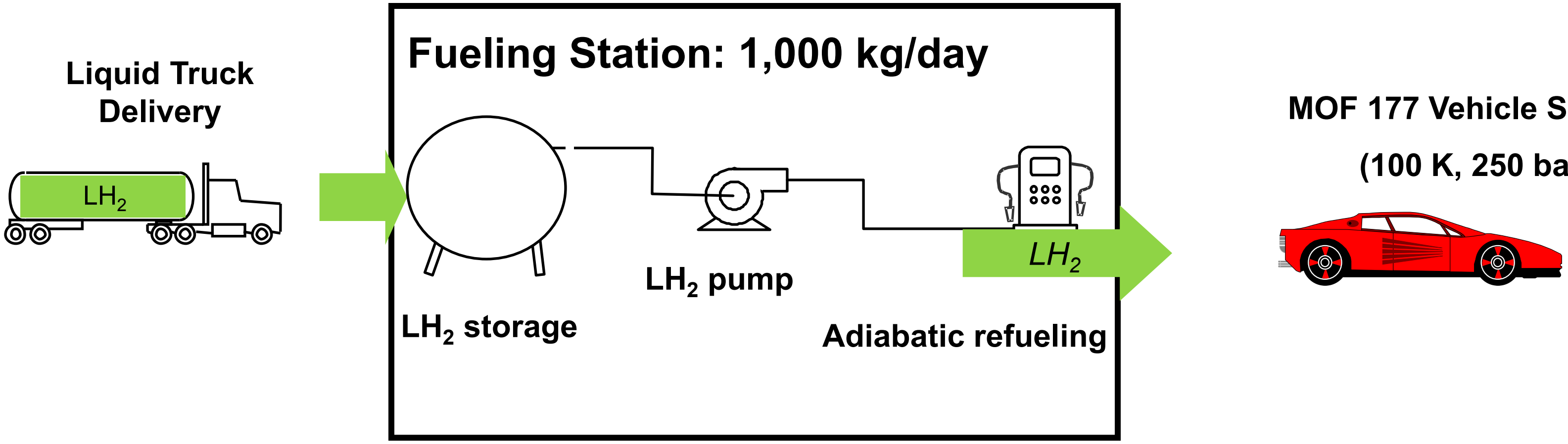
Cryo-compressed fueling station costs ($2.20/kg H_2)



Note that these results should be evaluated in context with other delivery costs as well as vehicle storage costs.

Furthermore, about $0.30/kg of "other" station cost is due to equipment for recovering and re-dispensing vented hydrogen.

Using adsorbent materials for storage generally requires low temperature and moderate pressure refueling.



Sorbent Refueling Station Notes:

- Properties for Metal Organic Framework (MOF) 177 are being considered as the baseline sorbent material properties, based on DOE input
- We assume adiabatic refueling with LH_2 to avoid the cost and complexity of a liquid nitrogen refrigeration system and vehicle tank heat exchange system
- Low-temp sorbent refueling station requirements will mirror cryo-compressed requirements, we have not included off-loading for the MOF scenario to show a 2nd option

MOF 177 Refueling station requirements and issues:

- Similar to cryo-compressed refueling station in terms of liquid storage, pumping and cryogenic dispensing needs
- Liquid H_2 is used to offset the PV work and the heat of adsorption during refueling
- If vehicles arrive at ~110 K (ANL 2010), no venting will be needed. We have taken this as the base scenario (rather than repeating the cryo-compressed off-loading requirements)
- LN_2 cooling can be used with gaseous refueling, but the energy requirements are similar to using delivered LH_2, requires a more complicated refueling heat exchange system, and therefore was ruled out as a viable cooling option

Major MOF 177 refueling station components:

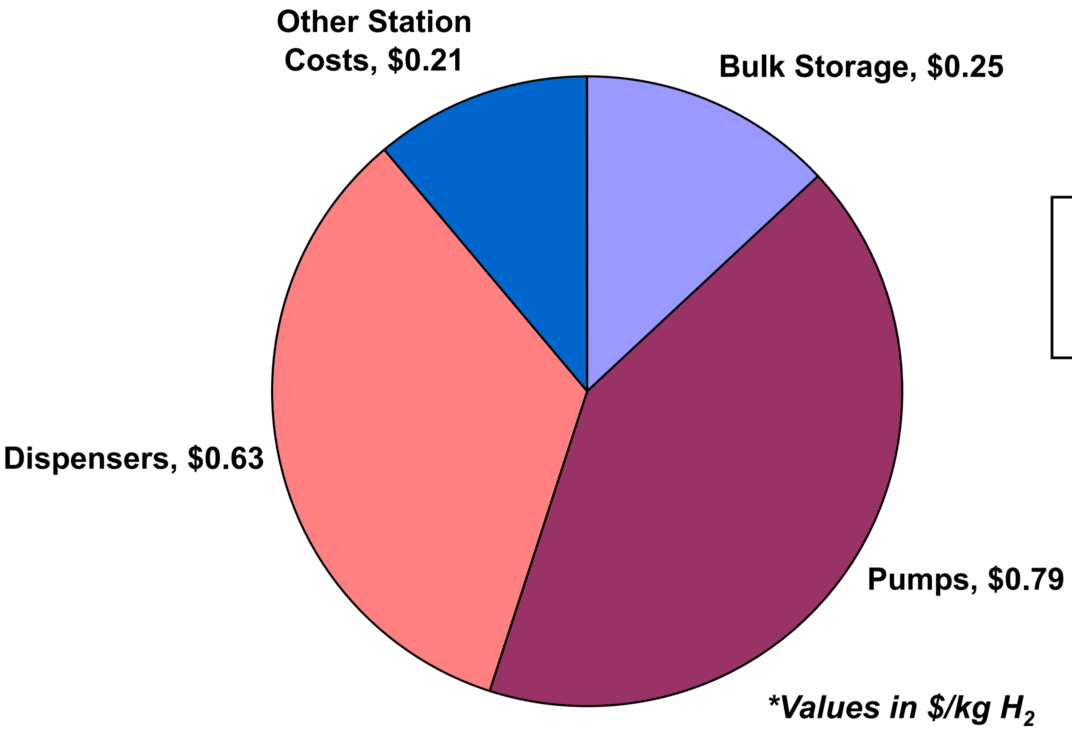
MOF 177 Fueling Station Components	Cost ($)	Specifications
Bulk storage	$323,000	4,613 kg H2, $70/kg LH2 storage
Pump	$792,000	2 pumps, 200 kg/hr capacity, 250 bar
High pressure, cryogenic dispenser	$772,000	2 units, dual hose, 250 bar, supercritical H_2

MOF-177 Refueling Station Notes:

- Bulk storage and pump costs and specifications are from HDSAM
- The cryo-dispenser is estimated to be significantly higher cost than baseline gas dispensers
- Costs of off-loading and re-dispensing gaseous H2 not included here (see cryo-comp scenario)

Similar to cryo-compressed, cryogenic fueling station costs for sorbent vehicles are dominated by pumping and dispenser costs.

MOF 177 fueling station costs ($1.87/kg H_2)

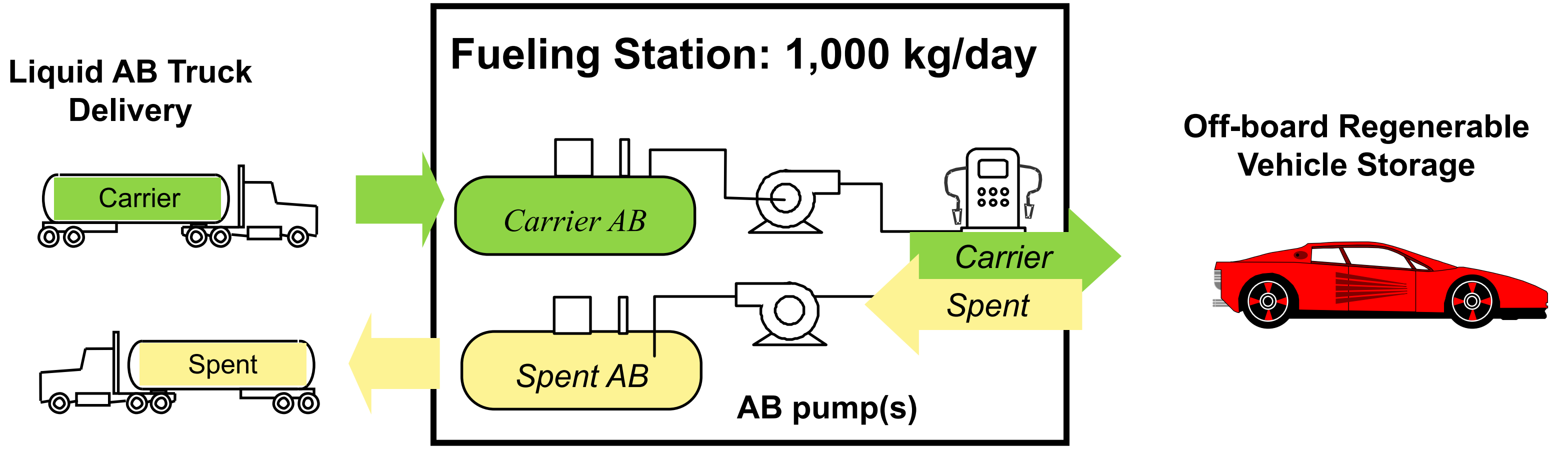


**Values in $/kg H_2*

Note that these results should be evaluated in context with other delivery costs as well as vehicle storage costs.

Equipment for recovering and re-dispensing 350 bar H_2 would add approximately $0.30/kg.

Off-board regenerable storage will utilize liquid ammonia borane (AB) as the media and will regenerate the material at a central plant.



Off-board Regenerable Refueling Station Notes:

- Delivered in liquid trucks as an ammonia borane (AB) with BMIMCl solution (LANL)
- 0.099 g_{H2}/g_{soln}; density 0.8 g/cm^3; 1.5 kg_{H2}/min results in 18.8 L/min pumping rate
- Stored at atmospheric temperature onsite
- Chemical/physical compatibility between the carrier/spent material solution and the storage tanks, pumps and dispensers will be evaluated as key components

Liquid AB refueling requirements and issues:

- Liquid AB refueling stations will operate in a similar way as conventional gasoline stations in terms of liquid storage, pumping, and dispensing
- Storage will be required for both the fresh and spent carrier material
- Station requirements and costs for a similar liquid hydrogen carrier (n-ethylcarbazole) have been evaluated using the Delivery Components Carrier Model v34[1]
- 4.6 kg H_2 (approximately 46 kg AB) in 2.8 minutes
- 2 dispensers, 4 nozzles per station, simultaneous filling
- The dispenser hose will have connect to two ports on the vehicle, one which will pump H2 rich material into vehicle and one which will pump spent material out of the vehicle

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1 - TIAX, 2009, "Liquid Hydrogen Carrier On-board and Off-board Storage System Cost Assessment," FreedomCAR Tech Team Meeting, June.

A liquid AB station has similar component requirements to a gasoline station, with the notable exception of needing to off-load and store spent material.

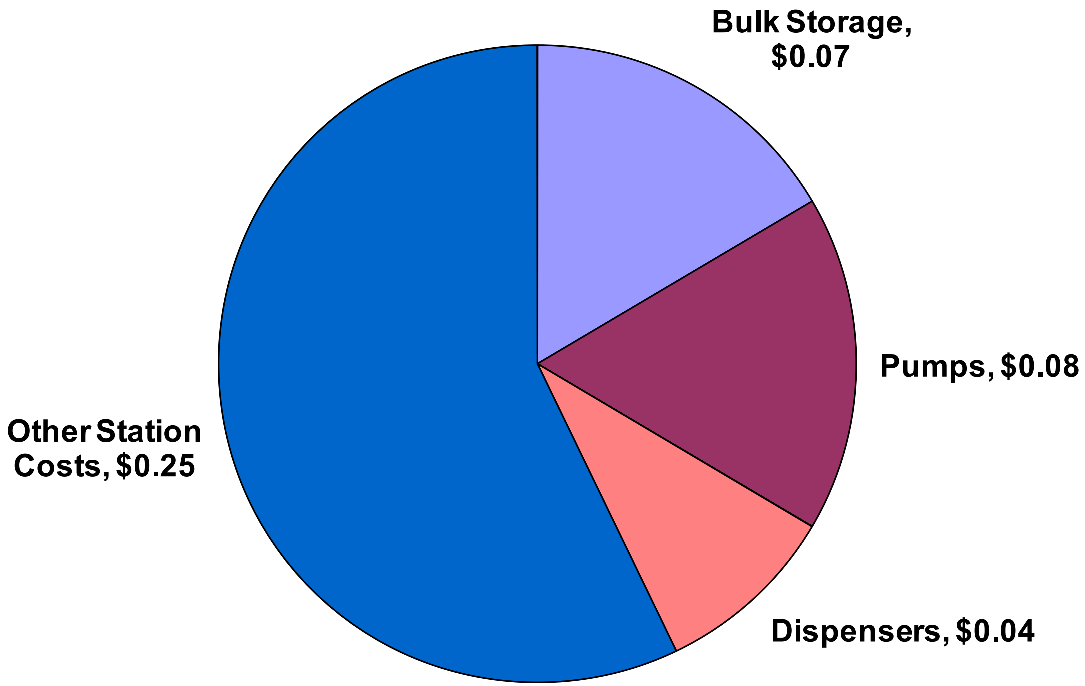
AB Fueling Station Components	Uninstalled Cost ($)	Specifications
Material	$146,000	16,200 gal of carrier material cost associated with station, $9/kg
Bulk storage	$105,000	24,300 gal split between fresh and spent material, $4/gal storage capacity
Pumps	$2,000	Four units, low pressure, ~5 gpm each
Dispensers	$40,000	2 units, dual hose, ambient temp, low pressure

Off-board Regenerable Refueling Station Notes:

- Bulk storage and pumping costs from previous LCH2 modeling efforts
- Dispenser cost similar to E85 dispenser costs (lower than HDSAM baseline)
- AB and other liquid chemicals often show relatively low fueling station costs

The major station components have relatively low costs due to the ambient temperature, low pressure requirements.

Liquid AB fueling station costs ($0.44/kg H_2)

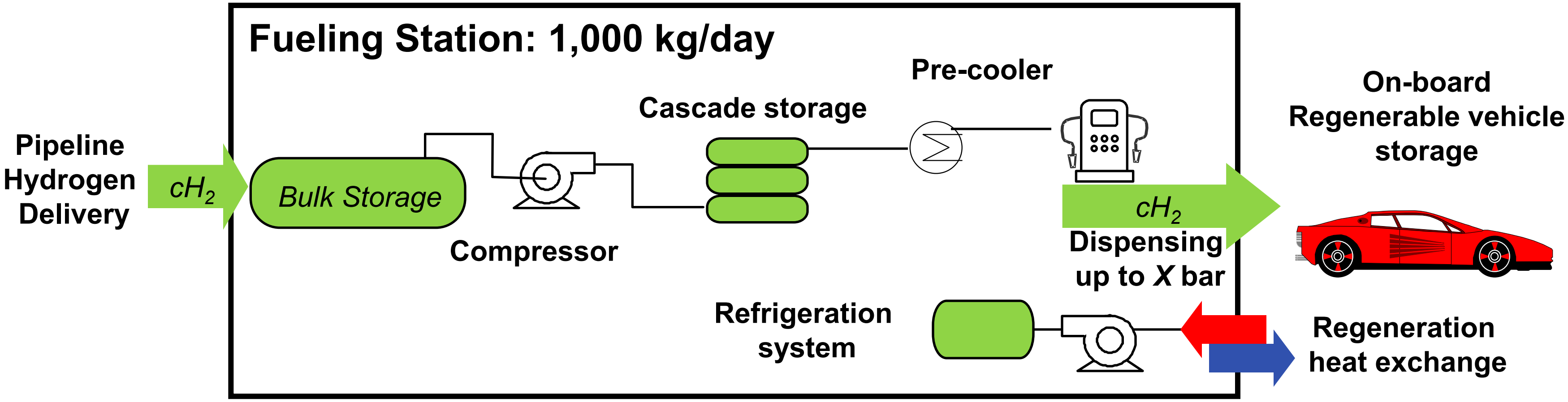


Note that these results should be evaluated in context with other delivery costs as well as vehicle storage costs

Also, solid state AB (not shown) may require a significantly different dispensing approach, but would likely not be a significant cost driver compared with regeneration

About half of the “other” station costs is from the cost of the AB material associated with the station.

On-board regenerable refueling stations are similar to medium pressure H_2 stations, but require a significant vehicle tank heat exchange system.



On-board Regenerable Refueling Station Notes:

- Cost estimations are based on sodium alanate ($NaAlH_4$)
- System will be similar to medium pressure gas dispensing at 100 bar
- A cooling loop (and/or precooling) is required to dissipate the heat of regeneration of approximately 40 kJ/mol
- We assume a high temperature oil with a high flash point in a multi-stage heat exchanger using a 10°C ΔT to maintain the kinetics of the reaction

Sodium alanate refueling station requirements and issues:

- Gaseous 100 bar hydrogen will dispensed similar to a 350 bar station, although dispensers and compressors will be less expensive
- 4.6 kg H2 in 2.8 minutes
- 2 dispensers, 4 nozzles per station, simultaneous filling
- Substantial heat exchangers and pumps will be required to reject the heat generated during vehicle refueling

Sodium alanate refueling station components:

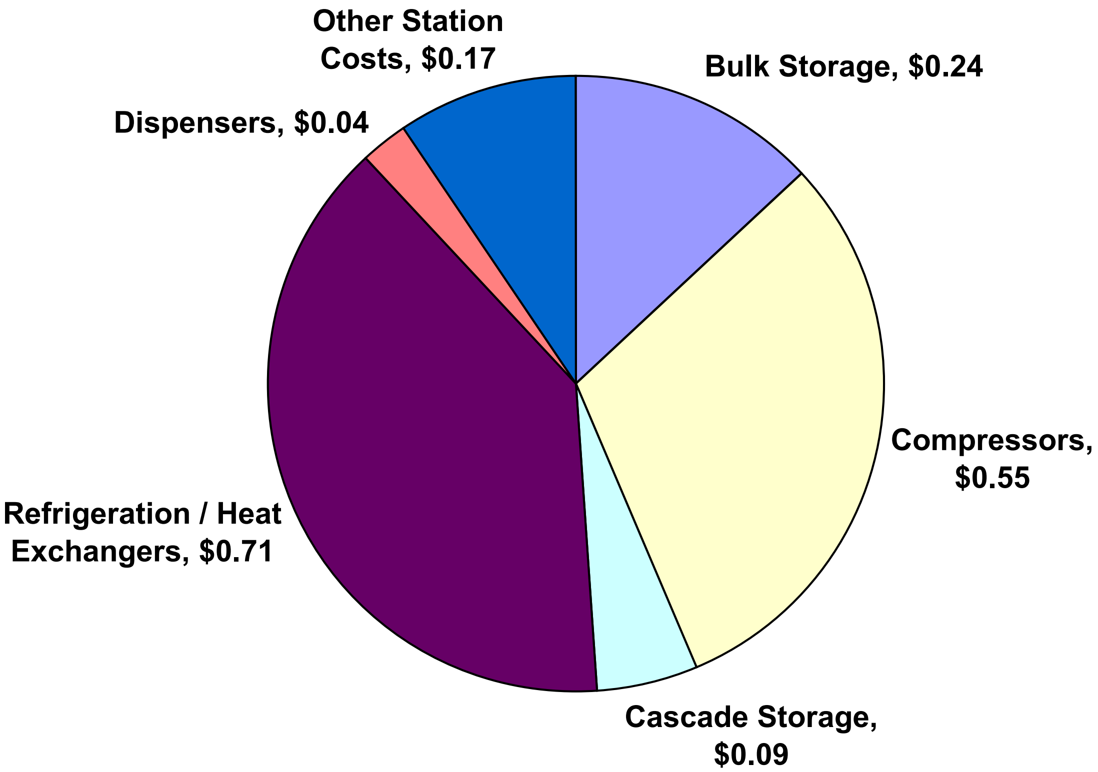
Sodium Alanate Fueling Station Components	Cost ($)	Specifications
Bulk storage	$320,000	4 units, 89 kg each, $900/kg capacity
Compressors	$398,000	3 units, 27 kg each
Cascade Storage	$126,000	136 kg, 125 bar peak
Dispenser	$80,000	2 units, dual hose, 100 bar
Heat Exchanger	$330,000	4 units, 2 MW capacity each
Heat Exchanger Pump	$400,000	4 units, 200 hp each

On-board Regenerable Refueling Station Notes:

- Bulk storage, compressor, cascade, and dispenser specifications and costs estimated by modifying HDSAM for the lower pressure requirement (i.e., 100 bar)
- Heat exchanger and pump specifications were modeled based on the heat of regeneration of sodium alanate (~40 kJ/mol) and the required refueling rate

Cooling equipment and compressors account for 70% of the fueling station costs.

Sodium alanate fueling station costs ($1.81/kg H_2)



Note that these results should be evaluated in context with other delivery costs as well as vehicle storage costs

Heat recovery could reduce the energy costs by about $0.30/kg, but there would be added costs for energy recovery equipment.

The on-board regenerable storage scenario will include a pump and heat exchanger for the cooling fluid removing heat during refueling.

Cooling System Sizing Calculation:

- Cool paratherm from 260^{o}C to 250^{o}C to still allow for the reaction to occur in the fueling talk
- Cooling load of 2,020 kW (17 MMBtu/hr)
- Very high paratherm pumping rate (~1600gpm)
- Estimated energy consumption 1.65 kWh/kg

Cooling Equipment Cost Estimate (Based on above capacity):

Heat exchanger (per nozzle)	$68,700*
Pump with explosion proof housing (per nozzle)	$83,300*
Installation factor (Consistent with H2A)	1.2
Total capital cost (per nozzle)	$182,400

*Cost estimates based on escalation assumptions from “Product and Process Design Principles”

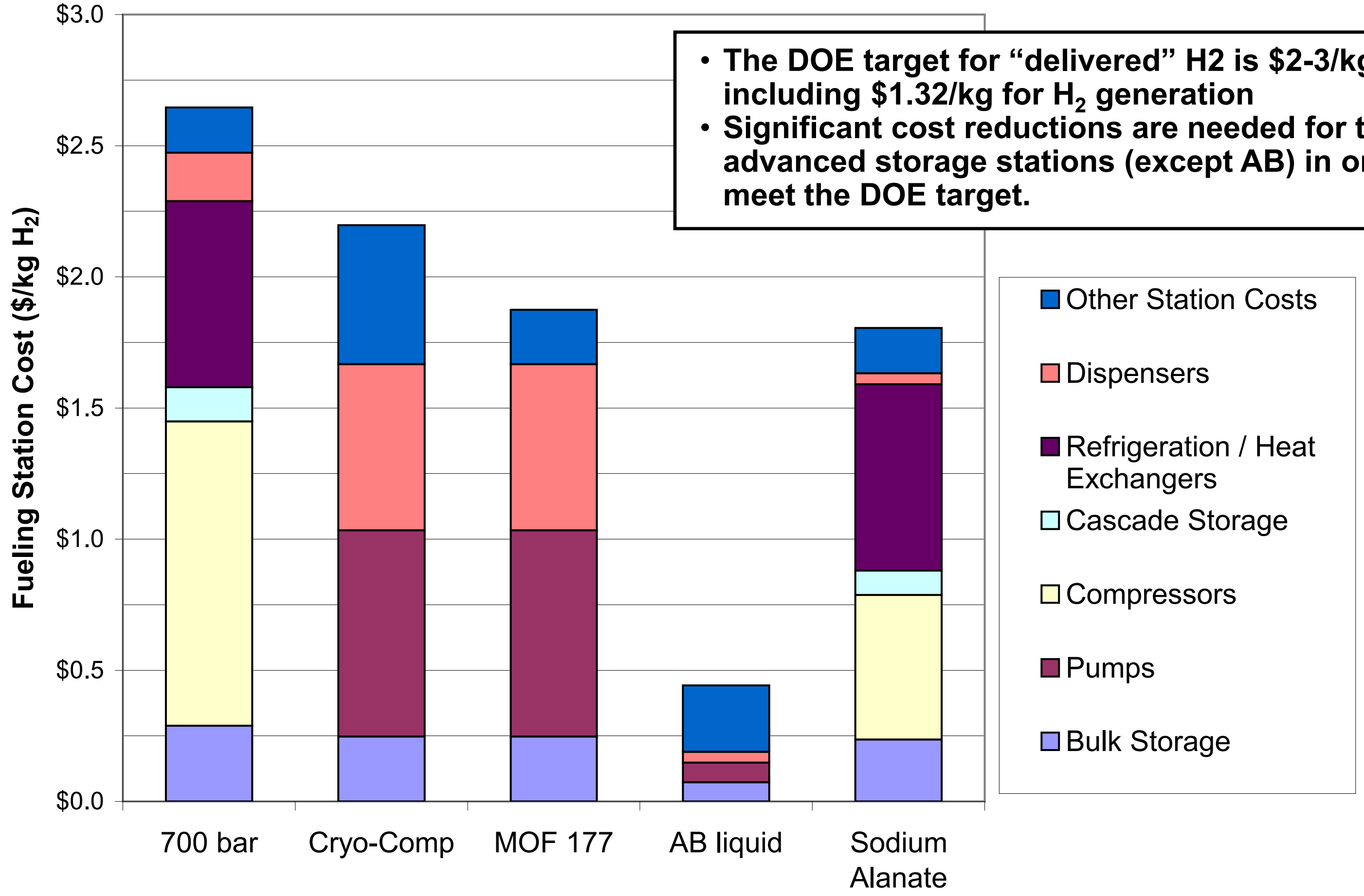
There would be approximately 7.5 GWh/yr available for energy recovery.

Energy recovery calculations:

- Approximately 217 cars/day at 2.8 mins/car and a 2 MW heat transfer rate during dispensing
- 20.5 MWh/day or 7.5 GWh/yr of potential energy rocovery.
- Assuming an organic Rankine cycle (ORC) energy recovery system operating at 250°C, 15% of the available energy might be recovered
- 1.1 GWh/yr of actual energy recovery.
- This is about equivalent to the pumping and compression energy needs (~1.2 GWh/yr) for the station
- Note, there may be other losses in the energy recovery and/or storage system before the energy is recovered in practice

The recoverable energy could approximately offset the energy needs of the pumps and compressors.

Generally, advanced storage stations are more costly than baseline HDSAM estimates due to increased cooling and dispensing estimates.



- **The DOE target for "delivered" H2 is $2-3/kg H_2 including $1.32/kg for H_2 generation**
- **Significant cost reductions are needed for these advanced storage stations (except AB) in order to meet the DOE target.**

Note that station costs should be evaluated in context with other delivery and vehicle storage costs.

In general, significant advanced storage station cost reductions are needed in order to meet the overall delivery target of \$2-3/kg H_2.

- Significant pre-cooling is needed to enable 4 vehicle, simultaneous, 700 bar fills while meeting the SAE draft J2601 fueling protocol requirements
- There may be the need to recovery vented hydrogen in cryo-compressed and cryogenic sorbent scenarios to be able to achieve full-fills in vehicles arriving relatively warm
- AB liquid (or solid) fueling stations would be relatively low cost, although plant regeneration costs may be very high
- There is approximately enough recoverable energy during sodium alanate refueling to offset compression and pumping energy, but this may not be an efficient delivery approach overall (i.e., well-to-wheels)
- In general, advanced dispenser costs will likely be higher than the baseline HDSAM assumption, particularly for cryogenic dispensers

Based on our research, we recommend the following next steps:

- Evaluate energy recovery options for 700 bar refueling stations
- Review constant “nozzle” temperature filling protocol and pre-cooling reduction with variable nozzle temperature
- Work with HDSAM developers to add pre-cooling to the compressor/cascade storage optimization
- Work with HDSAM developers to adjust/add HDSAM assumptions for refueling stations supporting advanced storage vehicles
- Model major station components and costs for solid AB dispensing

This project required a significant amount of feedback and collaboration with equipment manufacturers and national labs.

Refueling Dynamics

- St. Croix Research

Dispensers:

- Cryostar
- FTI International
- Kraus Global
- Northwest Pump and Equipment

Compressors and pumps:

- Argonne National Laboratory
- BMW
- Air Products

Materials:

- Los Alamos National Laboratory
- Pacific Northwest National Laboratory

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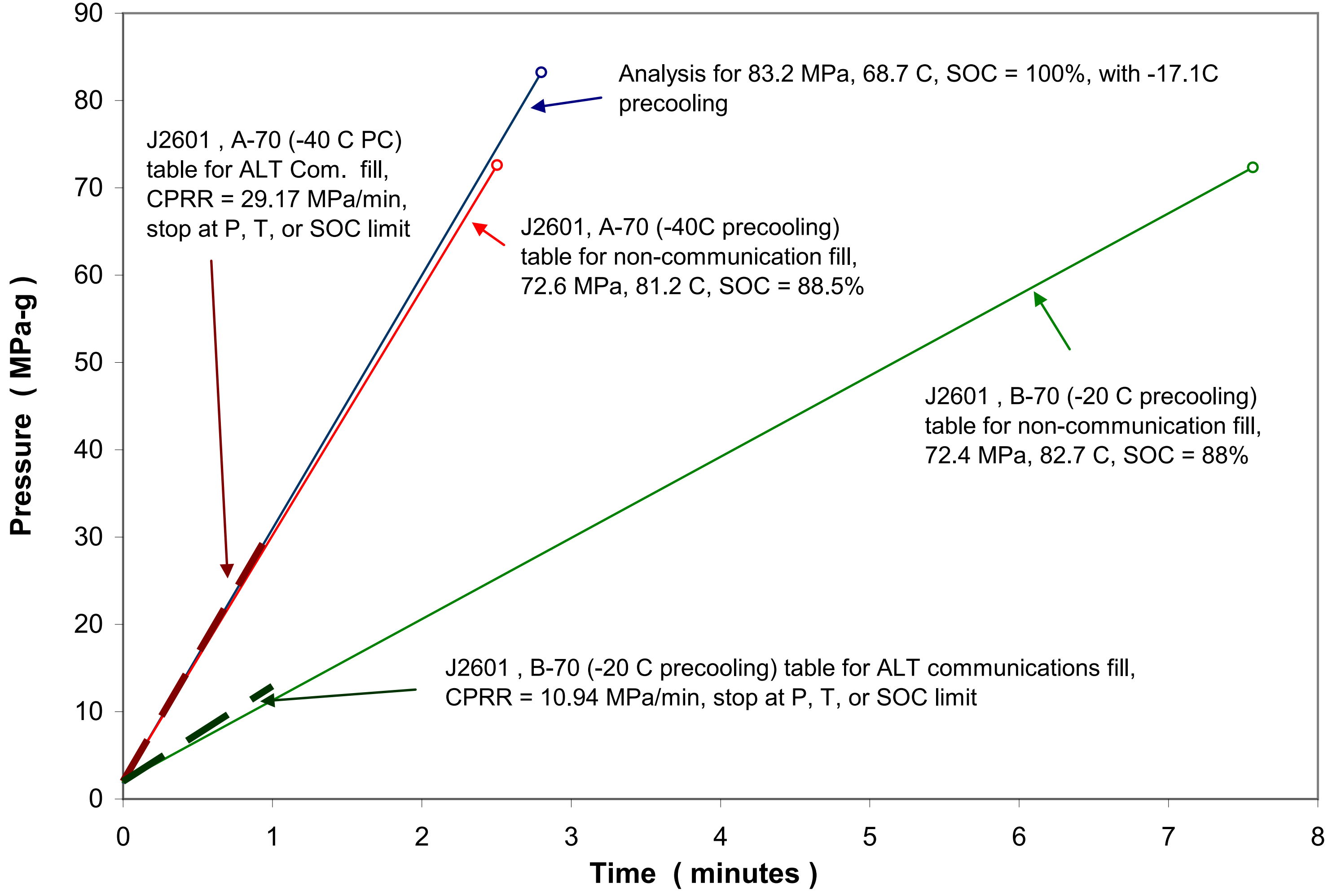
The modeling of the filling process compares well with J2601 standards, although there are minor differences.

- J2601 considers two types of fills: communication and non-communication. 70 MPa Type III and IV tanks are lumped into only two groups: 1-7 kg and 7-10 kg. Pre-cooling is lumped into two possibilities -40 C and -20 C. For non-communication filling, tables specify the constant pressure ramp rate, the fueling target (i.e., stop filling) pressure, and the anticipated lower limit ending state-of-charge (SOC) as a function of the ambient temperature and initial tank pressure. Note that the SOC numbers in the tables are sort of a worst case (the “hot soak” assumption), because the initial tank temperature may be unequal to ambient.
- For communication fills, only an initial CPRR is specified as a function of initial tank pressure and temperature, because the communication and control system is supposed to tell the dispenser when to stop the fill.
- Four of the J2601 tables could be considered to apply to the modeled vehicle tank: A-70 (1-7 kg, -40C) non-com, B-70 (1-7 kg, -20C) non-com, A-70 (1-7 kg, -40C) com, and B-70 1-7 kg, -20C) com.

The modeling of the filling process compares well with J2601 standards, although there are minor differences.



Analysis for 83.2 MPa, 68.7 C, SOC = 100%, with -17.1C precooling

J2601 , A-70 (-40 C PC) table for ALT Com. fill, CPRR = 29.17 MPa/min, stop at P, T, or SOC limit

J2601, A-70 (-40C precooling) table for non-communication fill, 72.6 MPa, 81.2 C, SOC = 88.5%

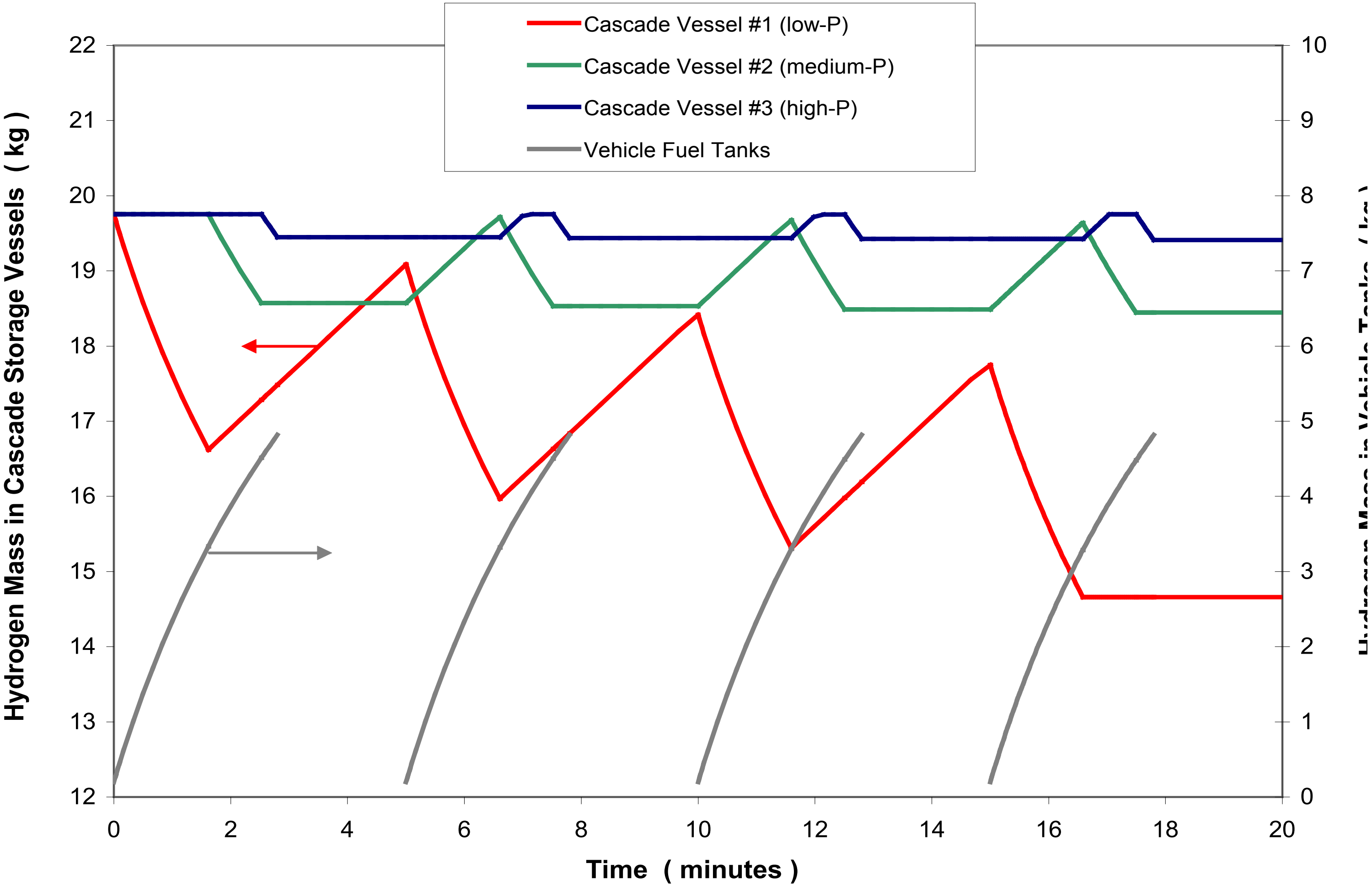
J2601 , B-70 (-20 C precooling) table for non-communication fill, 72.4 MPa, 82.7 C, SOC = 88%

J2601 , B-70 (-20 C precooling) table for ALT communications fill, CPRR = 10.94 MPa/min, stop at P, T, or SOC limit

The following assumptions were used to analyze the case of four vehicles filling sequentially

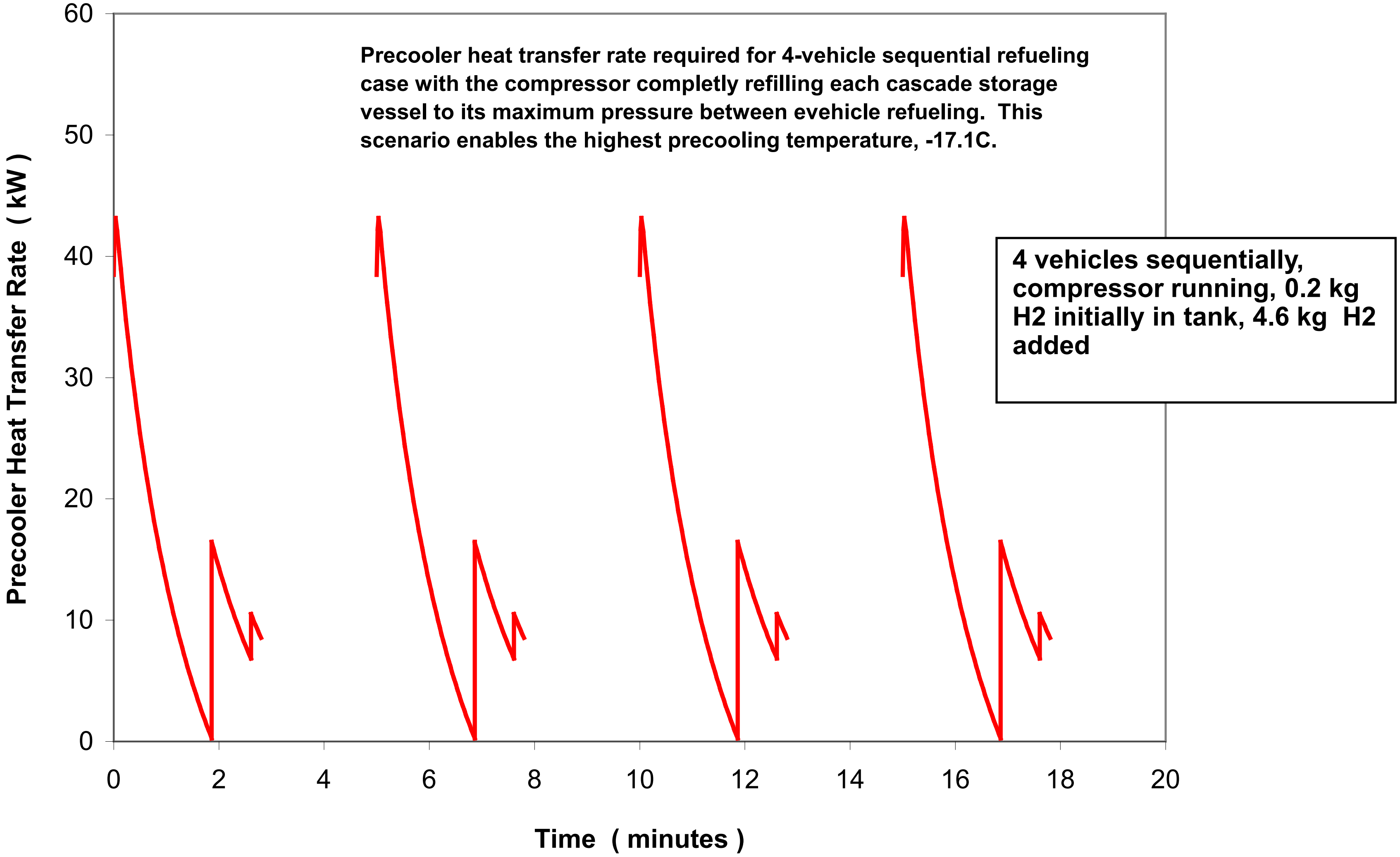
- Four vehicles refueled in sequence (2.8-minute refueling & 2.2-minute linger)
- All four vehicles receive full fills (SOC = 100%, which corresponds to each vehicle receiving 4.6 kg)
- All four vehicles are refueled with a constant pressure ramp rate and hydrogen pre-cooled to -17 C,
- Providing full fills to all four vehicles in a sequence with 5-minute cycle times definitely requires compressor operation during this refueling scenario in order to partially refill each cascade vessel with hydrogen.

Another scenario examined was the cooling requirements for four vehicles filled sequentially.



4 vehicles sequentially, compressor running, 0.2 kg H2 initially in tank, 4.6 kg H2 added

Another scenario examined was the cooling requirements for four vehicles filled sequentially.



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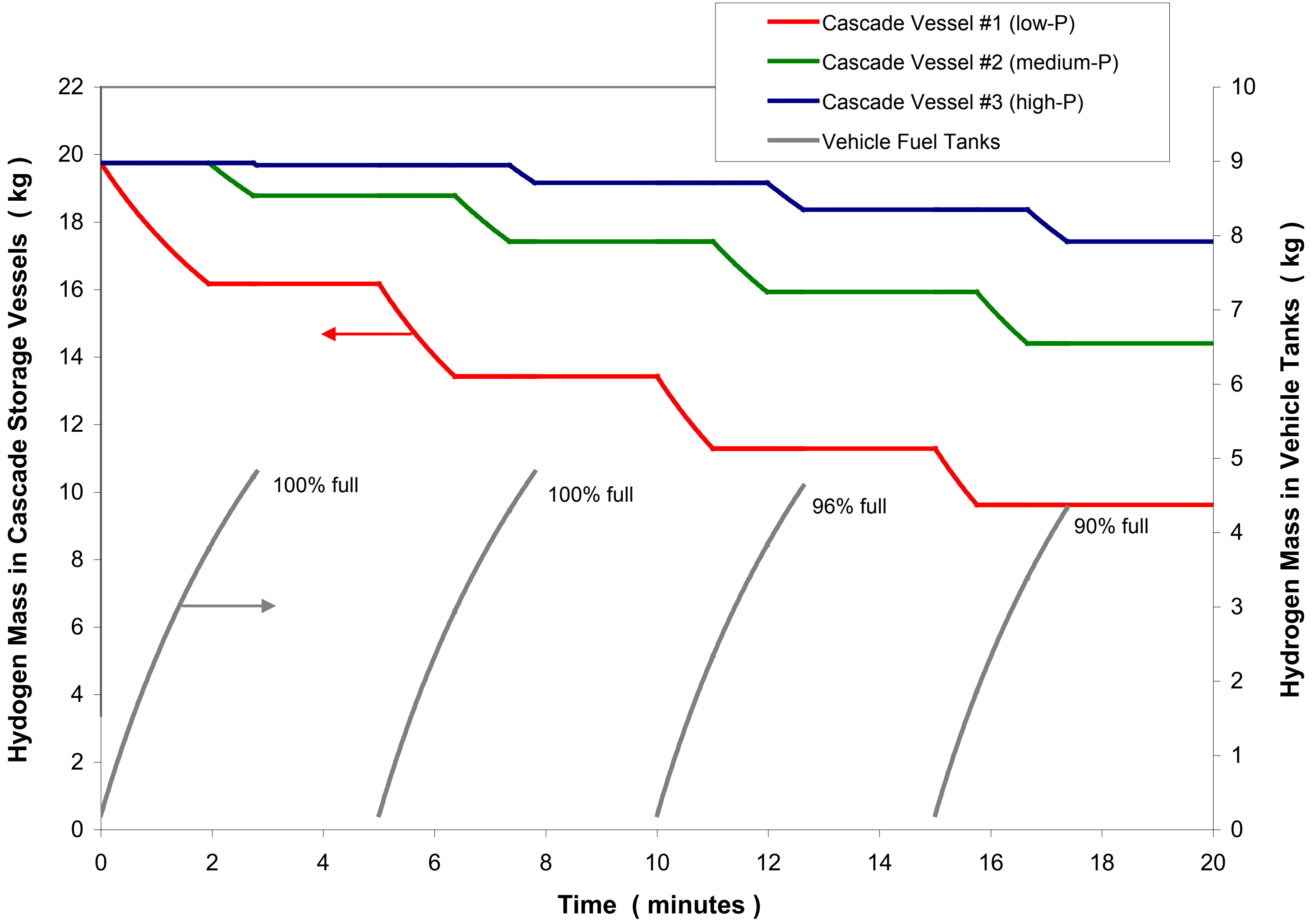
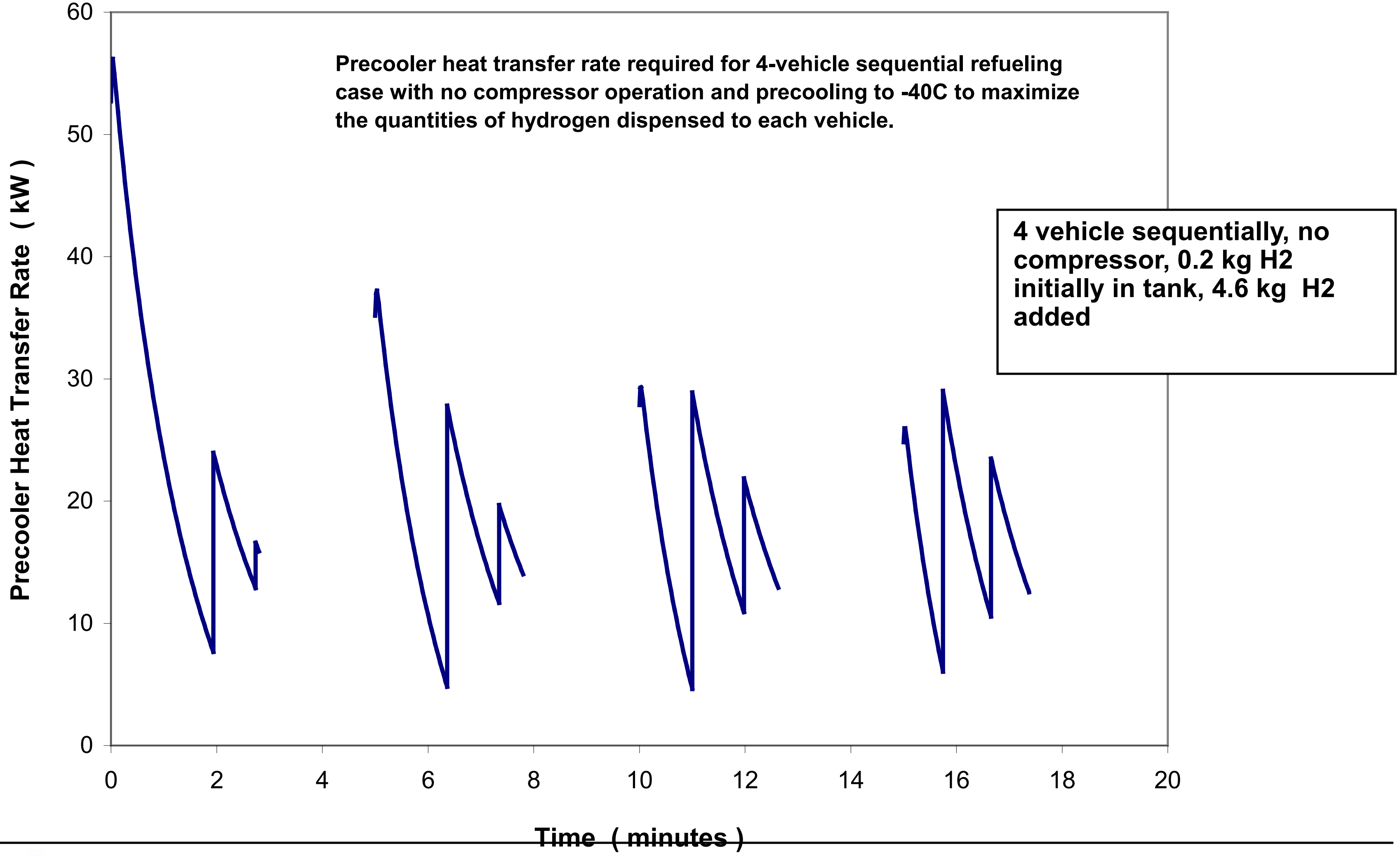


4 vehicle sequentially, no compressor, 0.2 kg H2 initially in tank, 4.6 kg H2 added

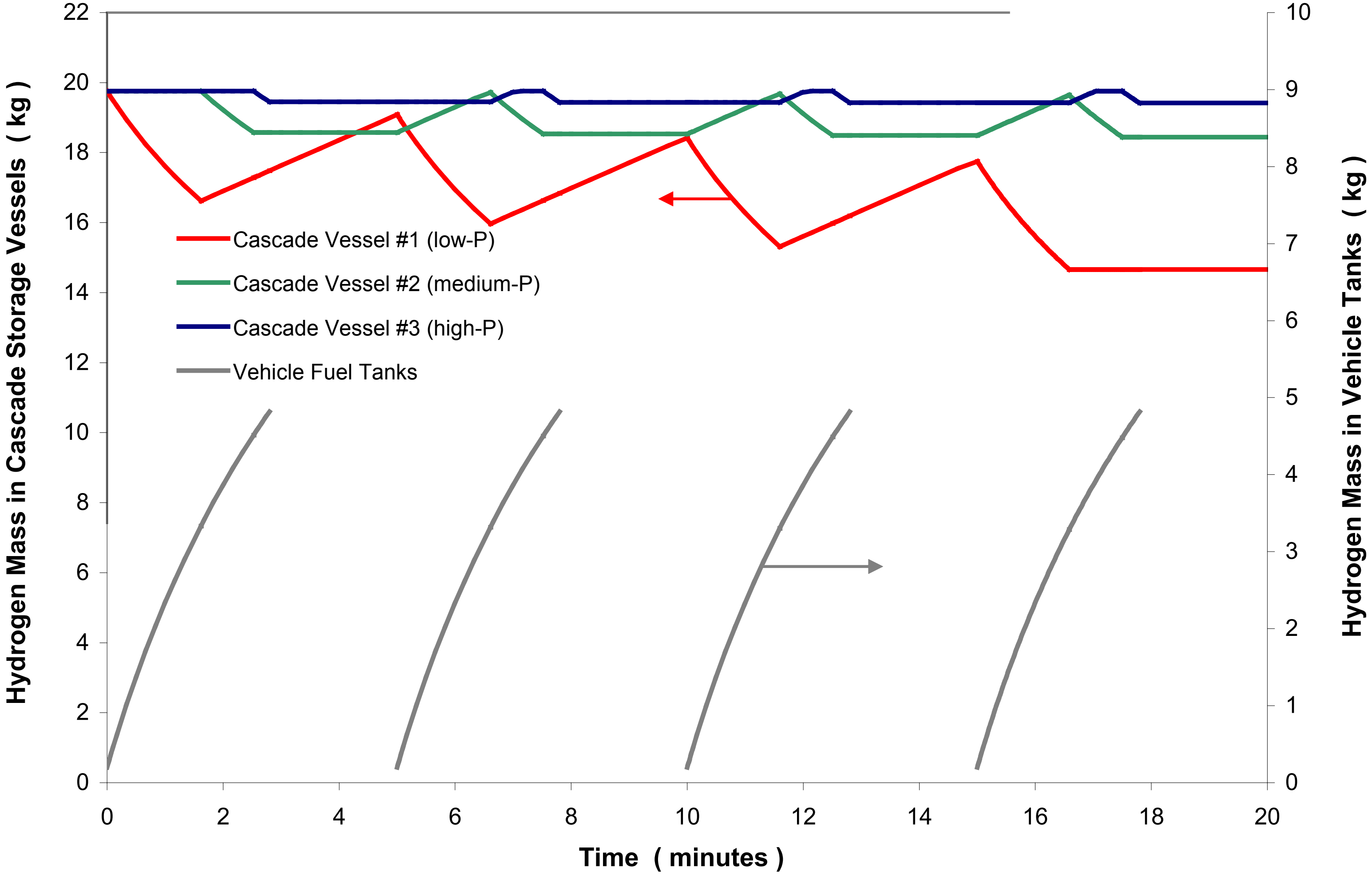
Another scenario examined was the cooling requirements for four vehicles filled sequentially.



Precooler heat transfer rate required for 4-vehicle sequential refueling case with no compressor operation and precooling to -40C to maximize the quantities of hydrogen dispensed to each vehicle.

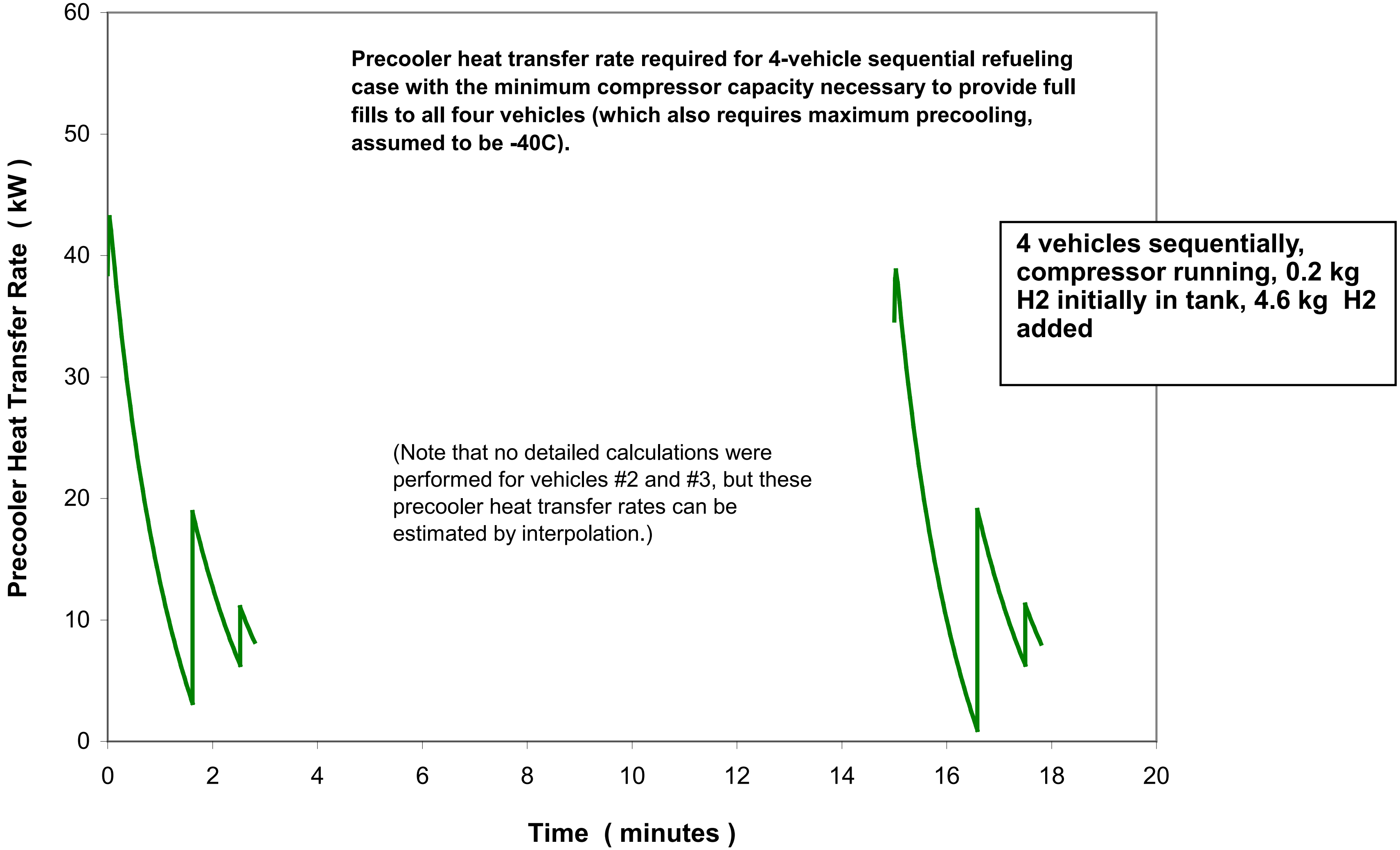
4 vehicle sequentially, no compressor, 0.2 kg H2 initially in tank, 4.6 kg H2 added

Another scenario examined was the cooling requirements for four vehicles filled sequentially.



4 vehicles sequentially, compressor running, 0.2 kg H2 initially in tank, 4.6 kg H2 added

Another scenario examined was the cooling requirements for four vehicles filled sequentially.



Precooler heat transfer rate required for 4-vehicle sequential refueling case with the minimum compressor capacity necessary to provide full fills to all four vehicles (which also requires maximum precooling, assumed to be -40C).

4 vehicles sequentially, compressor running, 0.2 kg H2 initially in tank, 4.6 kg H2 added

(Note that no detailed calculations were performed for vehicles #2 and #3, but these precooler heat transfer rates can be estimated by interpolation.)