the Energy to Lead

Compressor-Less
Hydrogen Refueling Station Using Thermal Compression

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Gas Technology Institute

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Project ID: PD126

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Overview

Timeline

- Start: August 2015
- End: August 2017
- Progress: 30% Complete

Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis
B. Reliability and Cost of Hydrogen Compression
I. Other Fueling Site/Terminal Operations

Budget

- Total Project Funding: $625k
  - Federal Funds - $500k
  - Cost Share - $125k
- Total DOE Funds Spent*: $117,000
- Cost Share Percentage: 15%

* as of 3/31/2016

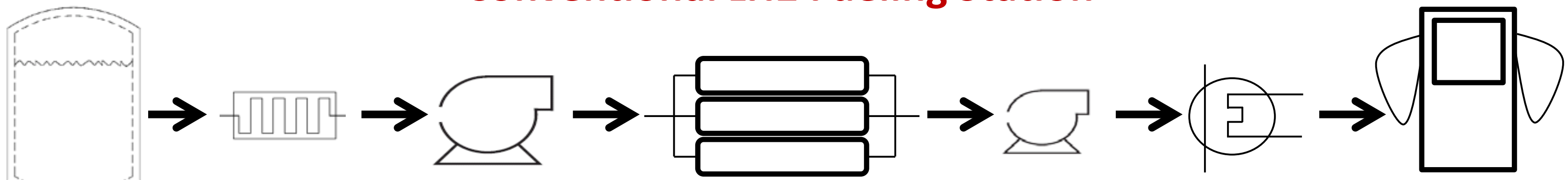
Partners

- **GTI:** Lead, fueling station design, BOP specification
- **LLNL:** Thermodynamic modeling, experimental proof of concept
- **ORNL:** Cost-effective stationary storage
- **Shell:** Refueling station operator perspective

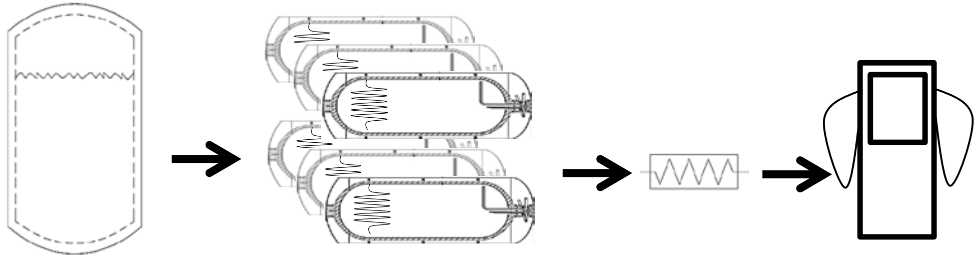
Relevance

Objective **-** Demonstrate the technical and economic feasibility of the thermal compression concept for 700 bar H2 fueling stations.

Conventional LH2 Fueling Station



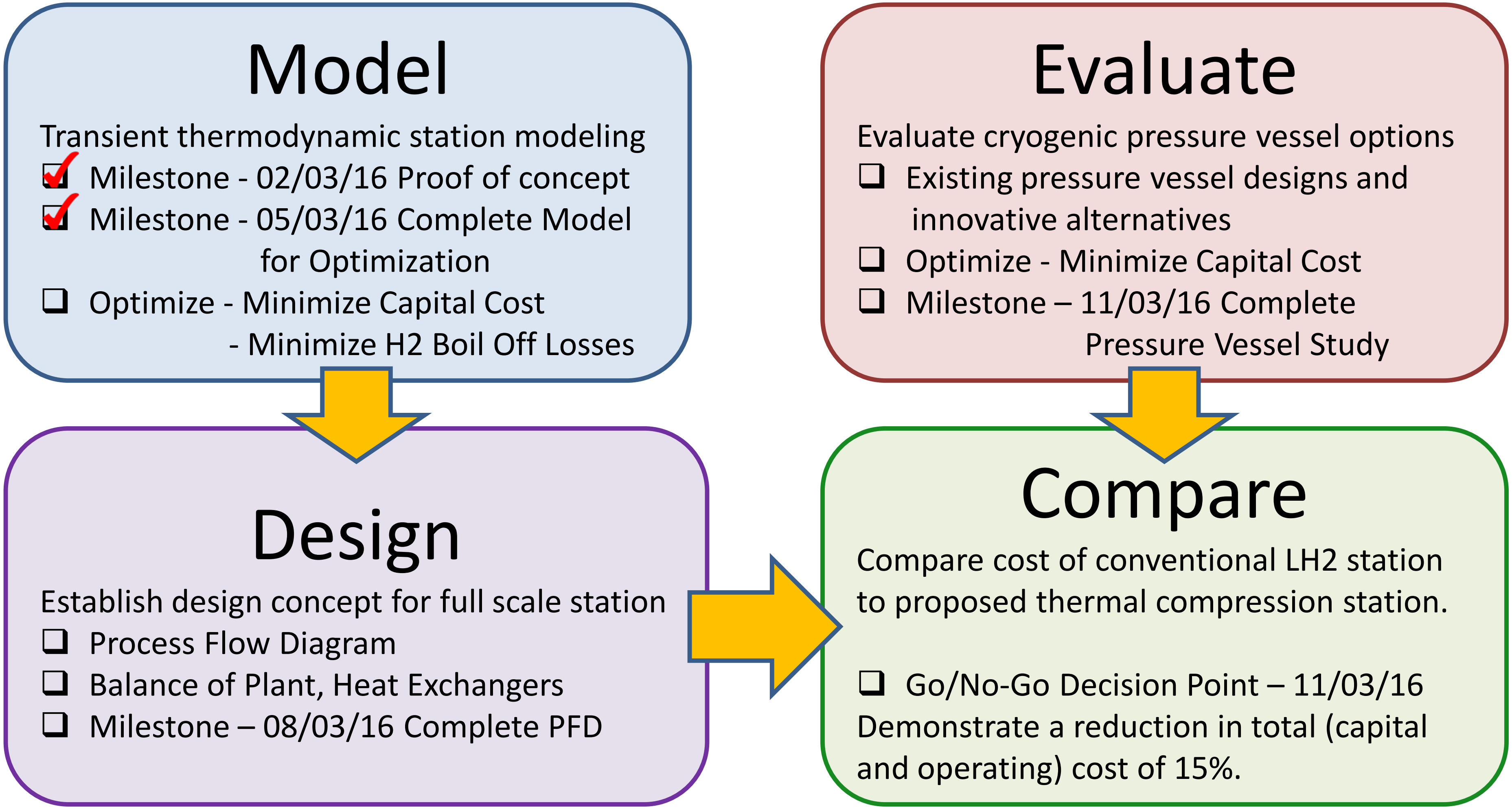
Thermal Compression LH2 Fueling Station



Impact on DOE Barriers	
A	Minimize energy loss in LH2 to GH2 refueling stations
B	Eliminate use of compressor(s)
I	Remove need of refrigeration chiller

Approach

Thermal Compression Refueling Station
Budget Period #1 (08/03/15 – 11/03/16)



Model

Transient thermodynamic station modeling
- ☑ Milestone - 02/03/16 Proof of concept
- ☑ Milestone - 05/03/16 Complete Model for Optimization
- ☐ Optimize - Minimize Capital Cost
  - Minimize H2 Boil Off Losses

Evaluate

Evaluate cryogenic pressure vessel options
- ☐ Existing pressure vessel designs and innovative alternatives
- ☐ Optimize - Minimize Capital Cost
- ☐ Milestone – 11/03/16 Complete Pressure Vessel Study

Design

Establish design concept for full scale station
- ☐ Process Flow Diagram
- ☐ Balance of Plant, Heat Exchangers
- ☐ Milestone – 08/03/16 Complete PFD

Compare

Compare cost of conventional LH2 station to proposed thermal compression station.

- ☐ Go/No-Go Decision Point – 11/03/16

Demonstrate a reduction in total (capital and operating) cost of 15%.

Approach

Thermal Compression Refueling Station

Budget Period #2 (11/03/16 – 8/03/17)

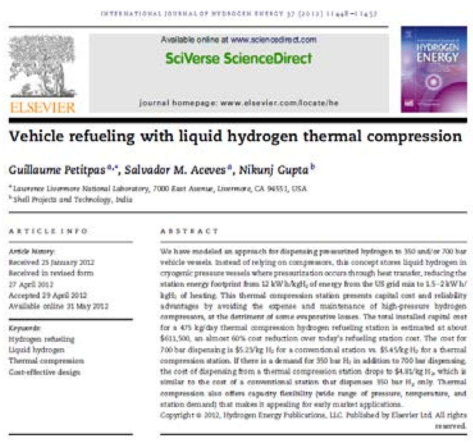
Demonstrate

Build and operate a small scale thermal compression test loop.

- ☐ Single pressure vessel (163L, 700bar, Type 3)
- ☐ 9 kg LH2 to 700 bar in < 3hrs
- ☐ Dispense at 1.5 kg/min for at least 1 minute
- ☐ Extrapolate thermodynamic system data from test loop to full-scale system
- ☐ Milestone – 05/03/17 Complete Demonstration Testing

Approach

Identification of 5 Steps of Thermal Compression Refueling



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Vehicle refueling with liquid hydrogen thermal compression

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ABSTRACT

We have modeled an approach for dispensing pressurized hydrogen to 350 and/or 700 bar vehicle vessels. Instead of relying on compressors, this concept stores liquid hydrogen in cryogenic pressure vessels where pressurization occurs through heat transfer, reducing the station energy footprint from 12 kWh/kgH$_2$ of energy from the US grid mix to 1.5–2 kWh/kgH$_2$ of heating. This thermal compression station presents capital cost and reliability advantages by avoiding the expense and maintenance of high-pressure hydrogen compressors, at the detriment of some evaporative losses. The total installed capital cost for a 475 kg/day thermal compression hydrogen refueling station is estimated at about $611,500, an almost 60% cost reduction over today's refueling station cost. The cost for 700 bar dispensing is $5.23/kg H$_2$ for a conventional station vs. $5.45/kg H$_2$ for a thermal compression station. If there is a demand for 350 bar H$_2$ in addition to 700 bar dispensing, the cost of dispensing from a thermal compression station drops to $4.81/kg H$_2$, which is similar to the cost of a conventional station that dispenses 350 bar H$_2$ only. Thermal compression also offers capacity flexibility (wide range of pressure, temperature, and station demand) that makes it appealing for early market applications.

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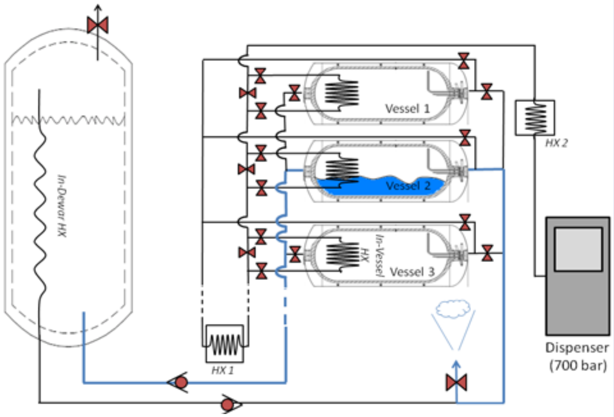
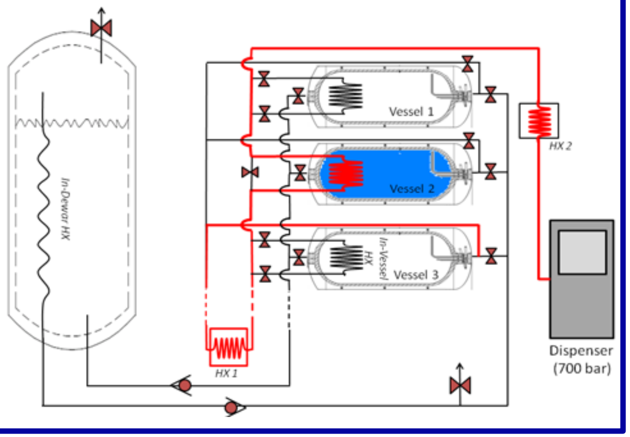
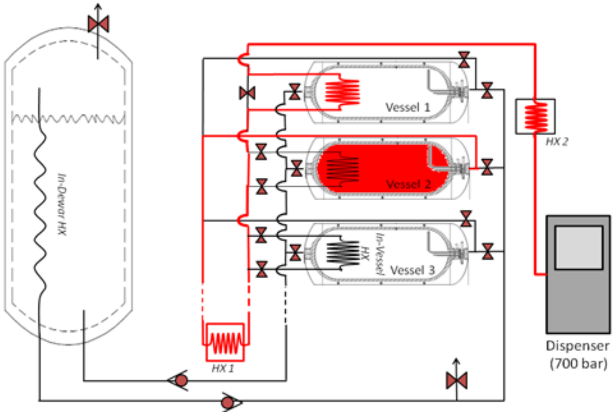
Step #1 – Fill CV with LH2



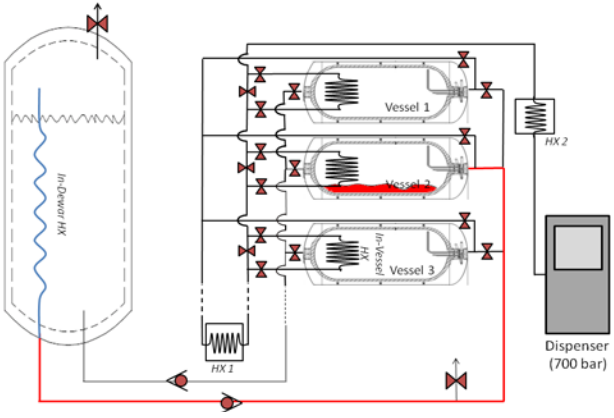
Step #2 – Heat to Increase CV Pressure



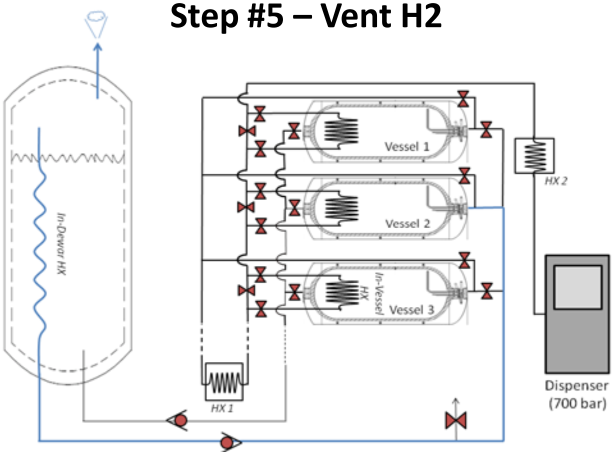
Step #3- Vehicle Fueling



Step #4 –Recycle H2 to Dewar



Step #5 – Vent H2



Project Accomplishments

Developed strategy for thermodynamic modeling approach

Station Design

Capacity: 400kg/24hr day

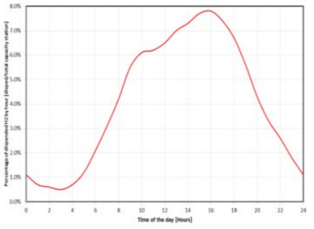
Vehicle Capacity : 5.6 kg

Amount Dispensed: 4.6 kg per car

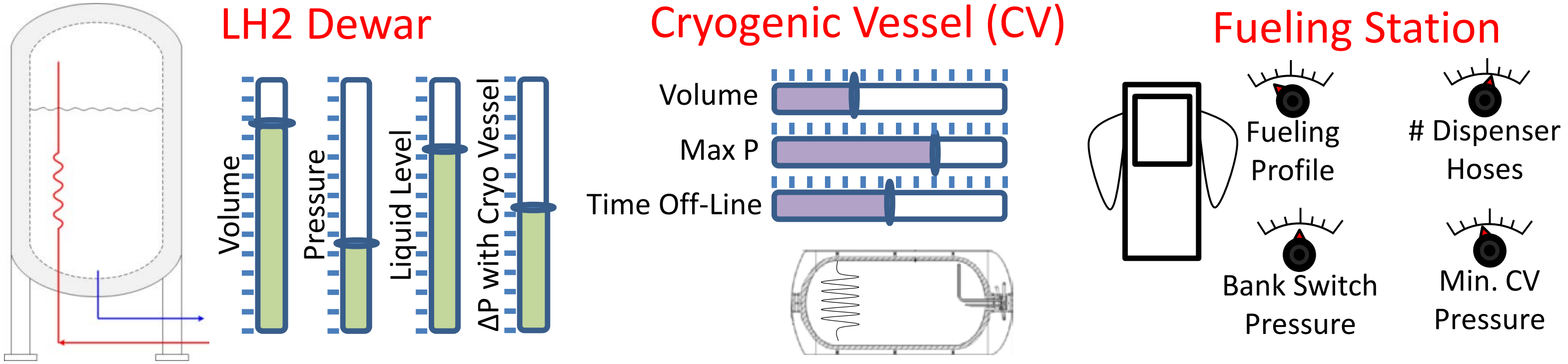
Fueling Profile: from ANL (Summer, Friday)

Fueling Temp: down to -40 C

Pressure Class: H70



Model Input Variables



LH2 Dewar

Cryogenic Vessel (CV)

Fueling Station

Model Output

and size of Cryogenic Vessels (CV)

% vented per kg H_2 delivered

Optimize

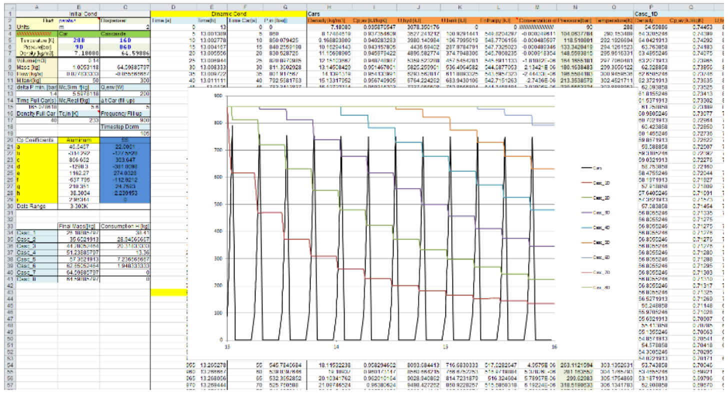
Minimize Overall Dispensing cost (Capital Cost and % Vented)

Project Accomplishments

Identified modeling framework with advantageous features for the required thermodynamic modeling

Preliminary model built on Excel (Visual Basic)

To make sure physics well captured



Drawbacks :

- Large file: 17280 x 180 spreadsheet for 20 CV over 24 hours, only for "Step 3"
- Long computation time per case, including "freezing"…

New modeling framework: Fortran 90

Advantages:

- Easy to manipulate (parameters sweep…)
- Same language as REFPROP
- Short computation time
- Free compilers are available

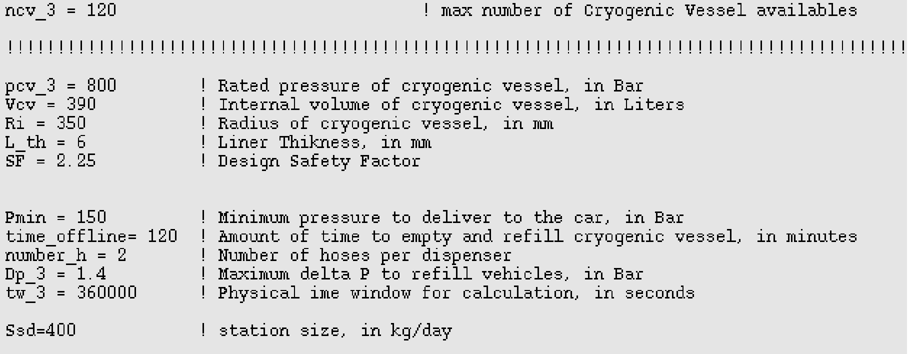
Drawbacks:

- GUI not as friendly as Excel
- Stiffer learning curve
- Debugging not straight forward

Project Accomplishments

Programmed, debugged, and evaluated the performance of the thermodynamic model

Two Fortran 90 sub-routines written (>2,000 lines each) to simulate:
(1) Transient cascading design to meet station demand
(2) H_2 boil-off during cryogenic vessel filling and recycling
(aka “Steps 1, 4 & 5”)



```
ncv_3 = 120                              ! max number of Cryogenic Vessel availables

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

pcv_3 = 800          ! Rated pressure of cryogenic vessel, in Bar
Vcv = 390            ! Internal volume of cryogenic vessel, in Liters
Ri = 350             ! Radius of cryogenic vessel, in mm
L_th = 6             ! Liner Thikness, in mm
SF = 2.25            ! Design Safety Factor


Pmin = 150           ! Minimum pressure to deliver to the car, in Bar
time_offline= 120    ! Amount of time to empty and refill cryogenic vessel, in minutes
number_h = 2         ! Number of hoses per dispenser
Dp_3 = 1.4           ! Maximum delta P to refill vehicles, in Bar
tw_3 = 360000        ! Physical ime window for calculation, in seconds

Ssd=400              ! station size, in kg/day
```

Screenshot of the input file for the transient cascading sub-routine

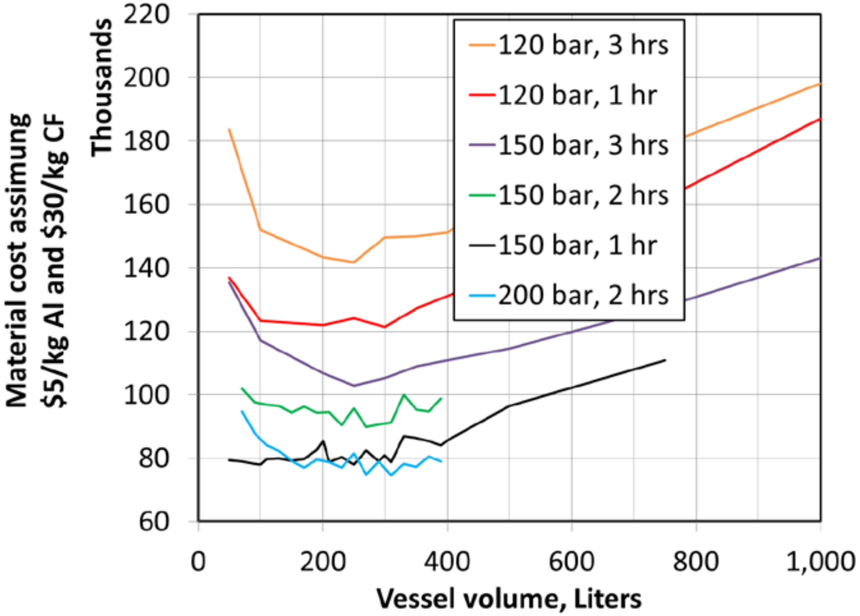
Computation time on 1 processor :

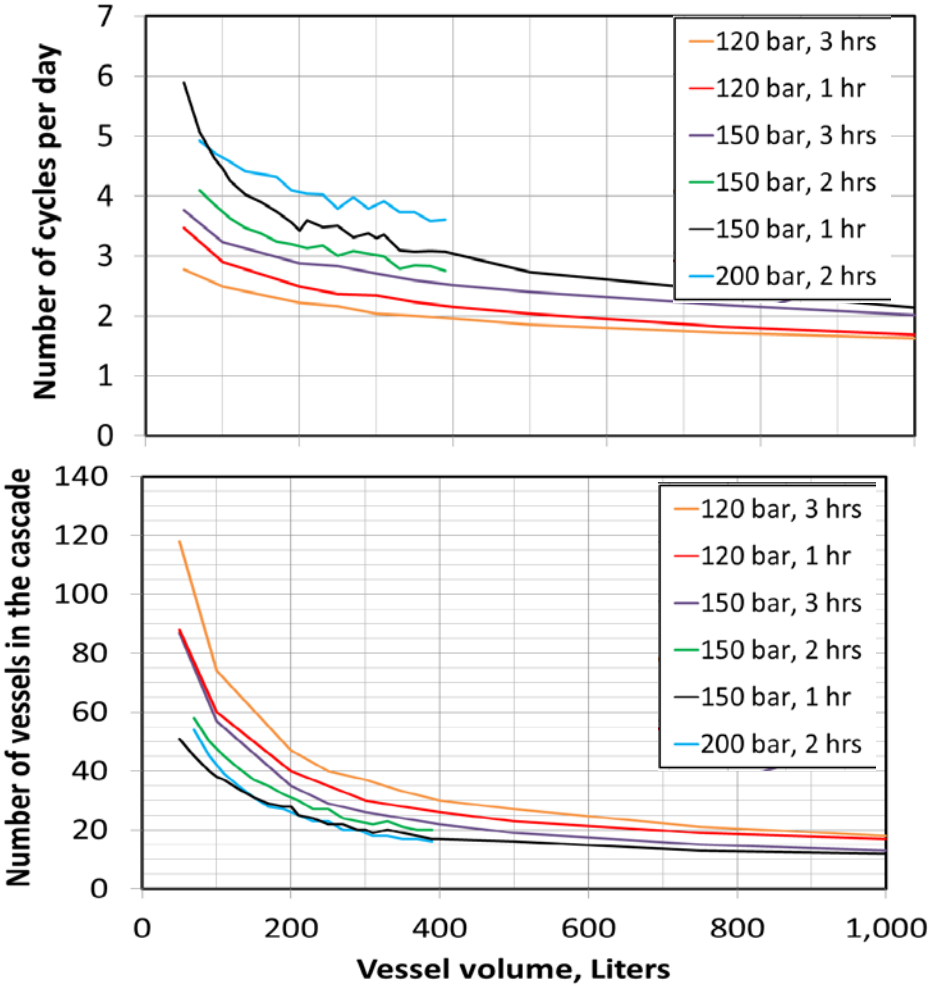
1 to 8 minutes for transient cascading
< 2 minutes for H_2 boil-off sub-routine

Project Accomplishments

Identified optimal size and quantity of type 3 cryogenic vessels necessary for 400kg/day hydrogen refueling station

Influence of switch pressure, time off-line and vessel volume on numbers and size of cryogenic vessels, thus material cost

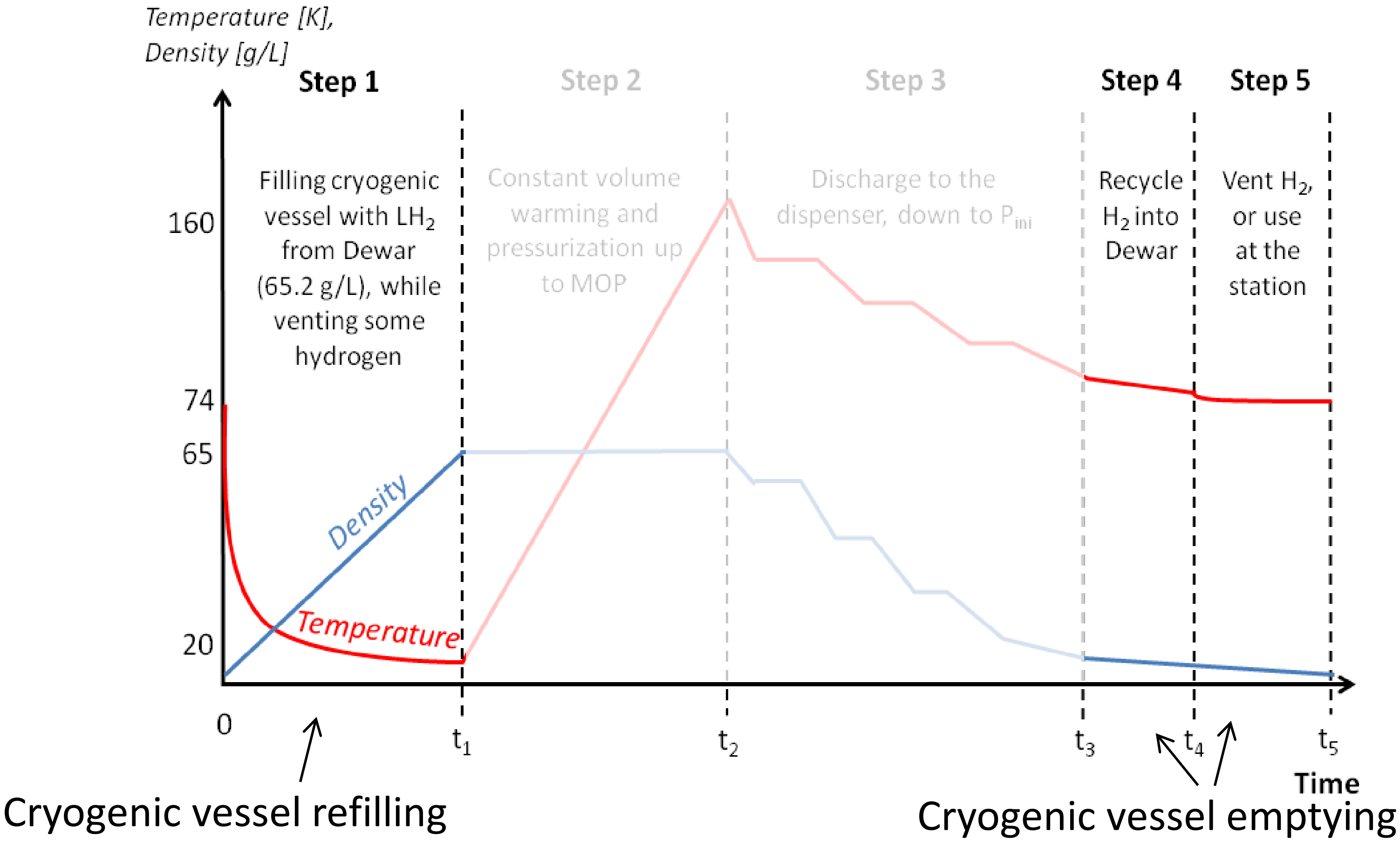




- "**Smaller & more vessels**" designs reduce material cost, by enabling more refilling/emptying cycles per vessel
- Optimal : ~200-300 Liters, ~30 vessels

Project Accomplishment

Developed model to quantify the amount of hydrogen lost to boil off during the thermal compression process



Boil-off occurs during Dewar/cryogenic vessel interactions due to temperature differences

Project Accomplishment

Defined the limits of the refueling station's design and operating parameters

- Tested 1000's of combinations of the 10 input parameters to explore best design and operating conditions that minimize boil-off, using a quasi Monte Carlo low discrepancy screening method (Sobol sequence)

#	Design parameters	Min	Max
1	CV rated pressure [bara]	700	900
2	CV volume [Liters]	100	1,000
3	CV L/D ratio [-]	1	20
4	Dewar rated pressure [bara]	1.5	6
5	Dewar volume [m^3]	10	40

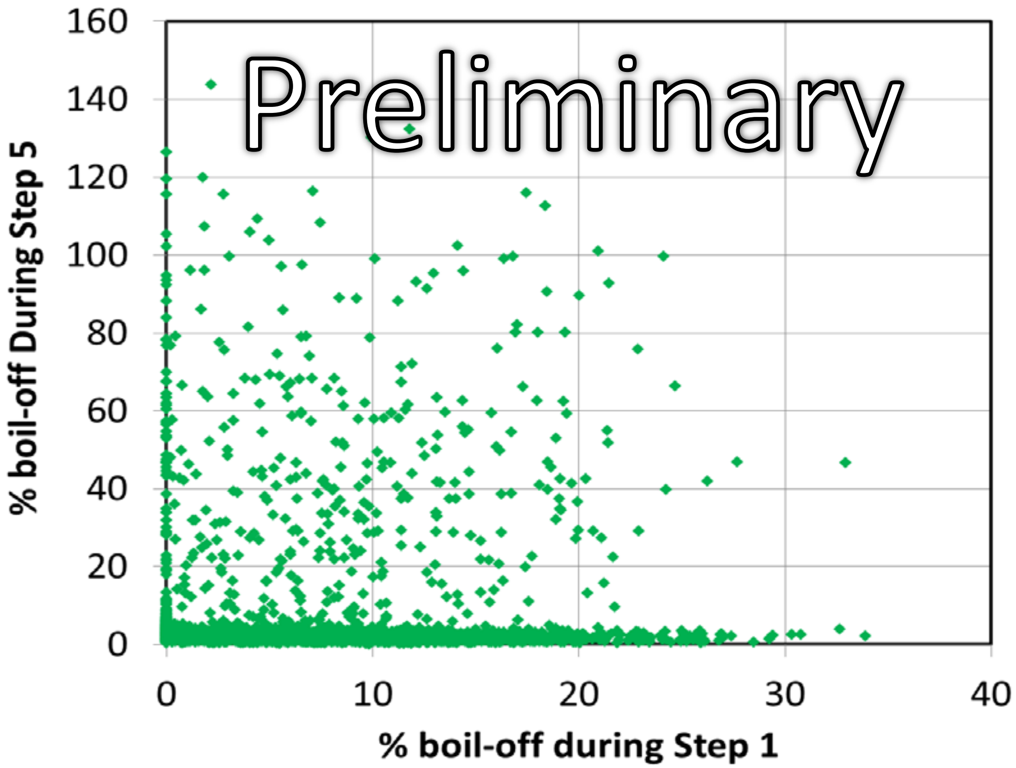
"CV"=Cryogenic Vessel

#	Operating parameters	Min	Max
6	%full (step1)	5	95
7	%full (step 4)	5	95
8	Liquid Temperature (step 1) [K]	20.3	24
9	Vapor Pressure (step 4) [bara]	1.5	6
10	Switch pressure [bara]	100	250

- Results can then be analyzed using machine learning techniques, such as High Dimensionality Model Representation (HDMR), to sort out most sensitive input parameters, including single and interaction effects

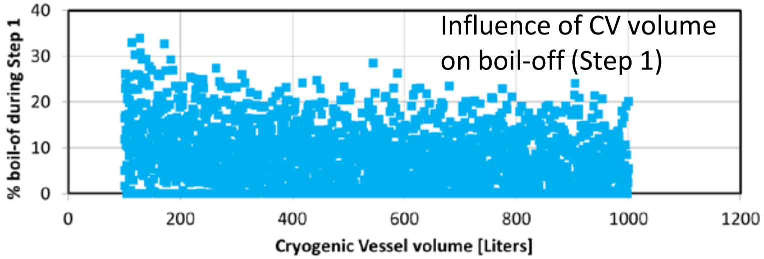
Project Accomplishment

Using thermodynamic model to identify parameters with most impact on the amount of hydrogen boil off

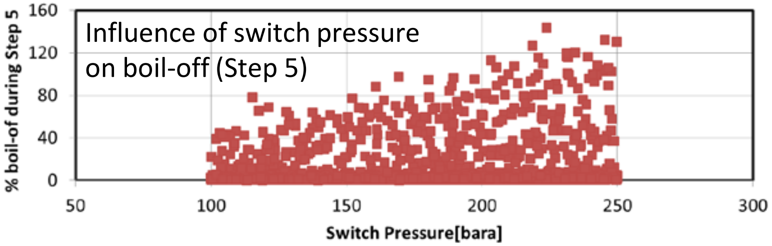


2,300 combinations of 10 parameters

	Mean	Standard Deviation
%boil-off Step 1	8	7
%boil-off Step 5	10	20
%boil-off Total	18	42



Influence of CV volume on boil-off (Step 1)

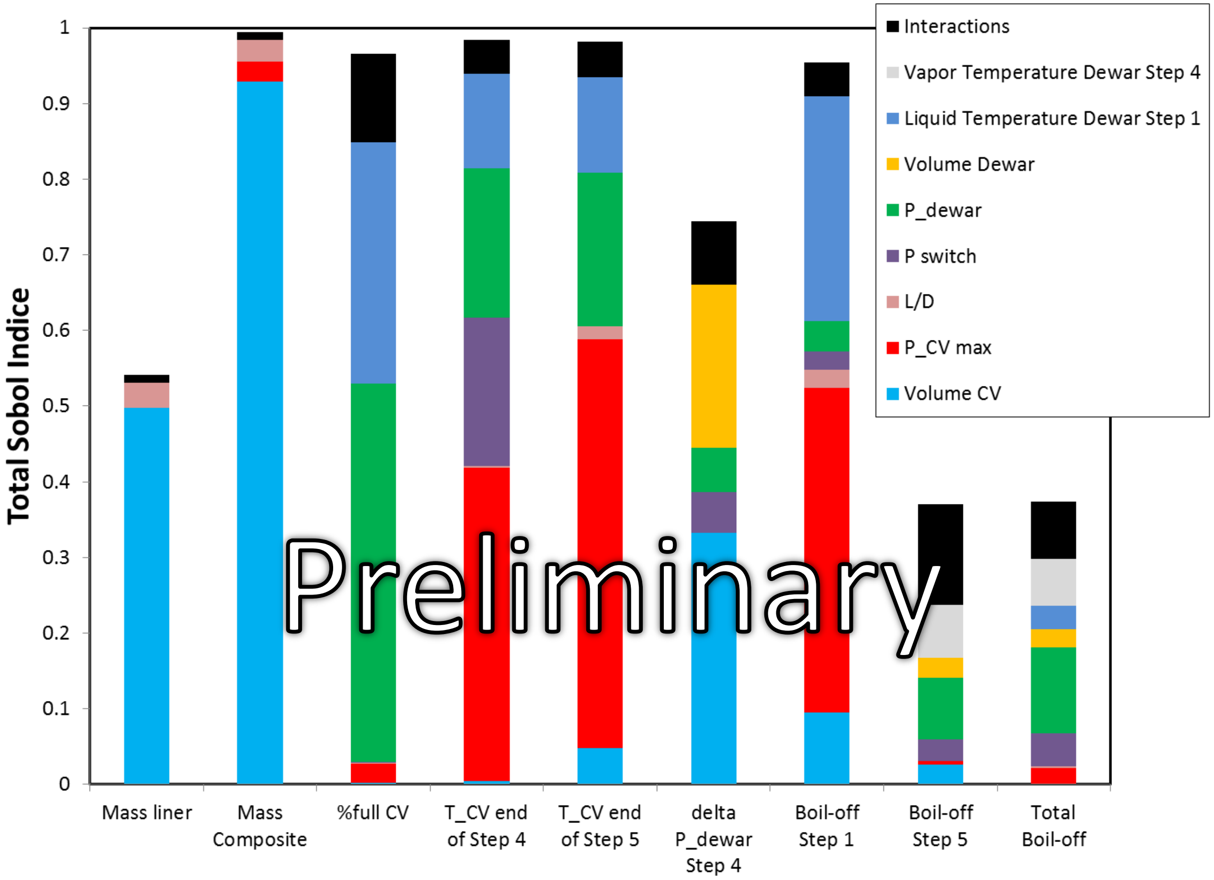


Influence of switch pressure on boil-off (Step 5)

Controlling (most sensitive) parameters difficult to single-handedly identify due to rather large distribution of the boil-off estimates, especially in Step 5

Project Accomplishment

Evaluating the impact of variables on hydrogen boil off using Sobol indices



- High Sobol Indice (up to 1) = Large influence of parameter on output
- If Total Sobol Indice close to 1 : very good polynomial fit
- Interaction between 2 parameters shown in black

Screening for "mock-up" Type 3 vessels only. Will repeat when more precise pressure vessel designs become available

Preliminary analysis of the parameter screening using High Dimensionality Model Representation shows major single effect contributions (P_CV max, Volume CV, liquid temperature Dewar, P_Dewar) but fails to adequately characterize boil-off from Step 5

Approach

Cryogenic Vessel (CV) Design

- Drivers for CV Pressure Vessel Design
  - Capable of sustaining high pressure cyclic loading and transient thermal loading over extreme temperature swing
  - Thermal mass considerations for CV operational efficiency
  - Economic and cost competitive
- Challenging CV pressure vessel operation conditions
  - Operation pressure and temperature window

    3bar @ 25K → 900 bar @ 200K   15-30 cycles/day
  - 60,000 to 110,000 cyclic loading over 10 years of service life. This is an order of magnitude higher than the life cycles for on-board cryogenic storage vessels
  - Limiting material selections and design options for cost

Project Accomplishment

Performed initial figure of merit analysis of cryogenic pressure vessels (200L @ 900 bar, 13kg H2)

Basic options	Material	Cost $/kg H2	Approx. Weight, lbs	Approx. Thermal mass, kJ/C	Remarks
Type III	Aluminum/CF [1]	High	400	250	Durability for 10^5 combined pressure and temperature loading cycles needs to be investigated for cryogenic applications[2]
	Aluminum/ Glass fiber	TBD	400	TBD	
Type I	Aluminum alloy	High	4,000	1800	ASME code compliant
	Stainless steel 304	High	5,000	1300	ASME code compliant
	Alternative steel	Low	3,000	600	Material under ASME code case consideration
	9% Ni. steel	High	2,500	500	ASME code compliant
SCCV (Type II)	Flexible	$600-800 [3]	2,500-3500	300	Design for cryogenic applications need to be refined/optimized
Type IV	Polymer liner/CF	$560-1100 @700bar [4]	TBD	TBD	Durability for 10^5 combined pressure and temperature loading cycles has been shown to be inadequate.

[1] LLNL has vessel for small scale demonstration

[2] O. Kircher, et al., BMW Group, (2011) Int. Conf. on Hydrogen safety, San Francisco, CA

[3] Z. Feng, W. Zhang, F. Ren et al. ORNL, (2013), ORNL/TM-2013/113. DOI: 10.2172/1072154

[4] Projected for projected for mass production. K. Simmons, https://www.hydrogen.energy.gov/pdfs/review13/st101_simmons_2013_o.pdf

Project Accomplishment

Completed initial design analysis for Type 1 cryogenic pressure vessel (200L @ 900 bar, 13kg H2, 200K)

- Different materials are considered for Type 1 vessel
- Initial design shows the vessel cost is lower when length/diameter ratio is larger.
- The results for a representative case **with 10in ID** are shown in the table below:
  - Balance with cost and the thermal mass, “low cost steel” is a potential candidate
  - Using ASME allowed material, Al6061, SS304 or 9%Ni, vessel cost will be above 2020 DOE cost target ($600/kg H2)
  - This low cost steel is under ASME code approval process for cryogenic service.

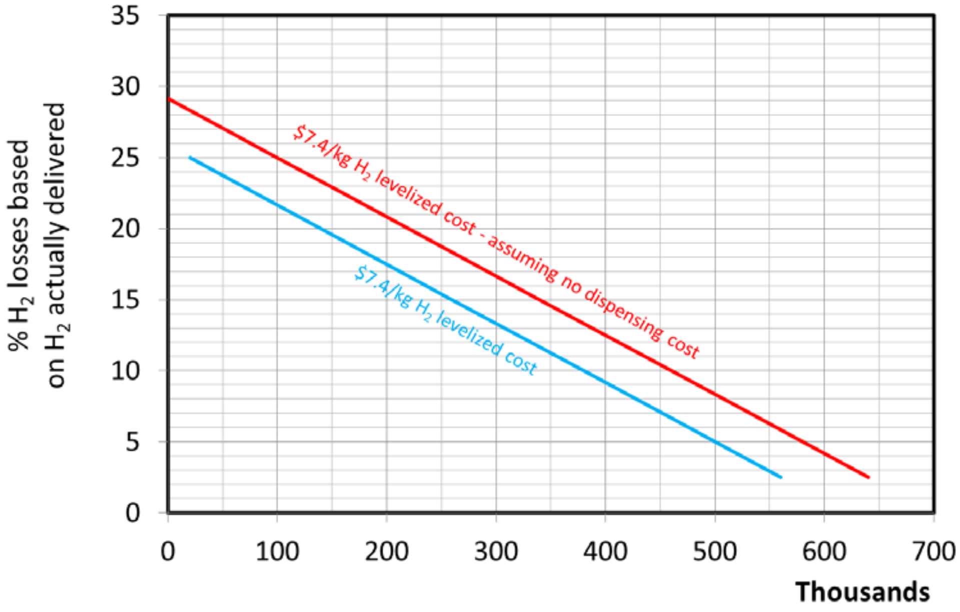
Material	Design Allowable, ksi	Relative raw material cost*	Relative total material cost*	Shell thickness, in	Total vessel weight, lbs	Approx. material cost, $/Kg H2	Total thermal mass, KJ/C
Al. 6061	22.08	1	1	4.4	4200	1,000	1,770
SS304	32.68	0.88	1.28	2.4	5750	1,770	1,300
Low cost steel	50	0.53	0.56	1.4	3000	400	600
9% Ni steel	58.3	1.14	2.05	1.2	2450	1,200	500

* Based on private communications with material suppliers. Material cost should be further refined for current market value and for mass production

Collaborations

Partner	Primary Investigator	Project Functions
GTI	Ken Kriha	Project Management, Station Design, Heat Exchanger Modeling, Cost Analysis
LLNL	Guillaume Petitpas	Transient Thermodynamic Modeling, Station Design, Cost Analysis, Lab Scale Demonstration
ORNL	Yanli Wang/Zhili Feng	Pressure Vessel Study, Cost Analysis
Shell	Herie Soto	Station Design, Cost Analysis

Remaining Barriers and Challenges



Uninstalled capital cost for the insulated high-pressure cascade

(based on HRSAM, from ANL)

Challenge: Design heat exchanger capable of building cylinder pressure in the desired amount of time.

Challenge: Design station to minimize H2 boil off losses.

Challenge : Determine economic material capable of withstanding cryogenic pressure cycling.

Proposed Future Work

2016 Milestones		
M1.2.1	Lock in station design and create process flow diagram	08/03/2016
M2.1.1	Complete analysis of vessels suitable for use in the thermal compression station	11/03/2016
Go/No-Go		
GN2.2.1	Cost analysis showing 15% total reduction cost over a $8.72/kg levelized baseline	11/03/2016
2017 Milestones		
M2.3.1	Complete analysis of what technologies need to be advanced in order to implement and commercialize this concept	02/03/2017
M3.2.1	Complete demonstration testing	05/03/2017

Summary

Objective **-** Demonstrate the technical and economic feasibility of the thermal compression concept for 700 bar H2 fueling stations.

Transient Thermodynamic Modeling used to size Station Components thus cost

- Transient Cascade Model
  - Indicating cryogenic vessel size between 200-300L
  - Indicating need for 25-30 cryogenic vessels in the cascade
- H2 Boil–Off Model – over 1300 runs already performed
  - Investigating 10 station variables (design and operations)
  - Using machine learning to understand how each variable influences station design

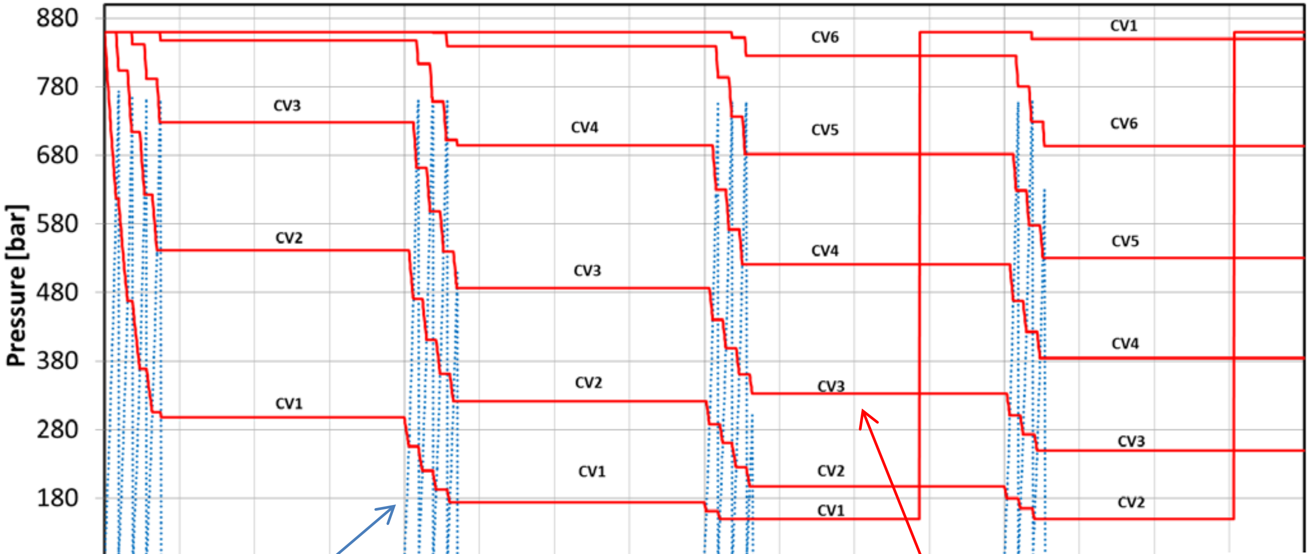
Cryogenic Vessel Study enables evaluation of cost-effective designs

- Identified several material options with economic advantages over Type 3
- Researching material’s ability to withstand thermal compression cycles
- Exploring cycle data at cryogenic temperatures and high pressure (900bar)

Technical Back-Up Slides

Project Accomplishments

Thermodynamic Model-Transient Cascading Subroutine

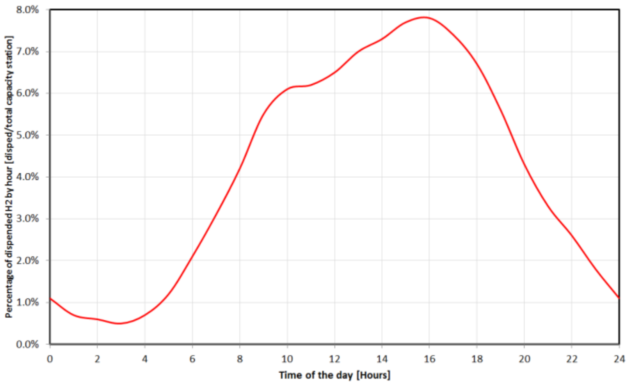


Pressure in Vehicle

Pressure in each vessel of the cascade (CV="Cryogenic Vessel")

Inputs:

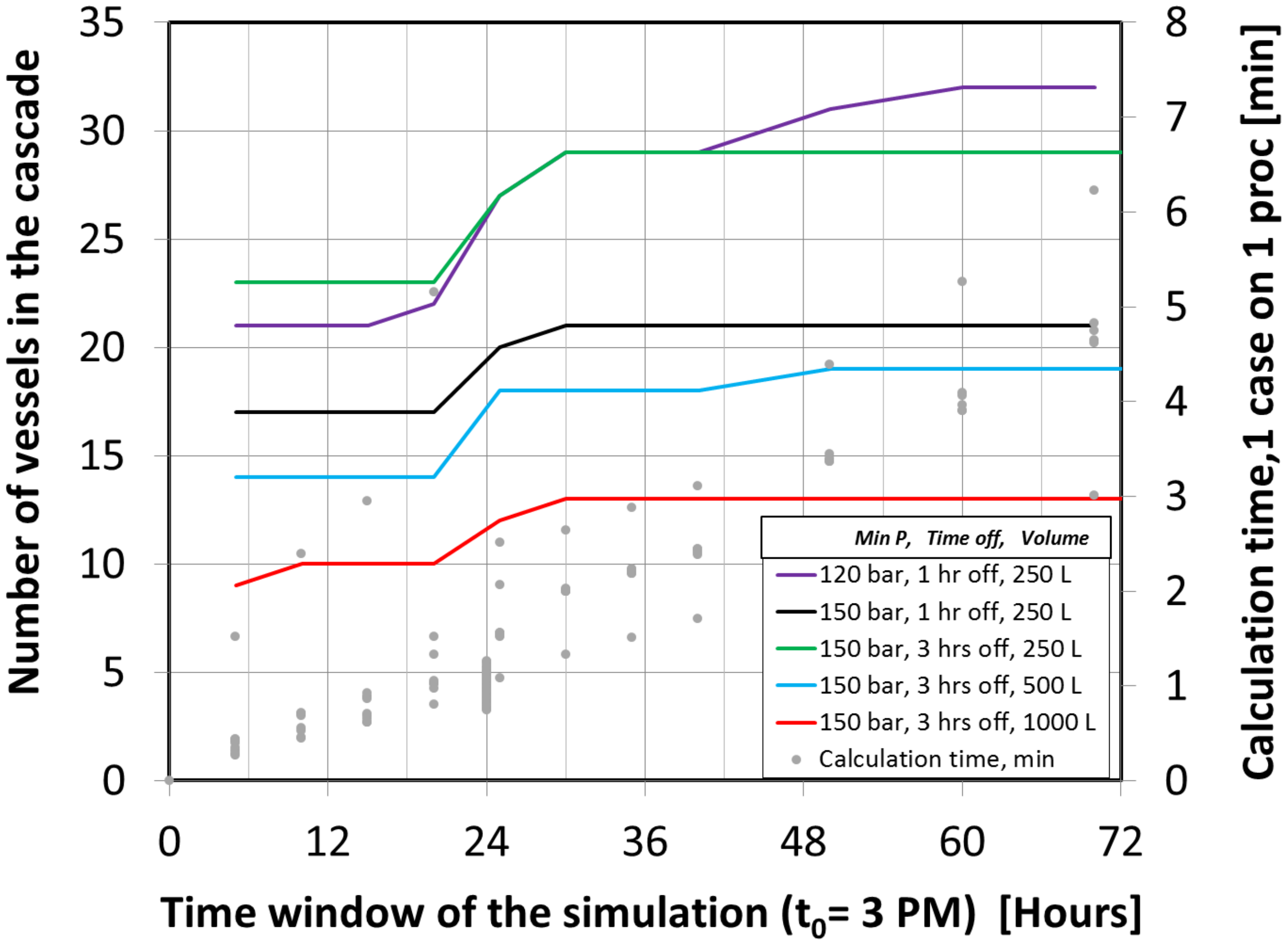
Refueling Station Capacity
# of dispenser hoses
Station demand profile
CV Volume
CV Liner Thickness
ΔP needed for fueling
Minimum P before venting
Etc…



Chevron profile.
Max demand: Friday in the summer

Project Accomplishments

Thermodynamic Model-Transient Cascading Subroutine



Model Input

Station Size = 400kg/day

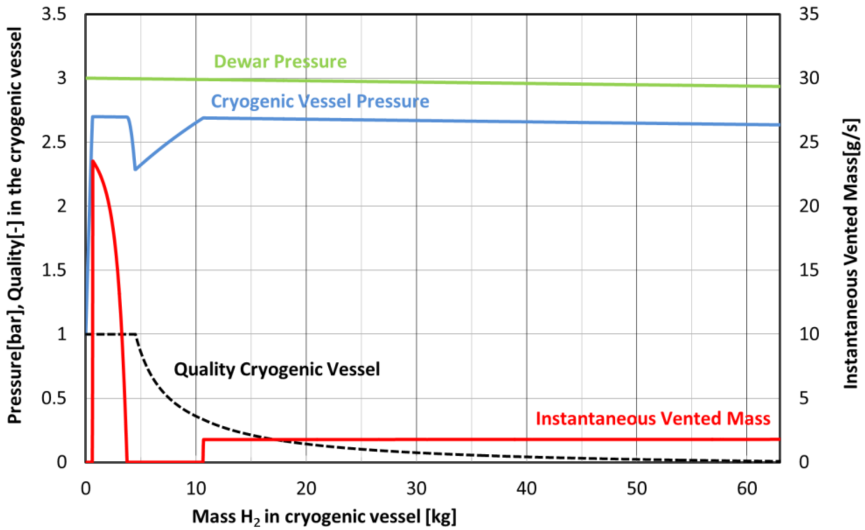
Fueling Profile = Chevron

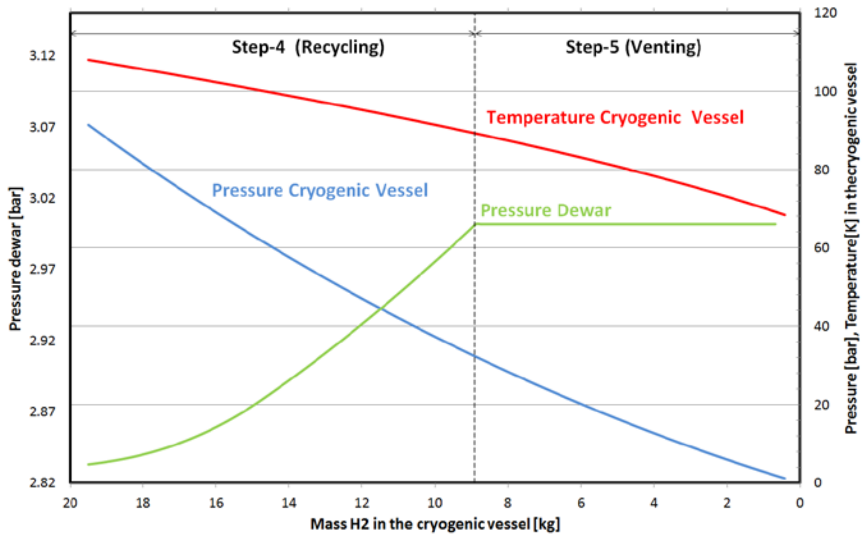
# of Dispenser Hoses = 2

Vehicle: 5.6kg @700bar

Accomplishment

Thermodynamic Model - H2 Boil Off Subroutine





Step 1

65 kg delivered to cryogenic vessel

6 kg vented

Steps 4 and 5

45 kg delivered to vehicle
(20 kg ullage at 90 bar)
9 kg vented (in Step 5)