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Refueling Infrastructure Scoping and Feasibility Assessment for Hydrogen Rail Applications

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ABSTRACT

The feasibility and component cost of hydrogen rail refueling infrastructure is examined. Example reference stations can inform future studies on components and systems specifically for hydrogen rail refueling facilities. All of the 5 designs considered assumed the bulk storage of liquid hydrogen on-site, from which either gaseous or liquid hydrogen would be dispensed. The first design was estimated to refuel 10 multiple unit trains per day, each train containing 260 kg of gaseous hydrogen at 350 bar on-board. The second base design targeted the refueling of 50 passenger locomotives, each with 400 kg of gaseous hydrogen on-board at 350 bar. Variations from this basic design were made to consider the effect of two different filling times, two different hydrogen compression methods, and two different station design approaches. For each design variation, components were sized, approximate costs were estimated for major components, and physical layouts were created. For both gaseous hydrogen-dispensing base designs, the design of direct-fill using a cryopump design was the lowest cost due to the high cost of the cascade storage system and gas compressor. The last three base designs all assumed that liquid hydrogen was dispensed into tender cars for freight locomotives that required 7,500 kg of liquid hydrogen, and the three different designs assumed that 5, 50, or 200 tender cars were refueled every day. The total component costs are very different for each design, because each design has a very different dispensing capacity. The total component cost for these three designs are driven by the cost of the liquid hydrogen tank; additionally, delivering that much liquid hydrogen to the refueling facility may not be practical. Many of the designs needed the use of multiple evaporators, compressors, and cryopumps operating in parallel to meet required flow rates. In the future, the components identified here can be improved and scaled-up to better fit the needs of heavy-duty refueling facilities. This study provides basic feasibility and first-order design guidance for hydrogen refueling facilities serving emerging rail applications.

ACKNOWLEDGMENT

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ACRONYMS AND DEFINITIONS

DOE Department of Energy

EERE Energy Efficiency and Technology Acceleration

GH$_2$ gaseous hydrogen

HFTO Hydrogen and Fuel Cell Technologies Office

HP high-pressure

LH$_2$ liquid hydrogen

LP low-pressure

MU multiple unit

NASA National Aeronautics and Space Administration

NFPA National Fire Protection Association

P&ID process and instrumentation diagram

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1.   INTRODUCTION

Use of hydrogen fuel for rail applications has the potential to significantly reduce pollutant emissions from rail technology, while at the same time increasing hydrogen demand in various regions of the U.S. and thereby reduce the overall cost of hydrogen technologies through economies-of-scale [1]. Hydrogen for rail applications has a number of benefits, including high energy density, fast fueling, and the ability to use existing non-electrified track [2]. In order for hydrogen to be utilized for rail rolling stock, infrastructure must exist to refuel the locomotive. This work considers different rail applications with varying operational requirements and examines the current feasibility and cost of refueling infrastructure. These example reference stations provide first-order design guidance on hydrogen rail refueling stations and also help to inform future studies on components and systems.

1.1.   Background

Prior efforts have explored the total cost of ownership for hydrogen fuel cell-powered locomotives, including both the cost of the locomotive and the hydrogen fuel usage [3]. However, the refueling infrastructure must also be considered in the total cost to an owner/operator of a hydrogen fuel cell rail fleet. Additionally, a facility for refueling heavy-duty rail applications will be much larger than current light-duty vehicle refueling facilities. Prior efforts in refueling station design and cost have focused on light-duty vehicles [4]. While the overall design and principles of refueling may be similar, the size and scale of these much larger refueling facilities mean that much larger components will likely be needed that are not currently commonly available for purchase. Furthermore, hydrogen-powered trains may require the dispensing of liquid hydrogen to achieve higher fuel transfer rates due to the increased density of liquid hydrogen, which is not typically considered for light-duty vehicles. This work aims to estimate the size, major component cost, and physical footprint for rail refueling facilities in order to inform future efforts for hydrogen in rail applications. In doing so, the overall feasibility of these refueling facilities is assessed.

1.2.   Approach

This work aims to assess different possibilities for hydrogen rail refueling facilities through representative example designs. This work does not enumerate every possible permutation of rail refueling facilities options, nor does this fully optimize cost or footprint based on every possibility. An actual real-world refueling facility for rail would need to consider the specific needs of the particular project (e.g., pressure and flow rate of the specific rail vehicle) and other site-specific considerations (e.g., footprint constraints, other fuels nearby) that would affect such an optimization. Instead, this work considers a few different example designs that are meant to be representative of different possibilities to inform future analyses. Trade-offs of capacity, design, cost, and footprint can be illustrated by comparisons between these example designs.

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For each design, a basic scenario is provided in order to define design boundary conditions and illustrate some of the overarching design inputs that are needed. For example, designs that have a small or large number of refuelings per day, designs that dispense either gaseous or liquid hydrogen (GH_2 or LH_2), and designs that service passenger or freight rail. This project does not consider different possible designs for multiple unit trains, locomotives, or tender car, but rather relies on a separate effort at Argonne National Laboratory [5].

Once overall inputs are defined for the design, specifics about the design can be estimated, such as necessary flow rates for desired hydrogen dispensing amounts and times and amount of storage required. These overall specifications (mass flow rate, storage capacity, and pressure) are then used to identify currently-available commercial components that can meet the desired needs of the design. This was accomplished by searching company websites and in direct communication with industry collaborators. It should be noted that the sources of the cost estimates are not included in this report, as they were non-public estimates or private communications with industry experts. It should also be noted that these costs are general component capital costs for simplicity, not installed costs and so does not include the cost for construction and installation of the refueling facility. Operating costs are not included in this study both for the sake of simplicity (variability in electricity and labor costs throughout the country) as the intention of this work is to identify feasibility/existence of needed components and major capital cost drivers to help inform future research. A real-world design for actual implementation would need to consider a much more detailed and specific design, including installation costs, component lifetime, and operating costs.

The identified components then have estimates for both the physical size and cost. For some components, the storage capacity is based on the internal hydraulic volume, while the outer dimensions are given. This is because the inner capacity is most relevant for sizing and cost for some components, but the physical layout requires knowledge of the outer dimensions. Liquid hydrogen storage tanks are the most noticeable example of this, as it was assumed that the double-walled vacuum insulation thickness was 1 m [6]. This includes not just the annular space/insulation, but outer and inner tank thicknesses as well; even so, it is likely an over-estimate of this thickness for modern tanks but does not impact results significantly.

After establishing that a design could meet the refueling targets of a particular situation, a process diagram, physical layout schematic, and overall component cost table are then constructed for each design, based on these identified components. The physical layouts include some relevant requirements from hydrogen codes and standards (i.e., National Fire Protection Association (NFPA) 2: Hydrogen Technologies Code) but only for within the facility layout itself; setback distances depend on what is nearby, and this study focuses only on the facility alone. The physical layouts are made using the SketchUp Pro software, and the process and instrumentation diagrams are made using Microsoft Visio. Thus, the critical metrics for each design are the specifications (operating conditions, required mass flow rates, and number of components), physical footprint, and component cost. These are then used to compare different designs to each other, as well as to help inform future analyses on hydrogen for rail applications.

2.   GASEOUS HYDROGEN DISPENSING DESIGNS

Some rail applications are likely to utilize high-pressure compressed gaseous hydrogen on-board the train. In this analysis, two applications were assumed: multiple unit (MU) passenger trains and locomotive passenger trains. MU trains are self-propelled trains in which multiple passenger carriages are joined together and controlled by a single operator. In this case, the passenger carriages are self-propelled, so they do not need a separate locomotive. On the other hand, passenger locomotive trains consist of a separate locomotive that pulls a number of passenger carriages that do not have their own motive power. In general, MU trains tend to be smaller and provide intra-city travel (within a city), while passenger locomotive trains tend to be larger and focus more on inter-city travel (between cities). These are by no means definitive categorizations, but rather generalizations used in this analysis to highlight potentially different capacities.

This work focuses on the refueling facility hardware and not on the train design. Section 2.1 considers refueling facilities for MU passenger trains and Section 2.2 considers refueling facilities for locomotive passenger trains, both refueled with compressed gaseous hydrogen at 350 bar. It should also be emphasized that while this analysis considers these two design scenarios for gaseous hydrogen refueling for passenger rail applications (MU and locomotive trains), this does not mean that gaseous hydrogen could not supply freight locomotives. Short-line and switcher freight locomotives may very well utilize gaseous hydrogen as a fuel. These passenger rail examples were chosen for illustrative purposes and to provide some context for the design inputs, but it should not be implied that gaseous hydrogen dispensing is not applicable for relevant freight rail applications. Passenger, shunter, and switcher service typically has a lighter duty-cycle and so does not require as much on-board energy as a freight rail application.

In all design scenarios, it is assumed that liquid hydrogen is delivered and stored on-site before being vaporized to gaseous hydrogen and dispensed onto the rail vehicles. Liquid hydrogen is much more dense than compressed gaseous hydrogen, so large deliveries are much more cost effective as liquid hydrogen than gaseous. Liquid hydrogen storage tanks and transfer lines need to be vacuum-jacketed, which can significantly increase cost compared to gaseous hydrogen piping. It is also possible to produce the hydrogen on-site or have a pipeline to a large-scale production facility, but this was deemed outside the scope of this initial study, which instead focused on the refueling hardware.

The gaseous hydrogen at the refueling facility needs to be compressed to a pressure of 450 bar (6,527 psi) in order to provide a sufficient pressure-difference to achieve fast-filling at 350 bar (5,076 psi), which both the MU and passenger locomotive train on-board storage are assumed to require. All refueling uses pressure-driven flow of the fuel from the refueling facility to the vehicle; traditional hydrocarbon fuels such as diesel utilize an on-demand pump to transfer the fuel. Compressed gaseous hydrogen dispensing also utilizes pressure-driven flow, although the difference in pressure between an "empty" and "full" tank can be large. This compression can be achieved either by first vaporizing the liquid hydrogen to gas and then using a compressor, or by using a cryogenic pump to pressurize the liquid hydrogen and then vaporizing it to high-pressure gaseous hydrogen. Both of these options are considered in the subsequent sections. Either the gas compressor or liquid cryopump can refuel the relevant rail vehicle directly, such that the output flow rate of the compressor or cryopump is equal to the mass flow rate into the rail vehicle.

Alternatively, the high-pressure gaseous hydrogen can be stored in a separate set of pressure vessels that serves as a pressure-cascade system in order to achieve fast refueling flow rates. In this case, the compressor or cryopump can be much smaller with a much smaller flow rate, such that the compressor/cryopump can run 24 hours per day, slowly refilling the cascade storage, while the dispensing flow comes from the stored hydrogen in the cascade system. These two extremes were considered in this analysis as bounding cases, but it is also possible to have an optimal setup somewhere in the middle of these two cases, with a larger compressor/cryopump that is supplemented by a smaller cascade storage system.

Regardless of whether the high-pressure gaseous hydrogen is generated by a compressor or a cryopump, or if the high-pressure gaseous hydrogen is first stored in the cascade storage system or not, hydrogen may need to flow through a chiller before it is dispensed to the rail vehicle. This is because hydrogen heats up upon expansion, meaning that when the high-pressure hydrogen flows into the lower-pressure (nearly empty) tanks on-board the rail vehicle, it can heat these tanks up. Depending on the construction and composition of the tanks, this increase in temperature can cause structural damage leading to tank failure. This is especially true for Type IV tanks made out of carbon-fiber composites and polymer liners. Different rail vehicles of different sizes and designs may utilize different types of tanks, and so this chiller may not be necessary. Additionally, longer refueling times (slower flow rates) do not need as much chilling due to less expansion (smaller pressure differential) and longer times for heat dissipation. Finally, designs that utilize a cryopump for the liquid hydrogen already have a supply of very cold (cryogenic) hydrogen at the desired pressure, meaning it is therefore possible to eliminate the need for a chiller by mixing some of the high-pressure gaseous hydrogen with this high-pressure cryogenic hydrogen. All of the designs considered include a chiller for completeness.

Finally, the high-pressure hydrogen flows through a dispenser. This dispenser will incorporate a flow rate meter to keep track of the flow of hydrogen (for inventory or sale purposes). The dispenser also contains pressure sensors and relief devices; these keep track of the pressure during the fill process and can relieve the pressure should the rail vehicle on-board tank pressure get too high. These sensors and relief devices can also be used to do air purges before filling begins and pressure-check holds to ensure that there is no leaking (pressure drop) before and during a fill. A flexible hose and handheld connector allow for an operator to connect the dispenser to the rail vehicle.

2.1. Multiple Unit Train Passenger Rail

2.1.1. Design Inputs

The refueling station was designed to handle a fleet of 10 MU trains, with each MU train containing 3 cars. The relevant specifications of the MU trains were provided by Argonne National Laboratory [5]. A total of 260 kg GH_2 will be dispensed per MU train; with 68 kg dispensed to two of the cars and 124 kg to the remaining car. The total refueling capacity of the station is thus 2,600 kg/day. A single dispenser (i.e., a single fuel transfer hose) is assumed for this case in order to explore the impact of larger mass flow rates from a single point. Multiple fuel transfer hoses per MU train (e.g., one to each car of the MU train) could potentially achieve faster

overall filling with a lower mass flow rate per transfer hose. Additionally, multiple dispensers may also be of interest to fuel multiple trains at one time and to provide operational redundancy (i.e., can still refuel one train if something is wrong with the other dispenser).

From conversations with equipment suppliers and train operators, the time it takes to refuel one MU train was chosen to be 15 minutes, with an average refueling flow rate of 17.3 kg/min. An additional 15 minutes were allocated for moving the MU train up to the dispenser, connecting the fueling nozzle from the MU train, disconnecting the nozzle after filling, and moving the MU train away from the dispenser (i.e., 7.5 minutes before filling and 7.5 minutes after filling). The entire fleet can then be refueled in 5 hours, since each of the 10 trains takes 30 minutes total. For comparison purposes, a 30-minute fill time per MU train was also analyzed, which results in a slower mass flow rate of 8.7 kg/min. For this case, the refueling time of the entire fleet will take longer than 5 hours (7.5 hours), since each of the 10 trains would take 45 minutes total. This is a somewhat arbitrary cut-off, but was chosen to illustrate the effect of fill time. Slightly faster overall refueling could be achieved by having fueling positions on either side of the dispenser; the next train could be brought up into position while the train of the opposite side is being refueled. It should be emphasized that current gaseous hydrogen fill rates are much lower than the ones assumed here; the intention is to determine if components exist that could meet the needs of these higher flow rates, but technical difficulties still remain, such as pre-cooling requirements for higher flow rates. Having a slower mass flow rate might be more cost effective since components that can handle lower flow rates might be more readily available.

2.1.2.   Station Configuration and Components

Eight different configurations were analyzed for the gaseous hydrogen multi unit train refueling station design, based on all of the combinations between the following design parameters:

1. two filling times per multi unit train (15 or 30 minutes),

2. two hydrogen compression methods (a low-pressure vaporizer leading to a gas compressor or a liquid cryopump leading to a high-pressure vaporizer), and

3. two filling methods (a larger mass flow rate compressor/cryopump to fuel directly or a cascade-fill storage system with a smaller mass flow rate compressor/cryopump).

2.1.3.   Bulk Liquid Hydrogen Storage

In this design, liquid hydrogen is assumed to be stored as a saturated liquid at 8 bar (116 psi) with a density of 54.6 kg/m^3 in two double-walled cylindrical storage tanks. Two LH$_2$ tanks were chosen to provide redundancy so that a tank maintenance problem would not shut down the entire refueling station. The vacuum void between the inner vessel and the outer jacket is filled with an insulating material that helps reduce the hydrogen boil-off [6]. Each tank has a capacity of 1,430 kg, for a total capacity of 2,860 kg. This 10% increase over the daily capacity of 2,600 kg allows for the station to function in case of delays in daily deliveries or variable amounts of fuel dispensed day-to-day. Depending on the operational needs of the refueling facility, additional

storage may be desired (even up to multiple days worth of operation), but this would need to be considered based on the specific needs of the facility and additional costs of the storage. Variations in the liquid density due to temperature and pressure changes during tank refueling and discharging were not considered in this high-level analysis, but would need to be considered in a more detailed design. Such considerations can lead to somewhat larger LH_2 tank sizes than considered in this study. Additionally, as liquid hydrogen leaves the tank, that volume must be replaced with gaseous hydrogen, either through boil-off or some other means. This was not directly considered in the sizing of these tanks but would need to be considered in a more detailed system design. With this liquid storage capacity, daily deliveries are necessary in order to function at full capacity. Some of the liquid hydrogen tanker trucks have a capacity up to approximately 4,000 kg of hydrogen [7], so a single tanker truck is sufficient to meet the daily hydrogen demand. It should be noted that increasing the on-site storage capacity would alleviate the need for daily deliveries, but it would also result in a higher refueling facility capital cost and footprint.

Tanks with an inner diameter of 8.2 ft (2.5 m) and an inner length of 17.7 ft (5.4 m) were selected to store 6,900 gal (26.2 m^3, 1,430 kg) of liquid hydrogen per tank. The inner dimensions were chosen based on keeping the same length to diameter ratio (2.18) as the LH_2 tank reported by Pratt and Klebanoff [8]. The vacuum void was assumed to be 3.3 ft (1 m) as described in Ewart and Dergance [6], resulting in an outer diameter of 14.7 ft (4.5 m) and an outer length of 24 ft (7.4 m). This includes not just the annular space/insulation, but outer and inner tank wall thicknesses as well; even so, it is likely an over-estimate of this thickness for modern tanks, but does not impact the layout significantly. It is important to note that the liquid storage tanks can be oriented either horizontally or vertically. In this work, the horizontal orientation was selected though conversations with industry experts, because the boil-off hold-time for horizontal tanks is somewhat longer than for vertically-mounted tanks. In addition, inspection and maintenance are more convenient for horizontally mounted tanks. However, selecting a vertical orientation would result in a smaller footprint.

The cost of each tank was estimated based on a survey of quoted liquid hydrogen tank prices at different capacities that suggested that normalized storage costs roughly asymptote to a single value at high volumes [9]. Using the largest tank capacity reported (68 m^3), this led to a normalized cost of $7,000 per m^3 of storage capacity. Based on this normalized cost with the storage capacity volume noted above, each tank is estimated to cost $180,000.

2.1.4.   Pipe Sizing

The minimum diameter of tubing in the system was calculated from the mass flow rate, $\dot{m}$, being equal to the density, ρ, of hydrogen times the velocity, v, of the flow times the cross-sectional area, A_c, of the tubing ($\dot{m} = \rho v A_c$). A maximum flow velocity (v_{max}) of 20 m/s is used to size the minimum diameter of the piping, which is within the typical range of flow velocities for pipe sizing of gaseous systems (15–30 m/s) [10]. This flow velocity and the mass flow rate can be used to estimate the minimum pipe diameter (D_{min}) from Equation 1.

$$D_{min} = \sqrt{\frac{4\dot{m}}{\pi \rho v_{max}}} \tag{1}$$

The size of the dispensing hose and connector is important to quantify in order to assess the feasibility of different refueling design assumptions. For the MU design, the dispensing mass flow rate is 17.3 kg/min for the 15-minute fill or 8.67 kg/min for the 30-minute fill. The density of gaseous hydrogen at -20°C (253 K) and 450 bar is 32.4 kg/m^3. This leads to minimum inner pipe diameters of 23.8 mm (0.94 in) for the 15-minute fill (17.3 kg/min) and 16.9 mm (0.66 in) for the 30-minute fill (8.67 kg/min).

2.1.5.   Direct-Fill Compressor Design

The direct-fill compressor design uses a gas compressor to directly fill the multiple unit train. This means that the output mass flow rate of the compressor is equivalent to the mass flow rate of the hydrogen dispensed to the multiple unit train. The size of the post-compressor buffer storage is minimal and only really serves to provide a buffer between the flow rates of the compressor/evaporator output and the chiller/dispenser input. Figure 2-1 shows a basic overall system schematic for this type of design.

Figure 2-1 Simple Schematic of Multiple Unit Train Refueling Facility Direct-Fill Compressor Design

2.1.5.1. Low-Pressure Evaporator
The low-pressure evaporator takes liquid hydrogen from the bulk storage and vaporizes it to gaseous hydrogen that is fed to the compressor. The desired mass flow rate for the low-pressure evaporator is 1,038 kg/hr (17.3 kg/min) for a 15-minute fill and 522 kg/hr (8.7 kg/min) for a 30-minute fill, as described in Section 2.1.1. An example ambient-air vaporizer for liquid hydrogen was identified with a mass flow rate of 198 kg/hr and outer physical dimensions of 8.2 ft (2.5 m) long by 6.5 ft (2.0 m) wide by 14.5 ft (4.4 m) high. The 15-minute fill time case requires six of these evaporators to meet the required flow rate, and the 30-minute fill time case requires three of these evaporators to meet the required flow rate. The required pressure of the evaporator is just above ambient (1.013 bar) while the example evaporator design pressure is 41.4 bar, which is more than sufficient. The cost of each of these example evaporators is $35,000, which was determined by interpolating the cost of two bounding evaporator quotes from manufacturers.

2.1.5.2. Compressor

The compressor takes gaseous hydrogen from the low-pressure evaporator and feeds it through the small buffer storage tank. The desired mass flow rate for the compressor is 1,038 kg/hr (17.3 kg/min) for a 15-minute fill and 522 kg/hr (8.7 kg/min) for a 30-minute fill, as described in Section 2.1.1. An example compressor for hydrogen was identified with a mass flow rate of 550 kg/hr and outer physical dimensions of 36 ft (11.0 m) long by 20 ft (6.1 m) wide by 17 ft (5.2 m) high. The 15-minute fill time case requires two of these compressors to meet the required flow rate, and the 30-minute fill time case requires one of these compressors to meet the required flow rate. The required output pressure of the compressor is 450 bar, which gives a high enough pressure to achieve fast-filling of the on-board tanks at 350 bar; the example compressor meets this requirement. The cost of each compressor is assumed to be $3,500,000, which was provided by the manufacturer.

2.1.5.3. Buffer Storage

In this design, a high-pressure storage tank with a capacity of 11 kg was selected to buffer any flow rate fluctuations that may occur from the compressor to the chiller. More capacity in the buffer may be needed for the large flow rates considered here, but this size was chosen so as to not exceed the quantity of non-bulk gaseous hydrogen storage in NFPA 2 (5,000 scf) and to provide a simple example. An example gaseous hydrogen storage pressure vessel with a diameter of 1.5 ft (0.5 m) and a length of 11 ft (3.4 m) was identified for a rated pressure of at least 450 bar. The cost of a single buffer storage tank was estimated to be $35,000, which was provided by the manufacturer.

2.1.5.4. Chiller

A chiller cools the high-pressure gaseous hydrogen to a temperature of -20°C in order to avoid thermal damage to the on-board storage tank during filling. It is important to note that the level of pre-cooling required for the multiple unit train might be different than the one chosen for this study. Currently, light-duty, medium-duty, and heavy-duty vehicles require a chiller output temperature from -40°C to 0°C [11, 12]. The temperature required to avoid thermal damage depends on the initial pressure of the hydrogen, the mass flow rate, and the configuration (physical size and material of construction) of the on-board storage tanks. The temperature in this study was assumed based on conversations with industry experts. Therefore, further analysis needs to be performed to determine the required pre-cooling temperature to prevent thermal damage on the on-board multiple unit train tanks. This will depend on tank type and dimensions, the fueling flow rate and pressure differential, and ambient conditions. The need for additional analysis with respect to pre-cooling requirements is an important point, particularly for the very high gaseous hydrogen mass flow rates assumed in this design.

An example chiller was identified with a mass flow rate capacity of 10 kg/min at 350 bar, and the outer physical dimensions of the chiller are 3 ft (0.9 m) long by 3 ft (0.9 m) wide by 5.2 ft (1.6 m) high. Note that these dimensions are for the heat exchanger only; the chiller equipment would take up additional space. The chiller cost is estimated to be approximately $150,000, based on estimates from an equipment manufacturer as well as a previously published report on light-duty vehicle refueling stations [13]. The 15-minute fill time case requires two of these chillers to meet

the required flow rate, and the 30-minute fill time case requires one of these chillers to meet the required flow rate.

2.1.5.5. Dispenser

An example gaseous hydrogen dispenser was identified with a mass flow rate of 20 kg/min at 350 bar and -20°C. The outer physical dimensions of the dispenser are 3.8 ft (1.2 m) long by 1.8 ft (0.5 m) wide by 8.2 ft (2.5 m) high. The dispenser is estimated to cost $250,000, which was estimated using a manufacturer quote for a similar dispenser and estimate from a research report on light-duty vehicle refueling facilities [13]. One dispenser meets the required flow rates for both the 15 minutes (17.33 kg/min) and 30 minutes (8.67 kg/min) fill times.

It should be noted that current refueling mass flow rates are significantly lower than 20 kg/min, and currently available hoses and nozzles that can meet these flow rates may not exist. For example, current 350 bar refueling dispensers have inside diameters of nominally 8–12 mm [14, 15], which are much smaller than the 23.8 mm and 16.9 mm inner diameters as calculated in Section 2.1.4. Larger dispenser nozzles and hoses are an active area of research and development, and so this work will rely on these specifications given by the dispenser manufacturer. Multiple fuel transfer hoses per train could potentially achieve faster overall filling with a lower mass flow rate per transfer hose, if faster filling times are needed or if this mass flow rate is not currently achievable.

2.1.5.6. Component and Cost Summary

The number of major components and associated costs for the multiple unit train refueling facility design that utilized a direct-fill and compressor are summarized in Tables 2-1 and 2-2 for the 15-minute and 30-minute fill times, respectively.

Table 2-1 Multiple Unit Train Refueling Facility Direct-Fill Compressor 15-Minute Fill Time Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
LP Evaporator	6	35,000	210,000
Compressor	2	3,500,000	7,000,000
Buffer Storage Tank	1	35,000	35,000
Chiller	2	150,000	300,000
Dispenser	1	250,000	250,000
Total			**8,155,000**

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
LP Evaporator	3	35,000	105,000
Compressor	1	3,500,000	3,500,000
Buffer Storage Tank	1	35,000	35,000
Chiller	1	150,000	150,000
Dispenser	1	250,000	250,000
Total			**4,400,000**

2.1.6.   *Direct-Fill Cryopump Design*

The direct-fill cryopump design uses a cryogenic liquid pump to directly-fill the multiple unit train. This means that the output flow rate of the cryopump is equivalent to the mass flow rate of the hydrogen dispensed to the multiple unit train. The size of the post-cryopump buffer storage is minimal and only really serves to provide a buffer between the flow rates of the cryopump/evaporator output and the chiller/dispenser input. Figure 2-2 shows a basic overall system schematic for this type of design.
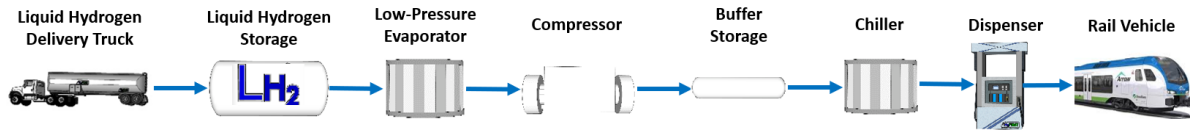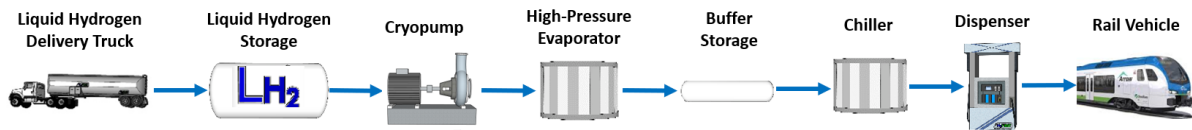

Figure 2-2 Simple Schematic of Multiple Unit Train Refueling Facility Direct-Fill Cryopump Design

2.1.6.1. Cryopump
The cryopump takes liquid hydrogen from the storage, pressurizes it, and feeds it through the high-pressure evaporator and small buffer system directly to the multiple unit train. The desired mass flow rate for the cryopump is 1,038 kg/hr (17.3 kg/min) for a 15-minute fill and 522 kg/hr (8.7 kg/min) for a 30-minute fill, as described in Section 2.1.1. An example cryopump for hydrogen was identified with a mass flow rate of 173.4 kg/hr. The 15-minute fill time case requires 6 cryopumps to meet the required flow rate, and the 30-minute fill time case requires 3 to meet the required flow rate. The size of this cryopump is 16.5 ft (5.0 m) long by 10 ft (3.0 m) wide by 3.3 ft (1.0 m) high. The desired output pressure of the cryopump is 450 bar, which the cryopump meets. The cost of this cryopump is estimated to be $100,000, which is a rough estimate provided by multiple industry sources.

2.1.6.2. High-Pressure Evaporator

The high-pressure evaporator takes liquid hydrogen from the cryopump and vaporizes it to gaseous hydrogen that is fed to the high-pressure buffer storage. The desired mass flow rate for the high-pressure evaporator is 1,038 kg/hr (17.3 kg/min) for a 15-minute fill and 522 kg/hr (8.7 kg/min) for a 30-minute fill, as described in Section 2.1.1. Two different example high-pressure evaporators were identified for this design, one for the 15-minute fill time and another for a 30-minute fill time, in order to better match the required flow rate.

For the 15-minute fill time, the mass flow rate of the selected high-pressure evaporator is 744 kg/hr. The desired pressure of the evaporator is 450 bar while this evaporator design pressure is more than sufficient at 600 bar. The size of this evaporator is 8.2 ft (2.5 m) long by 9.6 ft (2.9 m) wide by 44.5 ft (13.6 m) high. The cost of this evaporator is estimated to be $100,000, which was provided by the manufacturer. The 15-minute fill case requires two high-pressure evaporators to meet the needed flow rate.

For the 30-minute fill time case, the mass flow rate of the selected high-pressure evaporator is 535 kg/hr. The desired pressure of the evaporator is 450 bar while the selected evaporator exceeds this with a design pressure is 600 bar. The size of evaporator is 8.4 ft (7.3 m) long by 9.5 ft (6.4 m) wide by 44.5 ft (13.6 m) high. The cost of each evaporator is estimated to be $75,000, which was determined by interpolating the cost using two bounding quotes from manufacturers. The 30-minute fill time requires a single (1) high-pressure evaporator to meet the required flow rate.

2.1.6.3. Buffer Storage

Refer to Section 2.1.5.3 for the high-pressure buffer storage system information.

2.1.6.4. Chiller

Refer to Section 2.1.5.4 for chiller component information. If high-pressure liquid hydrogen is able to perform the pre-cooling, a chiller might not be required for this design.

2.1.6.5. Dispenser

Refer to Section 2.1.5.5 for dispenser component information.

2.1.6.6. Component and Cost Summary

The number of major components and associated costs for the multiple unit train refueling facility design that utilized a direct-fill and cryopump are summarized in Tables 2-3 and 2-4 for the 15-minute and 30-minute fill times, respectively.

Table 2-3 Multiple Unit Train Refueling Facility Direct-Fill Cryopump 15-Minute Fill Time Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
Cryopump	6	100,000	600,000
HP Evaporator	2	100,000	200,000
Buffer Storage Tank	1	35,000	35,000
Chiller	2	150,000	300,000
Dispenser	1	250,000	250,000
Total			**1,745,000**

Table 2-4 Multiple Unit Train Refueling Facility Direct-Fill Cryopump 30 Minute Fill Time Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
Cryopump	3	100,000	300,000
HP Evaporator	1	75,000	75,000
Buffer Storage Tank	1	35,000	35,000
Chiller	1	150,000	150,000
Dispenser	1	250,000	250,000
Total			**1,170,000**

2.1.7. *Cascade-Fill Compressor Design*

The cascade-fill compressor design uses a high-pressure cascade storage system to provide the refueling flow rate and a gas compressor to slowly refill the cascade storage system. The size of the cascade storage system is maximized to be able to handle all refueling needs with a minimum flow rate from the compressor. Figure 2-3 shows a basic overall system schematic for this type of design.

Figure 2-3 Simple Schematic of Multiple Unit Train Refueling Facility Cascade-Fill Compressor Design

2.1.7.1. Low-Pressure Evaporator

The low-pressure evaporator vaporizes the liquid hydrogen from the bulk storage, similar to the evaporator described in Section 2.1.5.1. However, for this design, it was assumed that the evaporator and compressor operate constantly (24 hours per day) to replenish the cascade system, so only a mass flow rate of 108.3 kg/hr (the total capacity 2,600 kg of the station divided by 24 hours) is needed for both the 15-minute and 30-minute fill cases. The cascade system is then designed to store the rest of the hydrogen needed to fuel the entire fleet.

An example low-pressure evaporator was identified with a mass flow rate of 132 kg/hr at a design pressure of 41.4 bar. This means that only one evaporator is needed to meet the required flow rate. The size of this evaporator is 7 ft (2.1 m) long by 6 ft (1.8 m) wide by 12.3 ft (3.7 m) high. The cost of this example evaporator is $25,000, which was provided by the manufacturer.

2.1.7.2. Compressor

The compressor takes gaseous hydrogen from the low-pressure evaporator and supplies high-pressure hydrogen to the cascade storage system, similar to the compressor described in Section 2.1.5.2. However, the desired mass flow rate for this cascade-fill compressor is only 108.3 kg/hr (1.8 kg/min) for both the 15-minute and 30-minute fill cases, as described in Section 2.1.7.1. An example compressor for hydrogen was identified with a mass flow rate of 125 kg/hr at 450 bar, which meets both the mass flow rate and pressure requirements of the design. This means that only a single (1) compressor is needed to meet the required flow rate. The size of compressor is 10 ft (3.0 m) long by 25 ft (7.6 m) wide by 17 ft (5.2 m) high. The cost of this compressor is estimated to be $700,000, which was provided by an estimate from the manufacturer.

2.1.7.3. Cascade System

The cascade system achieves fast-filling using a pressure cascade of multiple gaseous hydrogen pressure vessels. All of the vessels in the cascade system are initially at a maximum pressure of 450 bar (6,527 psi). When fueling starts, an initial section of the cascade system supplies the on-board tanks to a "low" pressure equilibrium of 157.5 bar (2,284 psi). Then another section of cascade tanks continues the refueling, starting again at the initial pressure of 450 bar (6,527 psi) to a "medium" pressure equilibrium of 299 bar (4,242 psi). Finally, the remaining section of the cascade tanks, which is still at 450 bar (6,527 psi), completes the fueling of the on-board tanks to the maximum on-board storage pressure of 350 bar (5,076 psi). The cascade system was sized in a modular fashion by estimating the number of tanks needed in the cascade to refuel a single rail vehicle (in this case, an MU train), then multiplying that number of tanks by the number of rail vehicles in the fleet. This is because the cascade system is assumed to refuel the entire rail vehicle, and then the compressor is assumed to refill all of the cascade "units" (one unit per filled vehicle) over the rest of the day while refueling is not occurring. Specifics on the methodology for sizing the cascade system can be found in Appendix A.

An example pressure vessel cylinder was identified to be used as the tanks in the cascade. This tank has a diameter of 16 inch (40.6 cm), a length of 30 ft (9.1 m), and a total hydraulic storage

volume of 765 L (0.765 m^3). Each of these example high-pressure storage tanks is estimated to cost $35,000, which was provided by the manufacturer.

For this design, the total amount of hydrogen dispensed per fill is 260 kg per fill, as described in Section 2.1.1. The flow rate into the cascade unit is 108.3 kg/hr (1.8 kg/min) for both the 15-minute and 30-minute fill cases, as described in Section 2.1.7.1. The flow rate out of the cascade unit during filling is 17.3 kg/min for the 15-minute fill case and 8.7 kg/min for the 30-minute fill case, as described in Section 2.1.1. Based on these design inputs for the 15-minute fill case, a cascade unit size is estimated to contain 9 "low" tanks, 14 "medium" tanks, and 13 "high" tanks, for a total of 36 tanks per dispensed rail vehicle; this gives a total cascade system size of 360 tanks for a fleet of 10 MU trains. For the 30-minute fill case, a cascade unit size is estimated to contain 8 "low" tanks, 12 "medium" tanks, and 11 "high" tanks, for a total of 31 tanks per dispensed rail vehicle; this gives a total cascade system size of 310 tanks for a fleet of 10 MU trains.

2.1.7.4. Chiller
Refer to Section 2.1.5.4 for chiller component information.

2.1.7.5. Dispenser
Refer to Section 2.1.5.5 for dispenser component information.

2.1.7.6. Component and Cost Summary
The number of major components and associated costs for the multiple unit train refueling facility design that utilized a cascade-fill and compressor are summarized in Tables 2-5 and 2-6 for the 15-minute and 30-minute fill times, respectively.

Table 2-5 Multiple Unit Train Refueling Facility Cascade-Fill Compressor 15-Minute Fill Time Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
LP Evaporator	1	25,000	25,000
Compressor	1	700,000	700,000
Cascade Tank	360	35,000	12,600,000
Chiller	2	150,000	300,000
Dispenser	1	250,000	250,000
Total			**14,235,000**

Table 2-6 Multiple Unit Train Refueling Facility Cascade-Fill Compressor 30 Minute Fill Time Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
LP Evaporator	1	25,000	25,000
Compressor	1	700,000	700,000
Cascade Tank	310	35,000	10,850,000
Chiller	1	150,000	150,000
Dispenser	1	250,000	250,000
Total			**12,335,000**

2.1.8.   Cascade-Fill Cryopump Design

The cascade-fill cryopump design uses a high-pressure cascade storage system to provide the refueling flow rate and a cryopump to slowly refill the cascade storage system. The size of the cascade storage system is maximized to be able to handle all refueling needs with a minimum flow rate from the cryopump. Figure 2-4 shows a basic overall system schematic for this type of design.
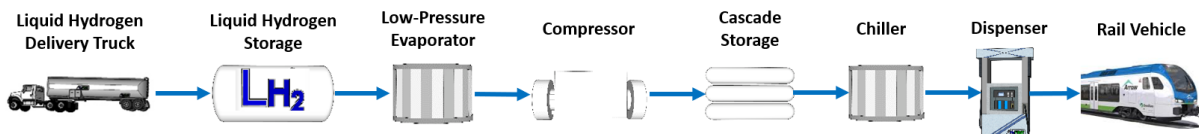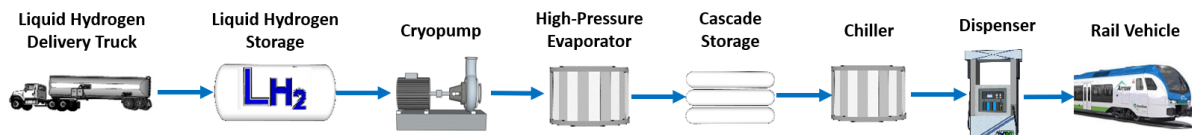

Figure 2-4 Simple Schematic of Multiple Unit Train Refueling Facility Cascade-Fill Cryopump Design

2.1.8.1. Cryopump
The cryopump takes liquid hydrogen from the bulk storage tank and supplies high-pressure liquid hydrogen to the high-pressure evaporator, similar to the cryopump described in Section 2.1.6.1. However, for this design, the desired mass flow rate for the cascade-fill cryopump is only 108.3 kg/hr (1.8 kg/min) for both the 15-minute and 30-minute fill cases, as described in Section 2.1.7.1. An example cryopump for hydrogen was identified with a mass flow rate of 112.6 kg/hr at 450 bar. One cryopump can therefore meet the flow rate of this design. The size of this cryopump is 16.5 ft (5.0 m) long by 10 ft (3.0 m) width by 3.3 ft (1 m) high. The cost of this cryopump is estimated to be $100,000, which is a rough estimate provided by multiple industry sources.

2.1.8.2. High-Pressure Evaporator
The high-pressure evaporator takes liquid hydrogen from the cryopump and vaporizes it to gaseous hydrogen that is fed to the high-pressure cascade storage, similar to the high-pressure

evaporator described in Section 2.1.6.2. However, for this design, the desired mass flow rate for the cascade-fill high-pressure evaporator is only 108 kg/hr (1.8 kg/min) for both the 15-minute and 30-minute fill cases, as described in Section 2.1.7.1. An example high-pressure evaporator was identified that has a mass flow rate of 112.9 kg/hr at 600 bar. A single (1) evaporator can therefore meet the flow rate and pressure needs of this design. The size of this evaporator is 6.3 ft (1.9 m) long by 5.2 ft (1.6 m) wide by 23.6 ft (7.2 m) high. The cost of this example evaporator is $25,000, which was determined by interpolating the cost using two bounding evaporator quotes from manufacturers.

2.1.8.3. Cascade System
Refer to Section 2.1.7.3 for cascade storage system information.

2.1.8.4. Chiller
Refer to Section 2.1.5.4 for chiller component information. If high-pressure liquid hydrogen is able to perform the pre-cooling, a chiller might not be required for this design.

2.1.8.5. Dispenser
Refer to Section 2.1.5.5 for dispenser component information.

2.1.8.6. Component Summary
The number of major components and associated costs for the multiple unit train refueling facility design that utilized a cascade-fill and cryopump are summarized in Tables 2-7 and 2-8 for the 15-minute and 30-minute fill times, respectively.

Table 2-7 Multiple Unit Train Refueling Facility Cascade-Fill Cryopump 15-Minute Fill Time Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
Cryopump	1	100,000	100,000
HP Evaporator	1	25,000	25,000
Cascade Tank	360	35,000	12,600,000
Chiller	2	150,000	300,000
Dispenser	1	250,000	250,000
Total			**13,635,000**

**Table 2-8 Multiple Unit Train Refueling Facility Cascade-Fill Cryopump 30 Minute Fill
Time Design Component and Cost Summary**

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	180,000	360,000
Cryopump	1	100,000	100,000
HP Evaporator	1	25,000	25,000
Cascade Tank	310	35,000	10,850,000
Chiller	1	150,000	150,000
Dispenser	1	250,000	250,000
Total			**11,735,000**

2.1.9.   Summary

Table 2-9 shows the total major component costs for the multiple unit train refueling facility designs. Each of these designs have the same overall inputs and outputs, i.e., each design refuels the same number of the same type of train. However, as Table 2-9 shows, the different designs can have very different total costs for major components, even up to an order of magnitude difference. For this design, the cryopump designs tend to cost less than the compressor designs. The cascade-fill designs appear to cost significantly more than the direct-fill designs.

Table 2-9 Multiple Unit Train Refueling Facility Designs Cost Summary

Design	Fill Time (min)	Total Cost ($)
Direct-Fill Compressor	15	8,155,000
Direct-Fill Compressor	30	4,400,000
Direct-Fill Cryopump	15	1,745,000
Direct-Fill Cryopump	30	1,170,000
Cascade-Fill Compressor	15	14,235,000
Cascade-Fill Compressor	30	12,335,000
Cascade-Fill Cryopump	15	13,635,000
Cascade-Fill Cryopump	30	11,735,000

The reason for these differences is shown in Figure 2-5. First, the reason for the high cost of the cascade-fill systems is shown to be driven almost exclusively by the cost of the cascade storage system itself. The very high storage requirements of the cascade system result in a very large and very expensive storage system. While not shown in this work, the effect on the physical layout of the refueling facility of this large cascade system would also be potentially problematic, especially for small rail yards.
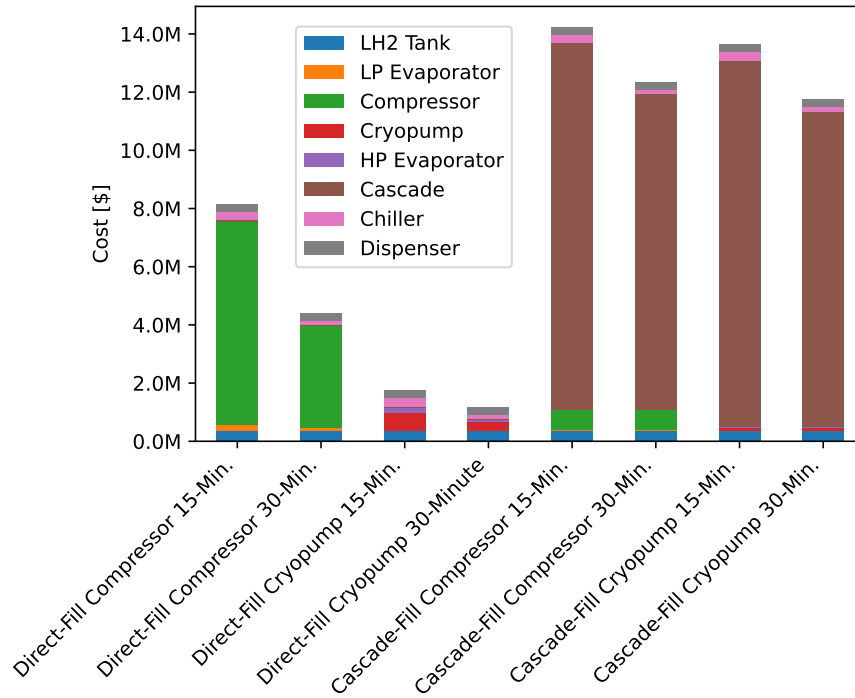
Figure 2-5 Multiple Unit Train Refueling Facility Cost Comparisons

Another major difference in the facility component costs for the MU train refueling facility designs is the high cost of the compressor relative to other components. The compressor cost is significantly higher than the analogous cryopump cost, even for the same flow rates. Additionally, the high cost of the compressor is highlighted in the need for 1 vs. 2 compressors in comparing the 15-minute to 30-minute designs for the direct-fill compressor designs. This is not to say that the cryopump cost is not significant; it is the highest component cost for the direct-fill cryopump 15-minute fill time design, and the second-highest component cost for the analogous 30-minute fill time design. This is because multiple (6 or 3, respectively) cryopumps are needed for these designs; if a larger-capacity cryopump could be designed for less than the cost of multiple pumps, this would introduce significant cost-savings. Cryopumps for liquid hydrogen are a somewhat nascent technology, so as demand increases for larger-capacity pumps, performance (such as flow rate) is likely to increase and costs are likely to decrease.

For all of these MU refueling designs, components were identified that should be able to meet the needs of the specified design. However, the feasibility and practicality of these designs and the identified components is more qualitative, since actual projects would need to be examined in more detail. Refueling pre-cooling requirements were not examined in detail in this analysis, and that will be critical for reaching the high mass flow rates necessary for fast filling at these large-scale systems. Current dispenser nozzles and hoses were not identified as being currently available for the flow rates considered, and may need to be custom-made or a new standard design needs to be established. Finally, many of the designs have multiple components (e.g., cryopumps or evaporators) running in parallel to meet the desired overall mass flow rate; this may not be

practical in the long-term and so rather larger-capacity single components may be more desirable.

2.1.10. *Process and Instrumentation Diagram*

Only the multiple unit train with 15-minute direct-fill and cryopump compression was investigated further. The reason for this is that having a direct-fill with a cryopump results in a significantly lower total cost compared to the designs that have direct-filling from a compressor and the designs that have a cascade system. The 30-minute fill resulted in a slightly lower cost that the 15-minute fill. However, the 15-minute fill was chosen for further analysis because realistically only the 15-minute fill can achieve full refueling of the entire fleet in the 10 hours allocated for refueling. Figure 2-6 shows the Process and Instrumentation Diagram (P&ID) for the multiple unit train refueling facility.
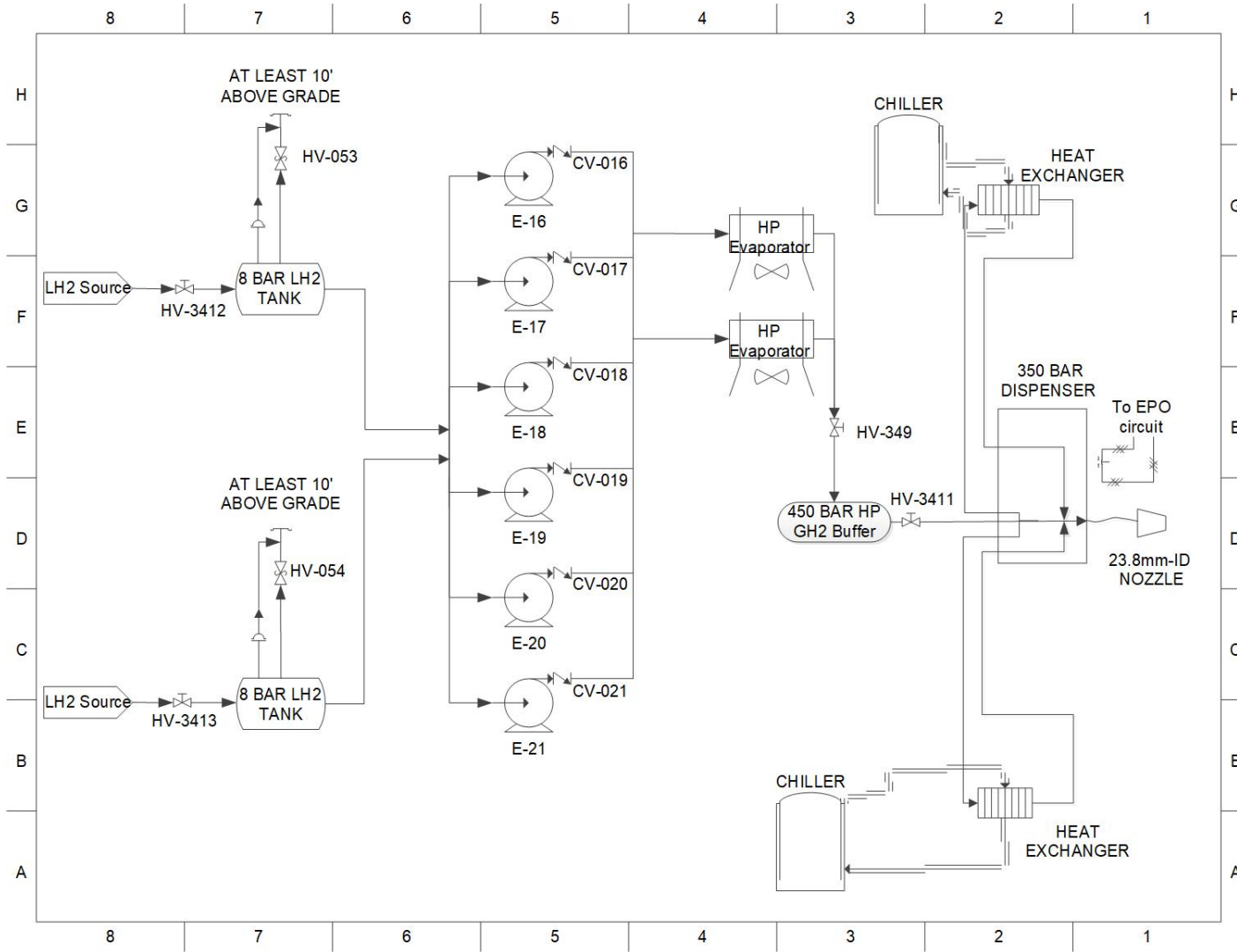
Figure 2-6 Multiple Unit Train Refueling Facility Direct-Fill Cryopump 15-Minute Fill Time Design P&ID

2.1.11. Code Compliant Fueling Station Layout

A code-compliant layout of the multiple unit train refueling facility with 15-minute direct-fill and cryopump was estimated and shown in Figure 2-7. The figure shows the major hydrogen system components on the left-hand side of the image, surrounded by a fire-rated barrier wall on three sides (described below). A fence is shown on the fourth side to limit access to the hydrogen system. An LH_2 delivery truck is shown next to the hydrogen system as if a delivery is being made. Finally, the multiple unit train currently being refueled is shown on the right-hand side of the image, with the dispenser under a light-blue colored awning.

NFPA 2 [16] was used to determine the physical layout based on required separation distances. The hydrogen system includes the liquid hydrogen storage tanks, the cryopumps, the evaporators, and the gaseous hydrogen buffer. A three-sided fire-rated wall was positioned around the hydrogen system as shown in Figure 2-7; this barrier wall allows for reduction of setback distances as per Sections 7.3.2.3.1.2(A) and 8.3.2.3.1.6(A)(2) of NFPA 2. The distance between the fire-rated walls and the liquid hydrogen tanks is required to be at least half the length of the liquid hydrogen tanks (per Section 8.3.2.3.1.6(A)(2)(c) of NFPA 2). The fire-rated walls need to be high-enough to interrupt line of sight between the system and the exposure (per Sections 7.3.2.3.1.2(A)(3) and 8.3.2.3.1.6(A)(2)(a) of NFPA 2); this can be design-specific, but here is assumed to be 10 ft (3 m). The fire-rated walls need be at least 5 ft (1.5 m) from the lot lines (property line) and any component in the hydrogen system (per Sections 7.3.2.3.1.2(A)(8), 8.3.2.3.1.6(A)(2)(f), and 8.3.2.3.1.6(A)(2)(g)). When gaseous and liquid hydrogen are part of a single system (as in this case), there must be a distance of at least 15 ft (4.6 m) between the gaseous and liquid portions of the system (per Section 7.3.2.3.1.3(B) of NFPA 2).

Separation distances for outdoor bulk liquid hydrogen storage are given in NFPA 2 and can be somewhat restrictive for locations with small areas available. These setback distances are given to different exposure types, such as air intakes, lot lines (property lines), people, parking, and the storage of other flammable or hazardous materials. Thus, whether or not a setback distance is met or not depends on what exposures are nearby. In this study, the hydrogen system and dispensers are positioned by themselves; this could be part of a larger rail yard (lot), in which case those distances to lot lines may be easily met. There are many different exposure types, and for liquid hydrogen systems, many have different setback distances. Therefore, each exposure will not be discussed here. However, it is worth noting that the separation distances for the liquid hydrogen system are based on the total liquid hydrogen volume (not mass or system parameters such as line size or pressure) as specified in NFPA 2 Table 8.3.2.3.1.6(A). The total liquid hydrogen volume in this design is 6,900 gal (26,000 L), which falls within the range 3,501 gal to 15,000 gal (13,251 L to 56,781 L) of Table 8.3.2.3.1.6(A) in NFPA 2, so those setback distances would apply.

The gaseous hydrogen buffer is considered non-bulk gaseous storage because the capacity is below 11.8 kg (5,000 scf) of hydrogen, so there must be at least 10 ft (3 m) from the lot lines and other storage areas, and these separations distance can be eliminated with a fire-rated wall (per Table 7.2.2.3.2 of NFPA 2). The gaseous hydrogen dispenser is required to be at least 10 ft (3 m) from the lot lines and 3 ft (1 m) from any storage containers (per Table 10.5.2.2.1.4 of NFPA 2). All of the separation distances described in this section are shown in Figure 2-7. Accounting for

all of the separation distances and component sizes, a 129 ft (39.3 m) by 99.5 ft (30.3 m) (12,836 ft^2) lot is needed for this station design.
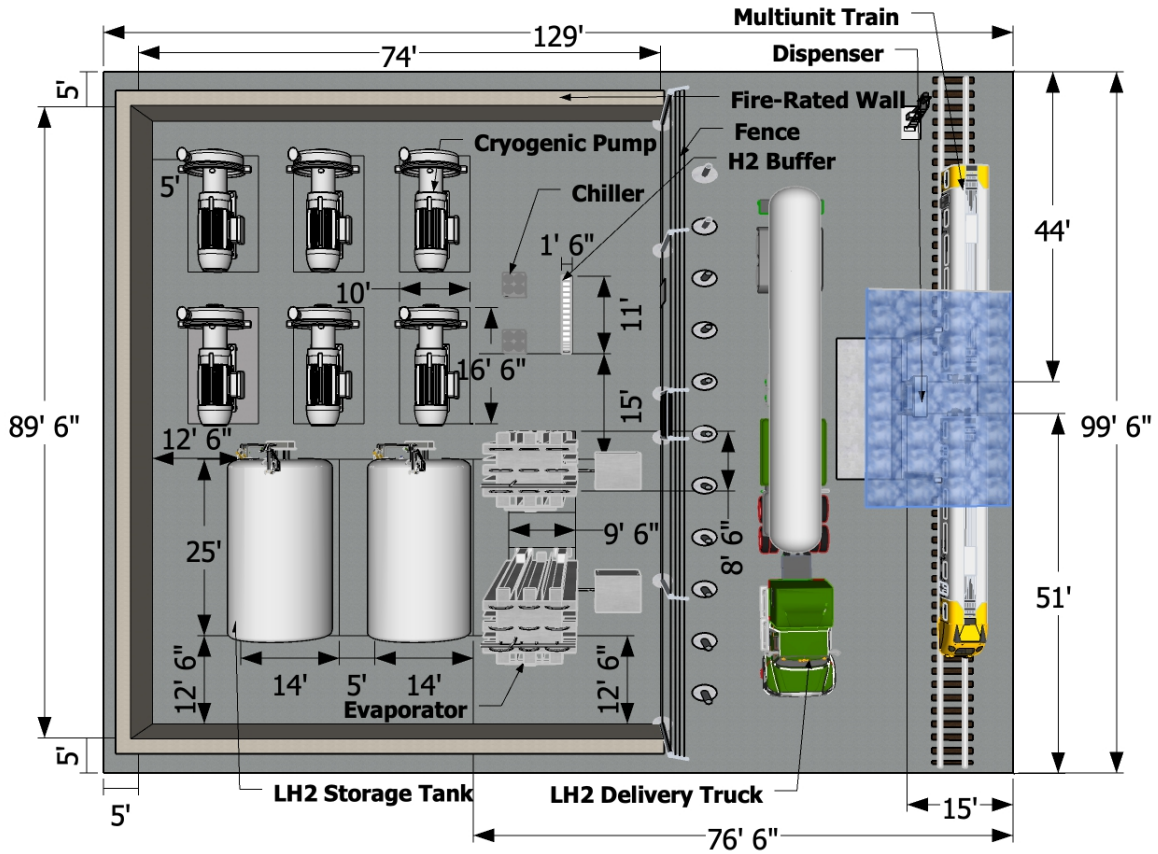
Figure 2-7 Multiple Unit Train Refueling Facility Direct-Fill Cryopump 15-Minute Fill Time Design Layout

2.2. Locomotive Passenger Rail

2.2.1. Design Inputs

The refueling station is designed to handle a 50 locomotive fleet. The relevant specifications of the locomotive passenger trains were provided by Argonne National Laboratory [5]. A total of 400 kg GH_2 will be dispensed to each locomotive. The total refueling capacity of the station is 20,000 kg/day, based on the number of locomotives and the amount of hydrogen dispensed per locomotives. A fuel transfer rate of 10 kg/min to the locomotive will be used for this design; this fuel transfer rate is in the middle of the two refueling rates considered for the multiple unit train refueling facility design (see Section 2.1.1) and is equivalent to the long-term DOE technical target for refueling of Class 8 heavy duty trucks [17]. This refueling would result in a fuel transfer time of 40 minutes. An additional 20 minutes total were allocated for moving the locomotive, connecting and disconnecting the dispenser hose, etc. A total time of 10 hours is allotted for refueling the entire fleet, which would be analogous to refueling the locomotives overnight after they operate during the day. Since each of the 50 locomotives takes more than 40 minutes to refuel, five separate dispensers were used for simultaneous refueling. Multiple fuel transfer hoses per locomotive could potentially achieve faster overall filling with a lower mass flow rate per transfer hose, if faster filling times are needed.

2.2.2. Station Configuration and Components

Four different configurations were analyzed for the gaseous hydrogen passenger locomotive refueling station design, based on the combinations between the following design parameters:

1. two hydrogen compression methods (a low-pressure vaporizer leading to a gas compressor or a liquid cryopump leading to a high-pressure vaporizer), and

2. two filling methods (a larger mass flow rate compressor/cryopump to fuel directly or a cascade-fill storage system with a smaller mass flow rate compressor/cryopump).

2.2.3. Bulk Hydrogen Storage

The total tank capacity is sized for a 10% larger capacity than the daily dispensing capacity, as described in Section 2.1.3. Liquid hydrogen tanker trucks have a capacity of approximately 4,000 kg of hydrogen [7], meaning that 5 separate full tanker trucks would be required to deliver sufficient hydrogen to this facility each day. It should also be noted that current hydrogen liquefaction facilities produce approximately 30,000 kg/day of liquid hydrogen [18, 19], meaning that potentially a dedicated liquid hydrogen production facility would be needed for this facility that dispenses 20,000 kg/day.

Two horizontal liquid hydrogen tanks will be used in this design to receive deliveries and store the hydrogen on-site. These tanks are estimated to be designed using the same LH_2 density and length/diameter ratio as described in Section 2.1.3. The system daily dispensing capacity is

20,000 kg, leading to a total tank capacity of 22,000 kg, based on the 10% over daily dispensing capacity. This leads to two tanks, each with a capacity of 11,000 kg. Each tank will therefore have an inner diameter of 16 ft (4.9 m) and an inner length of 35 ft (10.7 m), which gives an inner volume of 53,000 gal (200 m^3). Based on the tank walls and vacuum void space, the outer dimensions of the tank are 23 ft (6.9 m) diameter and 42 ft (12.7 m) length.

The same cost per storage volume as described in Section 2.1.3 is used to estimate tank cost. Based on this normalized cost with the storage capacity volume noted above, each tank is estimated to cost $1,400,000.

2.2.4. Pipe Sizing

The diameter of the dispensing tubing was calculated in the same way as described in Section 2.1.4. The dispensing flow rate for this design is 10 kg/min. This leads to a minimum inner pipe diameter of 18.1 mm (0.7 in).

2.2.5. Direct-Fill Compressor Design

The direct-fill compressor design uses a gas compressor to directly fill the locomotive. This means that the output flow rate of the compressor is equivalent to the mass flow rate of the hydrogen dispensed to the locomotive. The size of the post-compressor buffer storage is minimal and only really serves to provide a buffer between the flow rates of the compressor/evaporator output and the chiller/dispenser input. Refer to Figure 2-1 for a simple schematic of this design concept.

2.2.5.1. Low-Pressure Evaporator
The low-pressure evaporator takes liquid hydrogen from the bulk storage and vaporizes it to gaseous hydrogen that is fed to the compressor. The desired mass flow rate per dispenser is 600 kg/hr (10 kg/min), as described in Section 2.2.1. Since there are up to 5 dispensers operating at any given time, the total mass flow rate supplies by the evaporator/compressor is therefore 3,000 kg/hr (50 kg/min).

An example ambient-air vaporizer for liquid hydrogen was identified with a mass flow rate of 352 kg/hr. The required total mass flow rate requires 9 evaporators. The outer physical dimensions of this evaporator are 4.3 ft (1.3 m) long by 7.9 ft (2.4 m) wide by 16.3 ft (5.0 m) high. The desired pressure of the evaporator is 1.013 bar while the selected evaporator exceeds this with a design pressure of 41.4 bar. The cost of this example evaporator is estimated to be $50,000, which was determined by interpolating the cost using two bounding evaporator quotes from manufacturers.

2.2.5.2. Compressor

The compressor takes gaseous hydrogen from the low-pressure evaporator and feeds it through the small buffer storage system directly to the locomotive. The desired mass flow rate for the compressor is 3,000 kg/hr (50 kg/min), as described in Section 2.2.5.1. An example compressor for hydrogen was identified with a mass flow rate of 550 kg/hr, meaning that 6 compressors would be needed to meet the total required flow rate. The outer physical dimensions of this compressor are 36 ft (11.0 m) long by 20 ft (6.1 m) wide by 17 ft (5.2 m) high. The desired pressure of the compressor is 450 bar, which the compressor meets. The cost of this example compressor is $3,500,000, which was an estimate provided by the manufacturer.

2.2.5.3. Buffer Storage

In this design, one high-pressure storage tank with a capacity of 11 kg was selected to buffer any flow rate fluctuations that may occur from the compressor to the chiller. Refer to Section 2.1.5.3 for more details on this high-pressure buffer storage tank.

2.2.5.4. Chiller

Specifics on the selected chiller and output temperature are discussed in Section 2.1.5.4. Each of the example chillers has a flow rate of 10 kg/min, so this design needs 5 chillers to meet the required flow rate.

2.2.5.5. Dispenser

An example gaseous hydrogen dispenser was identified with a mass flow rate of 20 kg/min at 350 bar and -20°C, the same as described in Section 2.1.5.5. The outer physical dimensions of this example dispenser are 3.8 ft (1.2 m) long by 1.8 ft (0.5 m) wide by 8.2 ft (2.5 m) high. The example dispenser is estimated to cost $250,000, which was estimated using a manufacturer quote for a similar dispenser and estimate from a research report on light-duty vehicle refueling facilities [13]. This dispenser meets the required per-locomotive mass flow rate. Since 5 locomotives can be refueled simultaneously, 5 dispensers are needed for this design.

It should be noted again that current refueling mass flow rates are significantly lower than this stated 20 kg/min, and currently available hoses and nozzles may not exist that can meet these flow rates. For example, current 350 bar refueling dispensers have inside diameters of nominally 8–12 mm [14, 15], which are much smaller than the 18.1 mm inner diameters as calculated in Section 2.2.4. As discussed in Section 2.1.5.5, this is an active area of research and development, and so this may change in the future. Additionally, multiple fuel transfer hoses per train could potentially achieve faster overall filling with a lower mass flow rate per transfer hose, if faster filling times are needed or if this mass flow rate is not currently achievable.

2.2.5.6. Component and Cost Summary

The number of major components and associated costs for the passenger locomotive refueling facility design that utilized a direct-fill and compressor are summarized in Table 2-10.

Table 2-10 Passenger Locomotive Refueling Facility Direct-Fill Compressor Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	1,400,000	2,800,000
LP Evaporator	9	50,000	450,000
Compressor	6	3,500,000	21,000,000
Buffer Tank	1	35,000	35,000
Chiller	5	150,000	750,000
Dispenser	5	250,000	1,250,000
Total			**26,285,000**

2.2.6. *Direct-Fill Cryopump Design*

The direct-fill cryopump design uses a cryogenic liquid pump to directly-fill the locomotive. This means that the output flow rate of the cryopump is equivalent to the mass flow rate of the hydrogen dispensed to the locomotive. The size of the post-cryopump buffer storage is minimal and only really serves to provide a buffer between the flow rates of the cryopump/evaporator output and the chiller/dispenser input. Refer to Figure 2-2 for a simple schematic of this design concept.

2.2.6.1. Cryopump

The cryopump takes liquid hydrogen from the storage and feeds it through the high-pressure evaporator and small buffer system directly to the locomotive. The total required mass flow rate for the cryopump is 3,000 kg/hr (50 kg/min), as described in Section 2.2.5.1. An example cryopump for hydrogen was identified with a mass flow rate of 173.4 kg/hr, meaning that 18 cryopumps would be needed to meet the total required flow rate. The size of this cryopump is 16.5 ft (5.0 m) long by 10 ft (3.0 m) wide by 3.3 ft (1.0 m) high. The desired pressure of the cryopump is 450 bar, which the cryopump meets. The cost of this example cryopump is $100,000, which is a rough estimate provided by multiple industry sources.

2.2.6.2. High-Pressure Evaporator

The high-pressure evaporator takes liquid hydrogen from the cryopump and vaporizes it to gaseous hydrogen that is fed to the high-pressure buffer storage. The total required mass flow rate for the high-pressure evaporator is 3,000 kg/hr (50 kg/min), as described in Section 2.2.5.1. An example high-pressure evaporator was identified with a mass flow rate of 744 kg/hr, meaning that 5 evaporators would be required to meet the total mass flow rate. As described in Section 2.1.6.2, the size of this evaporator is 8.2 ft (2.5 m) long by 9.6 ft (2.9 m) wide by 48.5 ft (14.8 m) high and the cost is estimated to be $100,000.

2.2.6.3. Buffer Storage
Refer to Section 2.2.5.3 for high-pressure buffer storage information.

2.2.6.4. Chiller
Refer to Section 2.2.5.4 for chiller component information. If high-pressure liquid hydrogen is able to perform the pre-cooling, a chiller might not be required for this design.

2.2.6.5. Dispenser
Refer to Section 2.2.5.5 for dispenser component information.

2.2.6.6. Component and Cost Summary
The number of major components and associated costs for the passenger locomotive refueling facility design that utilized a direct-fill and cryopump are summarized in Table 2-11.

Table 2-11 Passenger Locomotive Refueling Facility Direct-Fill Cryopump Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	1,400,000	2,800,000
Cryopump	18	100,000	1,800,000
HP Evaporator	5	100,000	500,000
Buffer Tank	1	35,000	35,000
Chiller	5	150,000	750,000
Dispenser	5	250,000	1,250,000
Total			**7,135,000**

2.2.7. *Cascade-Fill Compressor Design*

The cascade-fill compressor design uses a high-pressure cascade storage system to provide the refueling flow rate and a gas compressor to slowly refill the cascade storage system. The size of the cascade storage system is maximized to be able to handle all refueling needs with a minimum flow rate from the compressor. Refer to Figure 2-3 for a simple schematic of this design concept.

2.2.7.1. Low-Pressure Evaporator
The low-pressure evaporator takes liquid hydrogen from the bulk storage and vaporizes it to gaseous hydrogen that is fed to the compressor. The desired mass flow rate for the low-pressure evaporator is 833.3 kg/hr (13.9 kg/min). This is because the cascade system supplies the different mass flow rates for dispensing hydrogen, whereas the cascade-fill evaporator and compressor are sized to slowly refill the cascade storage system over the course of 24 hours.

An example low-pressure evaporator was identified with a mass flow rate of 352 kg/hr, meaning that 3 evaporators are needed for this design. The desired pressure of the evaporator is 8 bar while this evaporator exceeds this with a design pressure of 41.4 bar. The size of this evaporator is 4.3 ft (1.3 m) long by 7.9 ft (2.4 m) wide by 16.3 ft (5.0 m) high. The cost of each evaporator is $50,000, which was determined by interpolating the cost using two bounding evaporator quotes from manufacturers.

2.2.7.2. Compressor
The compressor takes gaseous hydrogen from the low-pressure evaporator and supplies high-pressure hydrogen to the cascade storage system. The desired mass flow rate for the cascade-fill compressor is 833.3 kg/hr (13.9 kg/min), as described in Section 2.2.7.1. An example compressor for hydrogen was identified with a mass flow rate of 550 kg/hr, which means that 2 compressors would be needed to meet the required total flow rate. The size of compressor is 36 ft (11.0 m) long by 20 ft (6.1 m) wide by 17 ft (5.2 m) high. The desired pressure of the compressor is 450 bar, which the compressor meets. The cost of this example compressor is $3,500,000, which was provided by the manufacturer.

2.2.7.3. Cascade System
The cascade system has the same cascade system configuration and methodology described in Section 2.1.7.3. The same example storage vessels as described in Section 2.1.7.3 are also used in this design.

For this design, the total amount of hydrogen dispensed per fill is 400 kg per fill, as described in Section 2.2.1. The total mass flow rate into the overall cascade system is 833.3 kg/hr (13.9 kg/min), as described in Section 2.2.7.1; however, since 5 locomotives are refueling simultaneously, the flow rate into any one cascade "unit" is 166.7 kg/hr (2.8 kg/min). The flow rate out of the cascade unit during filling is 10 kg/min for each locomotive, and so for each cascade unit, as described in Section 2.2.1.

Based on these design inputs, a cascade unit size is estimated to contain 11 "low" tanks, 17 "medium" tanks, and 16 "high" tanks, for a total of 44 tanks per dispensed rail vehicle. This gives a total cascade system size of 2,200 tanks for a fleet of 50 locomotives.

2.2.7.4. Chiller
Refer to Section 2.2.5.4 for chiller component information.

2.2.7.5. Dispenser
Refer to Section 2.2.5.5 for dispenser component information.

2.2.7.6. Component and Cost Summary
The number of major components and associated costs for the passenger locomotive refueling facility design that utilized a cascade-fill and compressor are summarized in Table 2-12.

Table 2-12 Passenger Locomotive Refueling Facility Cascade-Fill Compressor Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	1,400,000	2,800,000
LP Evaporator	3	50,000	150,000
Compressor	2	3,500,000	7,000,000
Cascade Tank	2,200	35,000	77,000,000
Chiller	5	150,000	750,000
Dispenser	5	250,000	1,250,000
Total			**88,950,000**

2.2.8. Cascade-Fill Cryopump Design

The cascade-fill cryopump design uses a high-pressure cascade storage system to provide the refueling flow rate and a cryopump to slowly refill the cascade storage system. The size of the cascade storage system is maximized to be able to handle all refueling needs with a minimum flow rate from the cryopump. Refer to Figure 2-4 for a simple schematic of this design concept.

2.2.8.1. Cryopump
The cryopump takes liquid hydrogen from the bulk storage tank and supplies high-pressure liquid hydrogen to the high-pressure evaporator. The desired mass flow rate for the cascade-fill cryopump is 833.3 kg/hr (13.9 kg/min), as described in Section 2.2.7.1. An example cryopump for hydrogen was identified with a mass flow rate of 173.4 kg/hr, meaning that 5 cryopumps are needed to meet the required flow rate. The size of this cryopump is 16.5 ft (5.0 m) long by 10 ft (3.0 m) wide by 3.3 ft (1.0 m) high. The desired output pressure of the cryopump is 450 bar, which the cryopump meets. The cost of this cryopump is estimated to be $100,000, which is a rough estimate provided by multiple industry sources.

2.2.8.2. High-Pressure Evaporator
The high-pressure evaporator takes liquid hydrogen from the cryopump and vaporizes it to gaseous hydrogen that is fed to the high-pressure cascade storage. The required mass flow rate for the cascade-fill cryopump is 833.3 kg/hr (13.9 kg/min), as described in Section 2.2.7.1. An example high-pressure evaporator was identified with a mass flow rate of 535 kg/hr, which means that 2 evaporators are needed to meet the required flow rate. As described in Section 2.1.6.2, the size of evaporator is 8.4 ft (7.3 m) long by 9.5 ft (6.4 m) wide by 44.5 ft (13.6 m) high, and the cost is estimated to be $75,000.

2.2.8.3. Cascade System
Refer to Section 2.2.7.3 for cascade system information.

2.2.8.4. Chiller
Refer to Section 2.2.5.4 for chiller component information. If high-pressure liquid hydrogen is able to perform the pre-cooling, a chiller might not be required for this design.

2.2.8.5. Dispenser
Refer to Section 2.2.5.5 for dispenser component information.

2.2.8.6. Component and Cost Summary
The number of major components and associated costs for the passenger locomotive refueling facility design that utilized a cascade-fill and cryopump are summarized in Table 2-13.

Table 2-13 Passenger Locomotive Refueling Facility Cascade-Fill Cryopump Design Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	1,400,000	2,800,000
Cryopump	5	100,000	500,000
HP Evaporator	2	75,000	150,000
Cascade Tank	2,200	35,000	77,000,000
Chiller	5	150,000	750,000
Dispenser	5	250,000	1,250,000
Total			**82,450,000**

2.2.9.   Summary

Table 2-14 shows the total major component costs for the passenger locomotive refueling facility designs. Each of these designs have the same overall inputs and outputs, i.e., each design refuels the same number of the same type of train. However, as Table 2-14 shows, the different designs can have very different total costs for major components, even up to an order of magnitude difference. For this design, the cryopump designs tend to cost less than the compressor designs. The cascade-fill designs appear to cost significantly more than the direct-fill designs.

Table 2-14 Passenger Locomotive Refueling Facility Designs Cost Summary

Design	Total Cost ($)
Direct-Fill Compressor	26,285,000
Direct-Fill Cryopump	7,135,000
Cascade-Fill Compressor	88,950,000
Cascade-Fill Cryopump	82,450,000

The reason for these differences is shown in Figure 2-5. First, the reason for the high cost of the cascade-fill systems is shown to be driven almost exclusively by the cost of the cascade storage system itself. The very high storage requirements of the cascade system result in a very large and very expensive storage system. While not shown in this work, the effect on the physical layout of the refueling facility of this large cascade system would also be potentially problematic, especially for small rail yards.
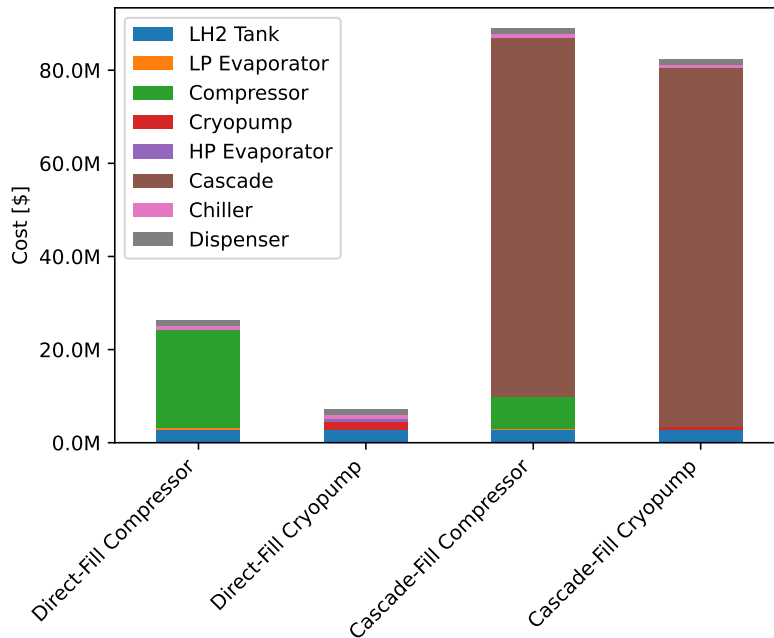
Figure 2-8 Passenger Locomotive Refueling Facility Cost Comparisons

Another major difference in the facility component costs for the passenger locomotive refueling facility designs is the high cost of the compressor relative to other components. The compressor cost is significantly higher than the analogous cryopump cost, even for the same flow rates. This design also highlights the fact that in almost every case, multiple compressors or cryopumps are required to meet the necessary flow rates. Even the design with the lowest total component cost (direct-fill cryopump design) needs 18 cryopumps to meet the needed flow rate. This is almost certainly a situation in which fewer, larger pumps could be less expensive overall and take up less space.

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Finally, it is worth noting that the liquid hydrogen storage tank is a significant contributor to the total cost, especially for the overall lowest cost design (direct-fill cryopump design). In this case, the cost of this storage is approximately 38% while for the lowest cost multiple unit design it is approximately 29% of the total component cost. For both designs, the liquid hydrogen storage tank was sized as proportional to the dispensing capacity of the facility; for larger-capacity systems, this storage cost becomes a larger proportion of the total component cost.

For all of these passenger locomotive refueling designs, components were identified that should be able to meet the needs of the specified design. However, the feasibility and practicality of these designs and the identified components is more qualitative, since actual projects would need to be examined in more detail. Refueling pre-cooling requirements were not examined in detail in this analysis, and that will be critical for reaching the high mass flow rates necessary for fast filling at these large-scale systems. Current dispenser nozzles and hoses were not identified as being currently available for the flow rates considered, and may need to be custom-made or a new standard design needs to be established. Finally, many of the designs have multiple components (e.g., cryopumps or evaporators) running in parallel to meet the desired overall mass flow rate; this may not be practical in the long-term and so rather larger-capacity single components may be more desirable.

2.2.10. *Process and Instrumentation Diagram*

Only the locomotive passenger train with cryopump compression was investigated further. The reason for this is that having a direct-fill with a cryopump results in a significantly lower total cost compared to the design that have direct-filling from a compressor and the designs that have a cascade system. Additionally, the siting (physical space) for that many cascade tanks seems impractical. Figure 2-9 shows the P&ID for the locomotive passenger train refueling facility.
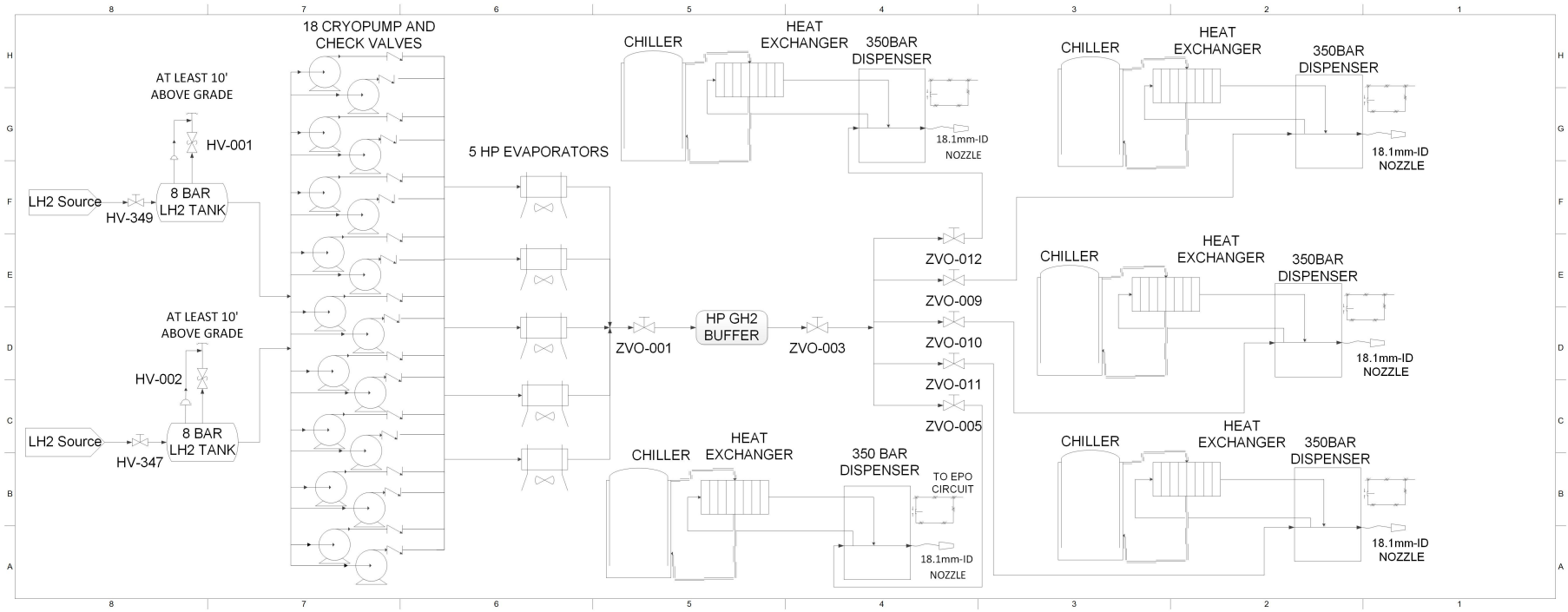
Figure 2-9 Passenger Locomotive Refueling Facility Direct-Fill Cryopump Design P&ID

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2.2.11. Code Compliant Fueling Station Layout

The code compliant layout of the locomotive passenger train refueling facility with 10 kg/min direct-fill and cryopump was investigated, and it is shown in Figure 2-10. The figure shows the major hydrogen system components on the left-hand side of the image, surrounded by a fire-rated barrier wall on three sides (described below). A fence is shown on the fourth side to limit access to the hydrogen system. An LH$_2$ delivery truck is shown next to the hydrogen system as if a delivery is being made. Finally, the passenger locomotives currently being refueled are shown on the right-hand side of the image, with the dispensers each under a light-blue colored awning.

Refer to section 2.1.11 for details on how the separation distances were obtained. The main difference in this design is that the total liquid hydrogen volume is 53,000 gal (201,000 L), which falls within the range 15,001 gal to 75,000 gal (56,782 L to 283,906 L) of Table 8.3.2.3.1.6(A) in NFPA 2, so those setback distances would apply. Accounting for all of the separation distances and component sizes, a 232 ft (70.7 m) by 131 ft (40.0 m) (30,392 ft^2) lot is needed for this station design.
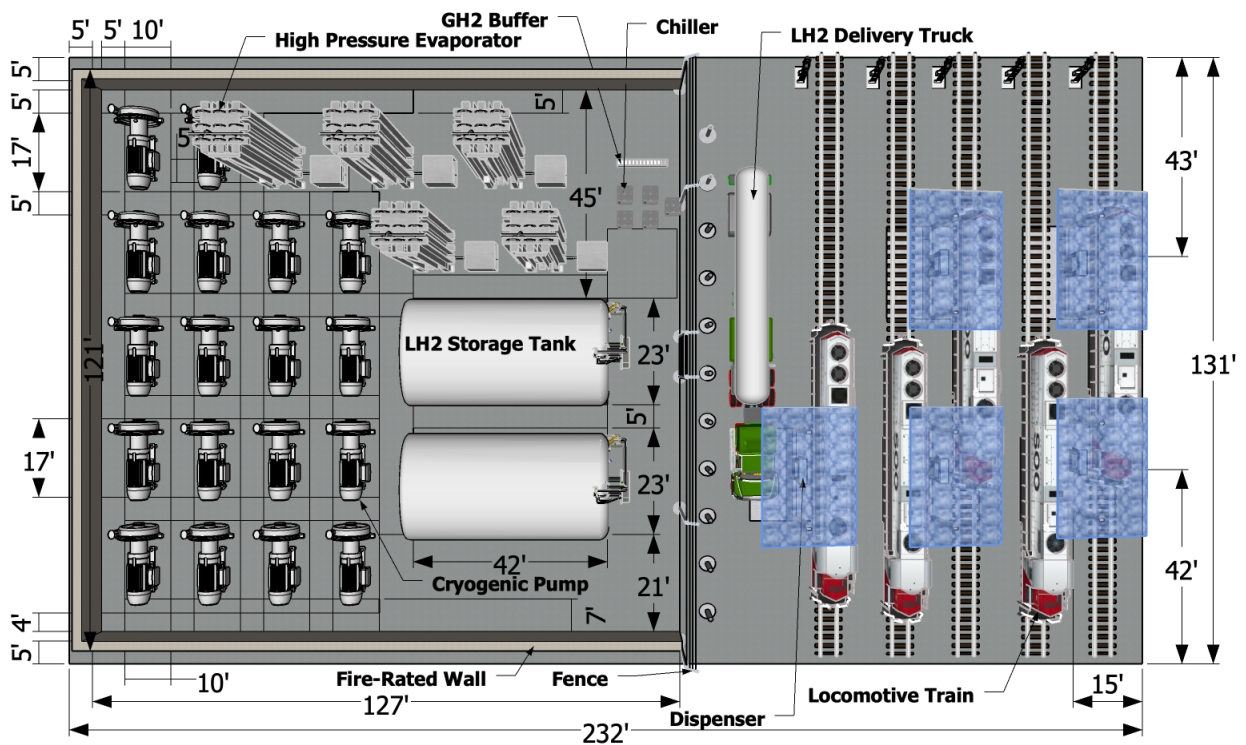
Figure 2-10 Passenger Locomotive Refueling Facility Direct-Fill Cryopump Design Layout

It should be noted that this layout configuration of so many pumps operating in parallel is likely not practical. Higher-capacity pumps would lead to a much more realistic configuration of fewer pumps.

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3.   LIQUID HYDROGEN DISPENSING DESIGNS

Some rail applications are likely to utilize cryogenic liquid hydrogen on-board the train due to the increased density for storage and refueling speed. This could potentially be stored on-board the locomotive (analogous to the gaseous hydrogen locomotive case in Section 2.2), but for more fuel storage capacity a tender car can be used. A tender car is a rail vehicle hauled by a locomotive containing its fuel. In this case, the tender car is somewhat similar to a tank car in that the whole car is taken up by the LH_2 storage tank and some associated valving and instrumentation. The locomotive would likely be supplied with gaseous hydrogen from the tender car (since the fuel cell requires gaseous hydrogen), meaning that the tender would have an on-board evaporator. A tender car could supply a single locomotive, but likely it would sit between two locomotives, supplying them both. This is similar to how the Florida East Coast Railway operates, with a liquefied natural gas tender car that supplies two locomotives [20]. There are advantages to using a tender car in this way; the much larger storage capacity allows for more fuel and therefore more range or larger capacity. Additionally, tender cars could be refueled separately from an engine, meaning that a train could exchange an empty tender for a full one without waiting to refuel. However, the locomotives would therefore need to haul an extra rail car that does not carry revenue-generating freight, and the tenders themselves may cost a significant amount. Likely locomotives with tender cars would be used for longer trips with larger trains. This is by no means a definitive characterization; liquid hydrogen could potentially be utilized on locomotives without a tender, and some shorter distance or smaller trains could utilize gaseous hydrogen without the need for liquid hydrogen.

This section considers three different designs that utilize LH_2 tender cars. In each case, the tender car is assumed to be the same in terms of storage capacity and operating conditions. The main difference between the three designs are the number of trains (tenders) refueled per day. Different refueling facilities have different dispensing capacities, depending on the particular needs of that given location. The intention of these designs is to show examples of how liquid hydrogen dispensing systems could work and also to show the same design scaled to different capacities. Section 3.1 describes a design for a "small"-sized refueling facility that can refuel 5 tenders per day, Section 3.2 describes a design for a "medium"-sized refueling facility that can refuel 50 tenders per day, and Section 3.3 describes a design for a "large"-sized refueling facility that can refuel 200 tender cars per day. In all design scenarios, it is assumed that LH_2 is delivered and stored on-site before being dispensed onto the rail vehicles. Figure 3-1 shows a basic overall system schematic for these types of designs.

Figure 3-1 Simple Schematic of Freight Tender Car Refueling Facility Design

One way to transfer large amounts of liquid hydrogen is to use a cryogenic liquid pump. Unlike the cryopumps for gaseous hydrogen (see Section 2), p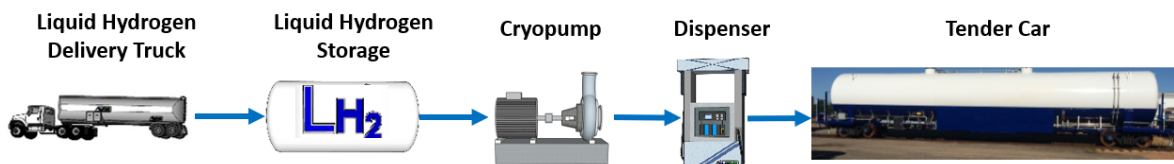umps for LH_2 dispensing do not need to reach the high pressure of 450 bar, but rather just enough to overcome the inherent pressure of the tender car itself. In this analysis, the tender cars are estimated to operate at approximately 5 bar gauge pressure [5]. However, the desired flow rate is likely to be much higher than the cryopumps used for gaseous hydrogen refueling. Each tender is assumed to have a usable capacity of 7,500 kg of LH_2 [5]. If a similar fill rate to gaseous hydrogen (10 kg/min), it would take 12.5 hours to completely fill an empty tender; this is not practical. However, if a flow rate of 300 or 1,200 kg/min were used, it would instead take 25 or 6.25 minutes, respectively. For this study, 300 kg/min will be considered as the dispensing flow rate, based on conversations with industry experts.

An alternative method of transferring the LH_2 would be to use a pressure-build loop, in which some of the LH_2 is passed through an evaporator and then returned as gaseous hydrogen to the top of the LH_2 tank, thus pressurizing the entire tank enough to drive the flow. This method does have some advantages: no power requirement like a pump would, no moving parts, and no energized equipment directly adjacent to (or submerged in) the LH_2. However, this increases the pressure and heat content of the tank, which can increase overall boil-off losses (hydrogen loss due to activation of the tank pressure relief valve). In order to achieve a flow rate of 300 kg/min of LH_2 out of the tank, a volume of 5.5 m^3 would need to be replaced with gaseous hydrogen every minute (using a LH_2 density of 54.6 kg/m^3 based on a saturated liquid at 8 bar). The mass of gaseous hydrogen needed to replace this volume would depend on the density of the evaporator output. Saturated vapor hydrogen at 8 bar has a density of 10.4 kg/m^3, meaning that a mass flow rate of 57 kg/min of hydrogen through the evaporator is needed, but gaseous hydrogen near ambient temperature (20°C) at 8 bar has a density of 0.66 kg/m^3, meaning that a mass flow rate of 3.6 kg/min (220 kg/hr) through the evaporator is needed; this is less than the flow rates achievable by some of the low-pressure evaporators discussed earlier (e.g., Section 2.1.5.1). It is possible to reduce the mass flow rate by redirecting the gaseous hydrogen from the tender car to the top of the LH_2 tank; this will be discussed further below.

After the cryopump (or pressure-build loop), the only other main component is the dispenser. A cascade system or chiller is not needed for LH_2 refueling, since the cryopump drives the flow directly (without the need for a cascade) and the same pressure-driven heating is not a concern for low-pressure LH_2. Some kind of flow rate meter might be needed to keep track of the fueling for inventory or sales purposes. The dispenser also contains pressure sensors and relief devices; these keep track of the pressure during the fill process and can relieve the pressure should an issue occur. A breakaway line for the dispenser hose will be needed, but was not considered in this study. Finally, a dispenser hose and connector are needed to actually make the connection to the tender car.

For gaseous hydrogen dispensing, the refueling facility pressurizes the on-board vehicle tank to fill it; therefore, a single fuel transfer connection is needed, in which hydrogen flows from the refueling facility to the on-board tank. For liquid dispensing, however, the tanks are not at high-pressure, and adding liquid to the tank would rapidly pressurize the gas remaining in an empty tank. Therefore, this gaseous hydrogen needs to be removed from the on-board tank as liquid is added. This can be done via a vent stack, in which the gas is simply vented to the

atmosphere; however, this wastes fuel. Additionally, liquid hydrogen can be put into the top of the tank, which should condense some of the gas already in the tank and reducing losses. Another way is to have a second fuel-transfer connection from the refueling facility to the on-board storage tank: this vapor return line would allow gaseous hydrogen from the top of the on-board tank to flow back to the refueling facility while LH_2 flows from the refueling facility to the on-board tank. This returned gaseous hydrogen could still be vented at the refueling facility, but could also be used for other purposes such as getting compressed and used for gaseous hydrogen refueling of other types of vehicles. The returned vapor could also be returned to the bulk liquid storage tank, so as to replace the volume displaced by the flow of LH_2 out of the tank.

3.1. Small Freight Locomotive

3.1.1. Design Inputs

The small freight LH_2 refueling station is designed to refuel 5 locomotive tenders per day, with 7,500 kg of LH_2 dispensed per tender. The total LH_2 dispensed per day for the small freight refueling station is 37,500 kg. A refueling rate of 300 kg/min will be used for this design. This fill rate will completely fill an empty tender car in 25 minutes, although this only accounts for the fuel transfer time, not connection times. Given the time required for refueling, two dispensers are assumed to be needed so that two tenders can refuel simultaneously.

3.1.2. Bulk Hydrogen Storage

The on-site liquid hydrogen storage is sized for 10% above the daily dispensing capacity, as discussed in Section 2.1.3. The system dispensing capacity is 37,500 kg, and so 10% above this is 41,250 kg. Liquid hydrogen tanker trucks have a capacity of approximately 4,000 kg of hydrogen [7], meaning that 10 separate full tanker trucks would be required to deliver sufficient hydrogen to this facility each day, which may not be practical. Each tanker truck delivery can take a significant amount of time (multiple hours) meaning that this many deliveries per day would need simultaneously delivery points, which would add additional cost and impracticality. Finally, current hydrogen liquefaction facilities produce approximately 30,000 kg/day of liquid hydrogen [18, 19], meaning that likely a dedicated liquid hydrogen production facility would be needed. Despite the practical challenges, it was assumed in this analysis that hydrogen could be delivered and transferred at this scale.

Two spherical LH_2 tanks will be used to store the hydrogen on-site for the design. These tanks are designed using the same LH_2 density as described in Section 2.1.3 but the tanks are assumed to be spherical rather than cylindrical. Spherical tanks are used for very large-scale systems due to more uniform distributions of mechanical stresses. Spherical tanks also minimize heat transfer by minimizing the surface area for a given storage volume. The system daily dispensing capacity is 37,500 kg, leading to a total tank capacity of 41,250 kg, based on the 10% over daily dispensing capacity. This leads to two tanks, each with a capacity of 20,625 kg. Each tank will therefore have an inner diameter of 29 ft (9.0 m), which gives an inner volume of 100,000 gal (378 m^3). For

context, the liquid hydrogen storage tanks at the National Aeronautics and Space Administration (NASA) Kennedy Space Center that serviced the Space Shuttle Program each had an inner volume of 850,000 gal (3,218 m^3) [21]. Based on the tank walls and vacuum void space, the outer diameter of the tank is 36 ft (11 m).

The cost of each tank was estimated using a metric of $5,000 per m^3 of storage capacity. This is based on the metric of $7,000 per m^3 used for the smaller LH$_2$ storage tanks (see Section 2.1.3) and a lower cost metric of $3,700 per m^3 for larger spherical LH$_2$ tanks described later in Section 3.2.2. Based on this normalized cost with the storage capacity volume noted above, each tank is estimated to cost $1,900,000.

3.1.3.   Cryopump and Sump System

The cryopump takes liquid hydrogen from the storage and supplies it to the dispenser to the tender. The total required mass flow rate for the cryopump is 36,000 kg/hr (600 kg/min), based on the flow rate per dispenser and two dispensers described in Section 3.1.1. An example cryopump for hydrogen was identified with a mass flow rate of 25,799 kg/hr (430 kg/min), meaning that 2 cryopumps would be needed to meet the total required flow rate. The size of this cryopump is 3 ft (0.9 m) long by 3 ft (0.9 m) wide by 6 ft (1.8 m) high. The desired pressure of the cryopump is at least 10 bar which aligns with the cryopumps design pressure differential of 5 bar. The cost of this example cryopump is $250,000, which is a rough estimate provided by an industry source. It should be noted that this or similar cryopumps may be able to meet even higher flow rates, which would enable faster refueling times.

The cryopump is a submerged pump, and so can either be submerged in the bulk storage tank itself or in a separate sump tank. The pump inlet must be below the liquid level at all times to ensure liquid flows into the pump via gravity since suction might cause liquid hydrogen to transform into the gas phase, causing a malfunction in the fueling system [22]. It is assumed that a separate sump tank is used, so that the main bulk storage tanks can feed either cryopump. Two sump tanks are required for the design, one for each cryopump, which will be placed below the level of the bulk storage tank. A rough estimate of the sump tank size is assumed to be the same dimensions as the cryopump: 3 ft (0.9 m) long by 3 ft (0.9 m) wide by 6 ft (1.8 m) high. The cost of each tank is estimated to be $150,000, which is a rough estimate provided by an industry source.

3.1.4.   Dispenser

Unlike the gaseous hydrogen dispensing, we were unable to identify any currently commercially available dispenser for liquid hydrogen. Therefore, we will include here a description of how the flow might be measured and how the connections might be made.

There are several methods to measure the dispensed mass flow. A tank level indicator on the bulk liquid hydrogen storage tanks can help keep track of inventory. Additionally, flow meters could be on individual pipes going to each dispenser; this would be especially relevant if a more specific amount is needed at each dispenser, such as for a point-of-sale system. An example turbine flow

meter was identified with a flow rate of up to 781 kg/min, which would meet the needs of each 300 kg/min dispenser. This meter is reasonably small (less than 1 foot (0.3 m) in any dimension) and is estimated to cost $6,000.

The liquid hydrogen will be dispensed into the tender car using bayonet connectors with an inner diameter of at least 2.63 inches (6.7 cm), as described in Section 3.1.5. Each dispenser is assumed to require 2 bayonet connections, one for the liquid hydrogen transfer line and one for the vapor return line. The largest commercially available bayonet connectors identified in this study have an inner diameter of 2 inches (5.1 cm) and so are slightly smaller than needed for this design. Per the manufacturer, the estimated cost of each set of connectors (male and female) is $3,000.

It should be noted that a bayonet connector set (male and female connectors) with an inner diameter of 2 inches (5.1 cm) would have a larger outer diameter (approximately 4.3 inches or 10.8 cm); a bayonet connector with a larger inner diameter would have a correspondingly larger outer diameter. While this may not be too impractical for operators to handle, the flexible hose/tubing and the connector would constitute a potentially significant amount of weight and bulk that operators would need to handle on a regular basis. This could be mitigated by having moveable support arms or other devices that could support the weight of the transfer line in a way that is maneuverable by an operator. For context, current liquefied natural gas trucks use a hand-held quick-connect connector, but these do not currently exist for liquid hydrogen. These types of connectors could be easier and quicker to connect and disconnect and could allow for sealing of the flow right at the connector itself, reducing purge requirements. The feasibility and practicality of these types of connectors for liquid hydrogen would need to be explored further.

3.1.5.   Pipe Sizing

The diameter of the dispensing tubing was calculated in the same way as described in Section 2.1.4. However, a maximum flow velocity of 2 m/s is used rather than 20 m/s; this flow velocity is within the typical range of flow velocity for pipe sizing of liquid systems (1–3 m/s) [10]. The density of liquid hydrogen at 30 K (based on the temperature of saturated liquid hydrogen at 8 bar in the storage tank) and 13 bar (based on the cryopump adding 5 bar to the tank storage pressure of 8 bar) is 57.5 kg/m^3. The flow velocity and density result in a minimum inner pipe diameter of 235 mm (9.3 in).

This is a very large size of hose and dispenser nozzle for the liquid hydrogen. Currently available components have a maximum diameter of 2 in (5.1 cm) per Section 3.1.4, and so much larger components would be needed. Section 3.1.4 also contains a discussion of how the connectors would be handled; larger diameter connectors would be correspondingly harder to handle, meaning that support systems would likely be even more necessary. The feasibility and practicality of these types of connectors for liquid hydrogen needs to be explored further.

3.1.6. Component and Cost Summary

Table 3-1 Small Freight Refueling Facility Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	1,900,000	3,800,000
Cryopump	2	250,000	500,000
Sump Tank	2	150,000	300,000
Flow Meter	2	6,000	12,000
Bayonet Connector Set	4	3,000	12,000
Total			**4,624,000**

3.1.7. Process and Instrumentation Diagram

The P&ID for the liquid hydrogen freight refueling designs is given in Figure 3-2. Note that this diagram is drawn in a modular fashion, in which connections and components are shown for a single dispenser. For this small freight design, two dispensers are used, so the components would all be doubled.
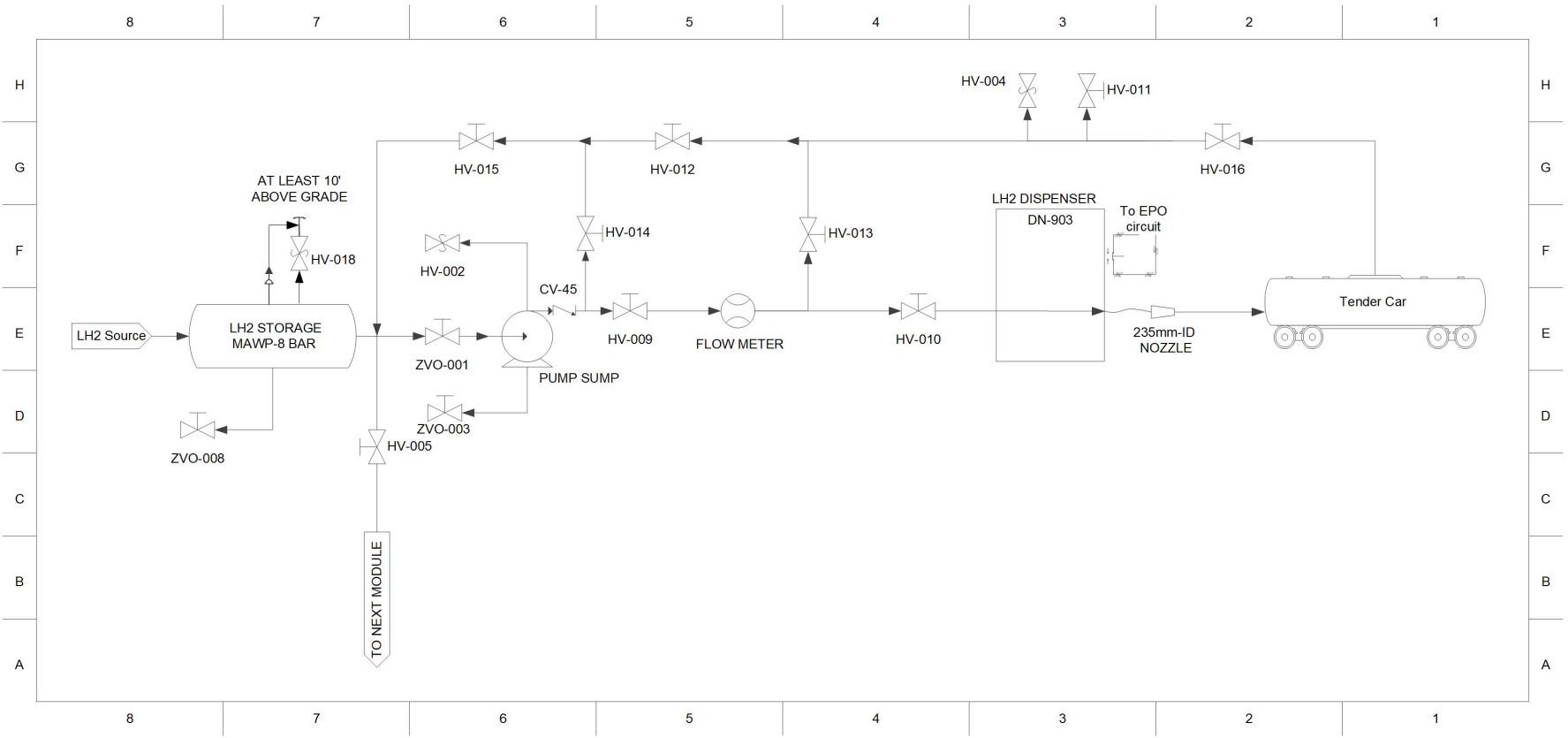
Figure 3-2 Small Freight Refueling Facility Design P&ID

3.1.8. Code Compliant Fueling Station Layout

The code compliant layout of the small freight locomotive refueling facility is shown in Figure 3-3. The figure shows the major hydrogen system components on the top of the image, surrounded by a fire-rated barrier wall on three sides (described below). A fence is shown on the fourth side to limit access to the hydrogen system. An LH_2 delivery truck is shown next to the hydrogen system as if a delivery is being made. Finally, the freight locomotives and tender cars currently being refueled are shown on the bottom of the image, with each dispenser under a light-blue colored awning.

NFPA 2 [16] was used to determine the physical layout based on required separation distances. In this design, the hydrogen system includes the liquid hydrogen storage tanks, cryopumps, evaporators, and sump tanks. A three-sided fire-rated wall was positioned around the liquid hydrogen system as shown in Figure 3-3; this barrier wall allows for reduction of setback distances as per Section 8.3.2.3.1.6(A)(2) of NFPA 2. The distance between the fire-rated walls and the liquid hydrogen tanks is required to be at least half the length of the liquid hydrogen tanks (per Section 8.3.2.3.1.6(A)(2)(c) of NFPA 2). The fire-rated walls need to be high-enough to interrupt line of sight between the system and the exposure (per Section 8.3.2.3.1.6(A)(2)(a) of NFPA 2); this can be design-specific, but here is assumed to be 10 ft (3 m). The fire-rated walls need be at least 5 ft (1.5 m) from the lot lines (property line) and any component in the hydrogen system (per Sections 8.3.2.3.1.6(A)(2)(f) and 8.3.2.3.1.6(A)(2)(g)).

The total liquid hydrogen volume in this station is 99,800 gal (378,000 L). Currently, NFPA 2 does not specify setback distances for liquid hydrogen storage volumes greater than 75,000 gal (283,906 L). This may be a significant issue for safe deployment of large hydrogen systems, as there is no guidance in NFPA 2 on what to do about this omission. This can affect many of the separation distances to all sorts of exposures, such as lot lines, air intakes, people, cars, other flammable liquid storage, and buildings. However, if on-site hydrogen liquefaction is used rather than this amount of storage, this particular gap in the NFPA 2 requirements may not apply.

The dispenser is required to be at least 25 ft (7.6 m) from lot lines, nearby buildings, and fixed sources of ignition (per Section 11.3.3.1.1 of NFPA 2). Accounting for all of the separation distances and component sizes, a 140 ft (42.7 m) by 143 ft (43.6 m) (20,020 ft^2) lot is needed for this station design.
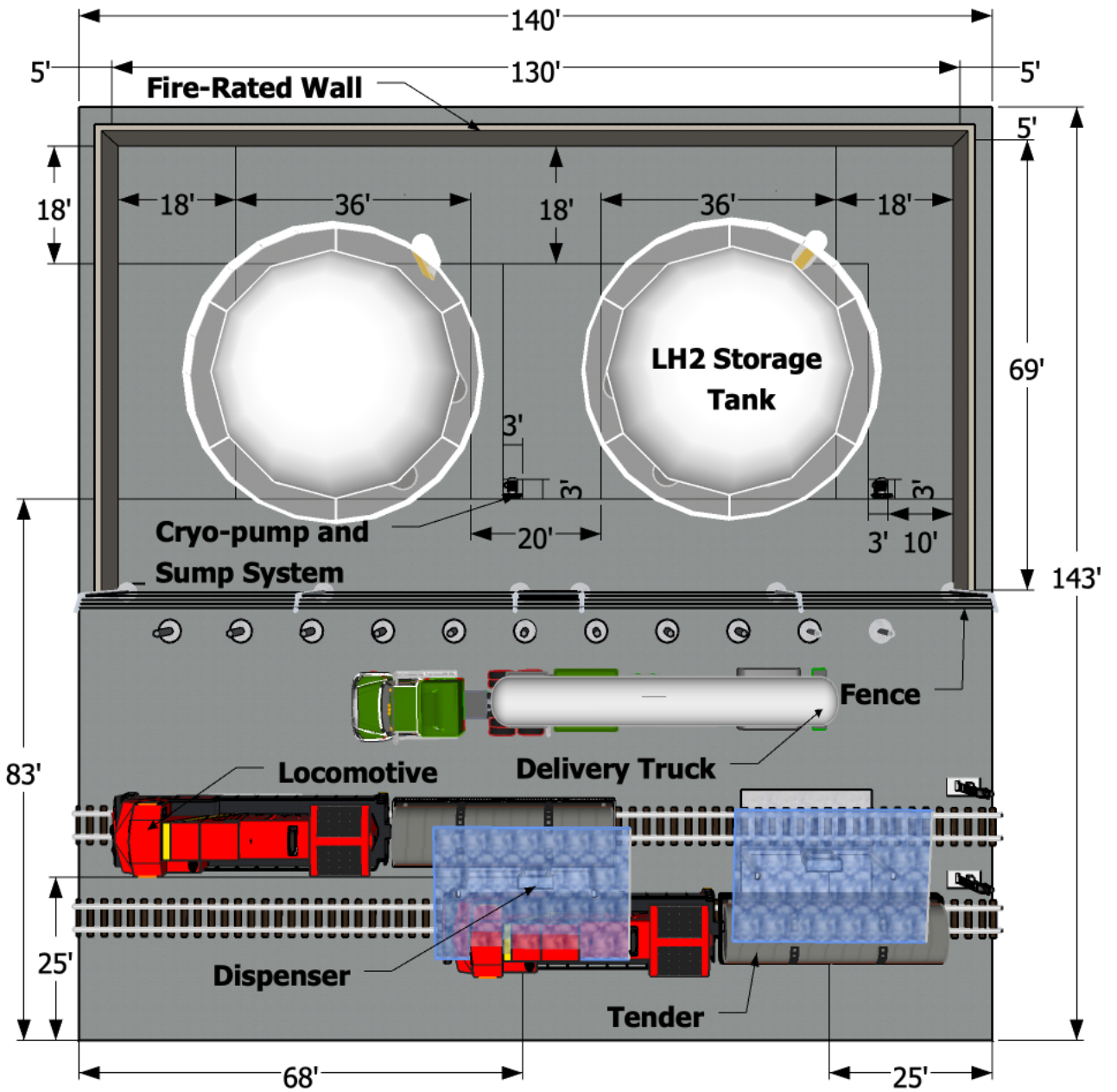
Figure 3-3 Small Freight Refueling Facility Design Layout

3.2. Medium Freight Locomotive

3.2.1. Design Inputs

The medium freight LH_2 refueling station is designed to refuel 50 tender cars per day, with 7,500 kg of LH_2 dispensed per tender. The total LH_2 dispensed per day for the medium freight refueling station is 375,000 kg. A refueling rate of 300 kg/min will be used for this design. This fill rate will completely fill a tender car in 25 minutes based on the usable capacity of 7,500 kg. This filling time only accounts for the fuel transfer time, not connection times. Given the time required for refueling, 5 dispensers are assumed to be needed so that multiple tenders can refuel simultaneously. This is analogous to the gaseous hydrogen passenger locomotive design (see Section 2.2) in terms of number of refuelings per day and number of dispensers.

3.2.2. Bulk Hydrogen Storage

Similar to other designs, the on-site liquid hydrogen storage is sized for 10% above the daily dispensing capacity, as discussed in Section 2.1.3. The system dispensing capacity is 375,000 kg, and so 10% above this is 412,500 kg. Liquid hydrogen tanker trucks have a capacity of approximately 4,000 kg of hydrogen [7], meaning that 94 separate full tanker trucks would be required to deliver sufficient hydrogen to this facility each day, which may not be practical. Each tanker truck delivery can take a significant amount of time (multiple hours) so that this many deliveries per day would need simultaneously delivery points, which would add additional cost and impracticality. Since current hydrogen liquefaction facilities produce approximately 30,000 kg/day of liquid hydrogen [18, 19], which means that a dedicated production facility with more than 10 times the current liquid hydrogen production capacity would be needed. Despite the practical challenges, it was assumed in this analysis that hydrogen could be delivered and transferred at this scale.

Two spherical LH_2 tanks will be used to store the hydrogen on-site for the design. These tanks are designed using the same LH_2 density as described in Section 2.1.3, but spherical rather than cylindrical. The system daily dispensing capacity is 375,000 kg, leading to a total tank capacity of 412,500 kg, based on the 10% over daily dispensing capacity. This leads to two tanks, each with a capacity of 206,250 kg. Each tank will therefore have an inner diameter of 63 ft (19 m), which gives an inner volume of 998,000 gal (3,780 m^3). For context, the liquid hydrogen storage tanks at the NASA Kennedy Space Center that serviced the Space Shuttle Program each had an inner volume of 850,000 gal (3,218 m^3) [21]. Based on the tank walls and vacuum void space, the outer diameter of the tank is 70 ft (21 m).

The cost of each tank was estimated based on a cost estimate from an industry expert for large spherical LH_2 tanks of $3,700 per m^3 of storage capacity. Based on this normalized cost with the storage capacity volume noted above, each tank is estimated to cost $14,000,000.

3.2.3. Cryopump and Sump System

The cryopump takes liquid hydrogen from the storage and feeds it to the bayonet connecter for dispensing to the freight locomotive. The total required mass flow rate for the cryopump is 90,000 kg/hr (1,500 kg/min), based on the flow rate per dispenser and number of dispensers described in Section 3.2.1. An example cryopump for hydrogen was identified with a mass flow rate of 25,799 kg/hr (430 kg/min), meaning that 4 cryopumps would be needed to meet the total required flow rate. However, it is not clear if there would be operational issues with 4 cryopumps supplying 5 dispensers; therefore, 5 cryopumps are assumed, one per dispenser. The specifics (dimensions and cost) of the example cryopump are provided in Section 3.1.3.

3.2.4. Dispenser

See Section 3.1.4 for dispenser information. This design uses 5 dispensers, so 5 flow meters and 10 (2 per dispenser) bayonet connectors will be used.

3.2.5. Pipe Sizing

See Section 3.1.5 for pipe sizing information.

3.2.6. Component and Cost Summary

Table 3-2 Medium Freight Refueling Facility Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH$_2$ Tank	2	14,000,000	28,000,000
Cryopump	5	250,000	1,250,000
Sump Tank	5	150,000	750,000
Flow Meter	5	6,000	30,000
Bayonet Connector Set	10	3,000	30,000
Total			**30,060,000**

3.2.7. Process and Instrumentation Diagram

See Section 3.1.7 for the liquid hydrogen dispensing P&ID. Note: that diagram is drawn in a modular fashion, in which connections and components are shown for a single dispenser. For this medium freight design, 5 dispensers are used, so the components would all be repeated 5 times (except for the LH$_2$ tanks, of which there are 2 total).

3.2.8. Code Compliant Fueling Station Layout

The code compliant layout of the medium freight locomotive refueling facility Figure 3-4. The figure shows the major hydrogen system components on the top of the image, surrounded by a fire-rated barrier wall on three sides. A fence is shown on the fourth side to limit access to the hydrogen system. An LH_2 delivery truck is shown next to the hydrogen system as if a delivery is being made. Finally, the freight locomotives and tender cars currently being refueled are shown on the bottom of the image, with each dispenser under a light-blue colored awning.

Refer to Section 3.1.8 for details on the separation distances used for this design. The main difference in this design is that the total liquid hydrogen volume is 998,000 gal (3,780,000 L), which is also greater than the maximum volume of 75,000 gal (283,906 L) specified in NFPA 2 Table 8.3.2.3.1.6(A). Similar to the small freight design, this will need to be addressed in future revisions to NFPA 2 if this much storage is going to be part of a system design. Accounting for all of the separation distances and component sizes, a 242 ft (73.8 m) by 260 ft (79.2 m) (62,920 ft^2) lot is needed for this station design.
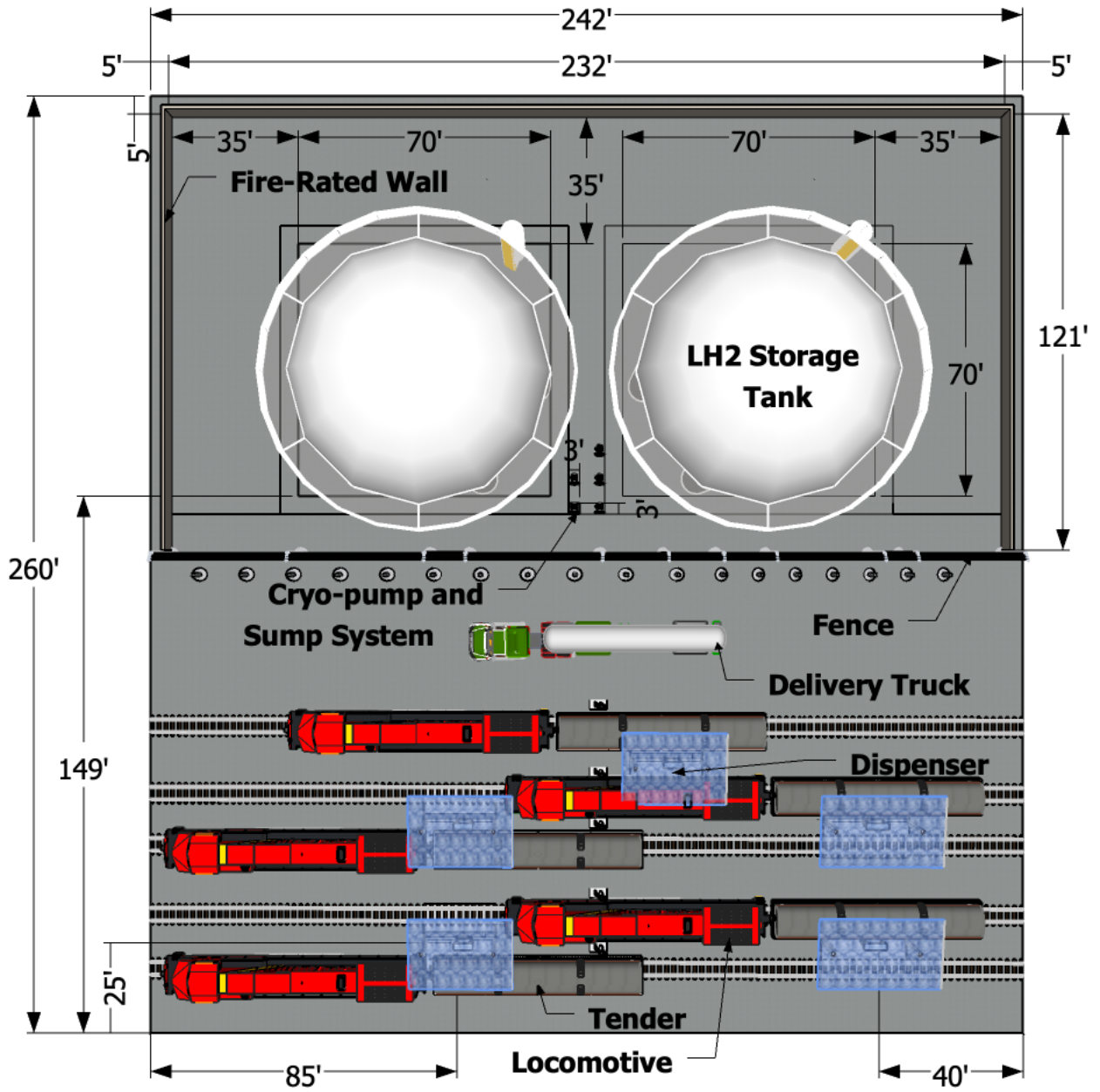
Figure 3-4 Medium Freight Refueling Facility Design Layout

3.3. Large Freight Locomotive

3.3.1. Design Inputs

The large freight LH_2 refueling station is designed to refuel 200 locomotive tenders per day, with 7,500 kg of LH_2 dispensed per tender car. The total LH_2 dispensed per day for the large freight refueling station is 1,500,000 kg. A refueling rate of 300 kg/min will be used for this design. This fill rate will completely fill an empty tender car in 25 minutes, although this only accounts for the fuel transfer time, not connection times. Assuming that this facility might operate 24 hours/day, that would mean that approximately 8.3 tenders would need to be refueled every hour. Given the time required for refueling and the fact that some hours may be busier than others, 13 dispensers are assumed to be needed so that multiple tenders can refuel simultaneously.

3.3.2. Bulk Hydrogen Storage

Similar to other designs, the on-site liquid hydrogen storage is sized for 10% above the daily dispensing capacity, as discussed in Section 2.1.3. The system dispensing capacity is 1,500,000 kg, so 10% above this is 1,650,000 kg. Liquid hydrogen tanker trucks have a capacity of approximately 4,000 kg of hydrogen [7], meaning that 375 separate full tanker trucks would be required to deliver sufficient hydrogen to this facility each day; this is almost certainly not practical. Each tanker truck delivery can take a significant amount of time (multiple hours); so many deliveries per day would need simultaneously delivery points, which would add additional cost and impracticality. Finally, current hydrogen liquefaction facilities produce approximately 30,000 kg/day of liquid hydrogen [18, 19], meaning that a dedicated production facility with 50× current liquid hydrogen production capacity would be needed. Despite the practical challenges, it was assumed in this analysis that hydrogen could be delivered and transferred at this scale.

Four spherical LH_2 tanks will be used to store the hydrogen on-site for the design. These tanks are designed using the same LH_2 density as described in Section 2.1.3, but spherical rather than cylindrical. The system daily dispensing capacity is 1,500,000 kg, leading to a total tank capacity of 1,650,000 kg, based on the 10% over daily dispensing capacity. This leads to four tanks, each with a capacity of 412,000 kg. Each tank will therefore have an inner diameter of 80 ft (24 m), which gives an inner volume of 2,000,000 gal (7,555 m^3). For context, the liquid hydrogen storage tanks at the NASA Kennedy Space Center that serviced the Space Shuttle Program each had an inner volume of 850,000 gal (3,218 m^3), while the new liquid hydrogen tank at that site will have an inner capacity of 1,250,000 gal (4,732 m^3) [21]. Based on the tank walls and vacuum void space, the outer diameter of the tank is 86 ft (26 m).

The cost of each tank was estimated based on a cost estimate from an industry expert for large spherical LH_2 tanks of $3,700 per m^3 of storage capacity. Based on this normalized cost with the storage capacity volume noted above, each tank is estimated to cost $28,000,000.

3.3.3. Cryopump and Sump System

The cryopump takes liquid hydrogen from the storage and feeds it to the bayonet connecter for dispensing to the freight locomotive. The total required mass flow rate for the cryopump is 234,000 kg/hr (3,900 kg/min), based on the flow rate per dispenser and number of dispensers described in Section 3.3.1. An example cryopump for hydrogen was identified with a mass flow rate of 25,799 kg/hr (430 kg/min), meaning that 10 cryopumps would be needed to meet the total required flow rate. However, it is not clear if there would be operational issues with 10 cryopumps supplying 13 dispensers; therefore, 13 cryopumps are assumed, one per dispenser. The specifics (dimensions and cost) of the example cryopump are provided in Section 3.1.3.

3.3.4. Dispenser

See Section 3.1.4 for dispenser information. This design uses 13 dispensers, so 13 flow meters and 26 (2 per dispenser) bayonet connectors will be used.

3.3.5. Pipe Sizing

See Section 3.1.5 for pipe sizing information.

3.3.6. Component and Cost Summary

Table 3-3 Large Freight Refueling Facility Component and Cost Summary

Component	Number of Components	Cost Per Component ($)	Total Cost ($)
LH_2 Tank	4	28,000,000	112,000,000
Cryopump	13	250,000	3,250,000
Sump Tank	13	150,000	1,950,000
Flow Meter	13	6,000	78,000
Bayonet Connector Set	26	3,000	78,000
Total			**117,356,000**

3.3.7. Process and Instrumentation Diagram

See Section 3.1.7 for the liquid hydrogen dispensing P&ID. Note: that diagram is drawn in a modular fashion, in which connections and components are shown for a single dispenser. For this large freight design, 13 dispensers are used, so the components would all be repeated 13 times (except for the LH_2 storage tanks, of which there are 4 total).

3.3.8. Code Compliant Fueling Station Layout

The code compliant layout of the large freight locomotive refueling facility Figure 3-5. The figure shows the major hydrogen system components on the left-hand side of the image, surrounded by a fire-rated barrier wall on three sides. A fence is shown on the fourth side to limit access to the hydrogen system. An LH_2 delivery truck is shown next to the hydrogen system as if a delivery is being made. Finally, the freight locomotives and tender cars currently being refueled are shown on the right-hand side of the image, with each dispenser under a light-blue colored awning.

Refer to Section 3.1.8 for details on the separation distances used for this design. The main difference in this design is that the total liquid hydrogen volume is 1,996,000 gal (7,555,000 L), which is also greater than the maximum volume of 75,000 gal (283,906 L) specified in NFPA 2 Table 8.3.2.3.1.6(A). Similar to the small freight design, this will need to be addressed in future revisions to NFPA 2 if this much storage is going to be part of a system design. Accounting for all of the separation distances and component sizes, a 539 ft (164.3 m) by 294 ft (89.6 m) (158,466 ft^2) lot is needed for this station design.
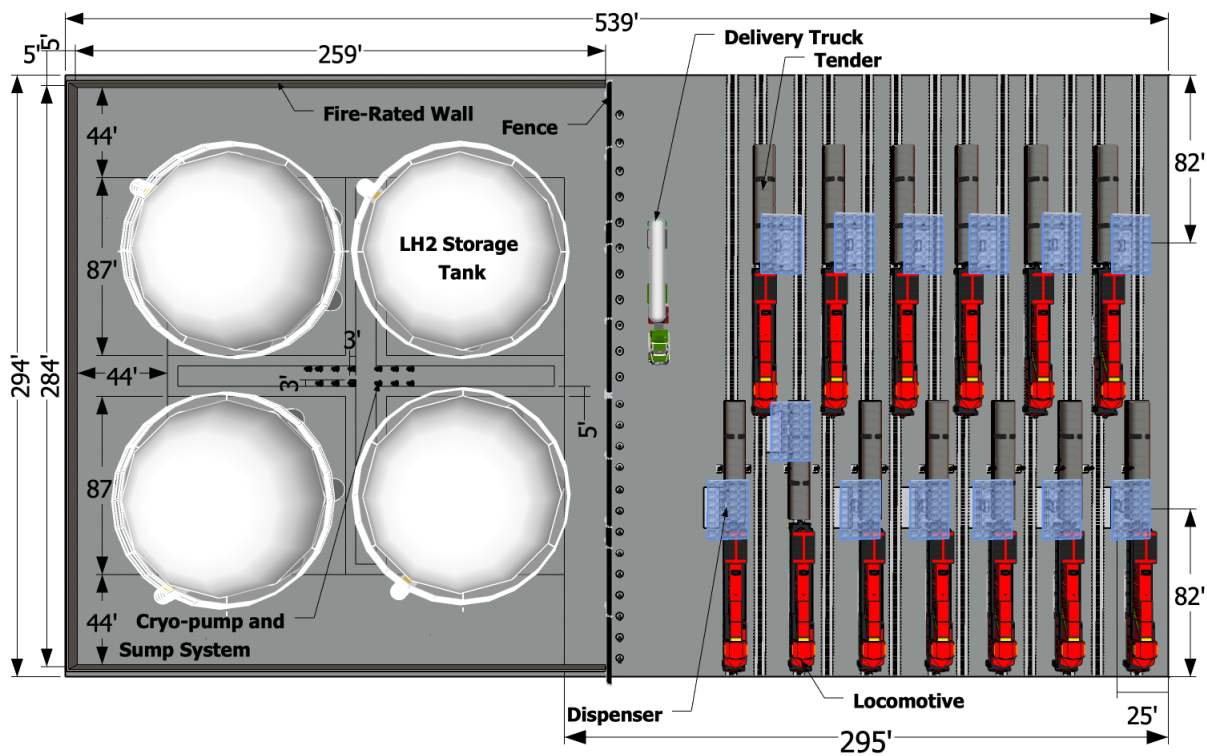

Figure 3-5 Large Freight Refueling Facility Design Layout

3.4. Freight Refueling Facility Designs Summary

The freight refueling facility designs that dispense liquid hydrogen are significantly different than the designs that dispense gaseous hydrogen. These designs do not involve gaseous hydrogen refueling, and so the possibility of a compressor or a cascade system is not applicable. Thus, multiple designs based on the same overall refueling needs were not considered, but rather different sizes of the same general design.

Figure 3-6 shows the major component costs for the three freight designs. The total component costs are very different for each design, but this is somewhat expected, given that each design has a very different dispensing capacity.
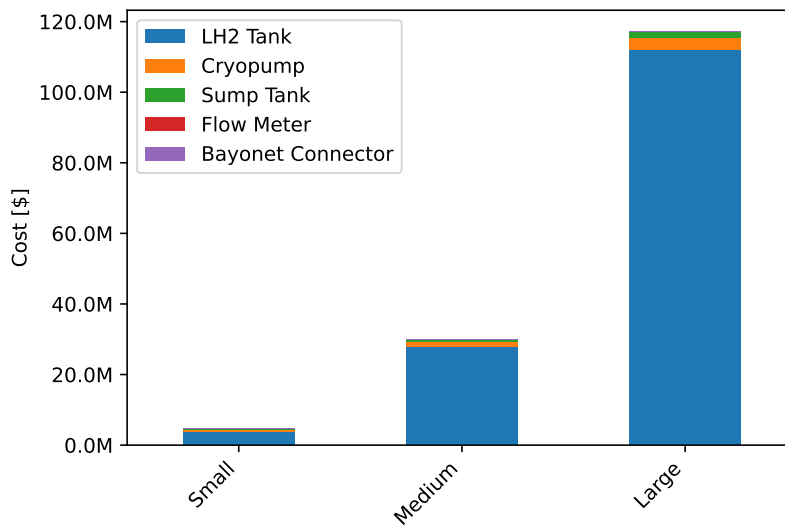
Figure 3-6 Freight Refueling Facility Cost Comparisons

Another item of note is the fact that the total component cost for each refueling facility is driven by the cost of the LH_2 Tank. The capacity of this storage component for each design was estimated using the dispensing capacity for the respective design. This means that the cost of the storage scales with the capacity of the refueling facility. However, even for the Small Freight Facility Design, the cost of the LH_2 storage tank component still dominates the total component system cost. This is notable since this is not true for the designs that dispensed gaseous hydrogen; those designs also used the same design metric (10% over daily dispensed capacity) and the same cost per unit storage volume. The much higher dispensing capacity for the freight tender car designs lead to a much higher cost of storage. It is also noteworthy that the physical layout for the non-dispenser portion of each of the freight refueling facility designs is again dominated by the liquid hydrogen storage tanks. For all three of these freight designs, it is likely a dedicated on-site liquid hydrogen production facility may be needed, rather than delivery to on-site storage.

It is also worth emphasizing that while heavy-duty refueling facilities that dispense gaseous hydrogen are not currently built at these capacities, the components are available commercially, even if they are not ideal or in widespread use. By contrast, the components for the liquid

hydrogen-dispensing designs are not nearly as commonly available. Liquid hydrogen tanks of this size, liquid hydrogen pumps of this capacity, and hose connectors of the required sizes are not currently commonly available, meaning that custom components would be needed for initial demonstration projects. The mass flow rate may require much larger piping and connection hardware to the tender car than can be handled easily. Additionally, the cryopumps for these types of pressures and flow rates are not as common. Thus, the costs and layouts of these designs should be viewed with greater uncertainty and should be explored further in more detail.

4.   CONCLUSIONS

This work considers different hydrogen rail applications with different refueling requirements and examines the current feasibility and cost of the hydrogen refueling infrastructure that would support these applications. Multiple variations on five basic design inputs were examined in order to be representative of different possibilities to inform future analyses. Operational costs and comparisons to existing diesel refueling facilities were not considered in this study due to the focus on determining basic feasibility and identifying major capital cost drivers. Both of these comparisons would be very useful for future analyses. Feasibility was assessed by identifying commercially-available components that could meet the needs of the specified example designs. More common equipment like piping and valves were not directly assessed in this study.

The first design was estimated to refuel 10 multiple unit trains per day, each with 260 kg of gaseous hydrogen at 350 bar on-board. Variations from this basic design were made to consider the effect of two different filling times (15 minutes (17.3 kg/min) or 30 minutes (8.7 kg/min)), two different hydrogen compression methods (a low-pressure evaporator leading to a gas compressor or a liquid cryopump leading to a high-pressure evaporator), and two different station design approaches (a larger mass flow rate compressor/cryopump to fuel directly or a cascade-fill storage system with a smaller mass flow rate compressor/cryopump). For each design variation, components were sized and approximate component costs were estimated. Of these 8 possibilities, the direct-fill cryopump 30-minute fill time was the lowest cost, although the analogous design for a 15-minute fill time was similar in cost and could accomplish all of the refuelings in less time. The layout and physical footprint of the direct-fill cryopump 15-minute design was estimated to be 12,836 ft^2.

The second base design was intended to be able to refuel a fleet of 50 passenger locomotives, each with 400 kg of gaseous hydrogen on-board at 350 bar. Variations from this base design assumed a single fuel transfer rate (10 kg/min), but did consider two different hydrogen compression methods (a low-pressure evaporator leading to a gas compressor or a liquid cryopump leading to a high-pressure evaporator) and two different station design approaches (a larger mass flow rate compressor/cryopump to fuel directly or a cascade-fill storage system with a smaller mass flow rate compressor/cryopump). Of these four possibilities, the direct-fill cryopump design was again the lowest cost. The layout and physical footprint for this design was estimated to be 30,392 ft^2.

The goal of using a cascade-fill system is typically to reduce the cost by requiring a cryopump or compressor with a smaller total mass flow rate while maintaining the same dispensing mass flow rate using storage tanks, which are cheaper than compressors or cryopumps. However, in these cases, the cascade-fill systems were much more expensive than the direct-fill design components. This is due in part to the fact that the cascade system was designed to be a bounding case of a maximum size; an optimal cost case could be found in which a smaller flow-rate is required from the compressor/cryopump than the direct-fill design, but less cascade storage is needed than the cascade-fill design. It is worth noting, however, that the direct-fill designs do have another benefit over the cascade-fill designs in that they are more easily scaled to larger capacities. The cascade capacity is designed to refuel the specified number of vehicles, meaning that if more vehicles/trains are added, the cascade would need to be expanded. However, as long as there is a

sufficient source of hydrogen, a direct-fill system could much more easily refuel additional vehicles.

The last three base designs all assumed that liquid hydrogen was dispensed into tender cars for freight locomotives. For each of these designs, it was assumed that each tender car required 7,500 kg of liquid hydrogen, and the three different designs assumed that 5, 50, or 200 tender cars were refueled every day. These designs do not involve gaseous hydrogen refueling, so the possibility of a compressor or a cascade system is not applicable. Thus, multiple designs based on the same overall refueling needs were not considered, but rather different sizes of the same general design. A single fill rate of 300 kg/min was assumed in all three cases. The total component costs are very different for each design, making minimum cost comparisons not directly applicable, given that each design has a very different dispensing capacity. However, it is worth noting that the total component cost for each refueling facility is driven by the cost of the liquid hydrogen tank. The design input assumptions scaled the size of the liquid hydrogen storage tank relative to the dispensing capacity, but in each of the freight designs, the total component costs were dominated by the storage cost. This was much less true for the gaseous hydrogen dispensing design; while the storage costs were still significant, they did not dominate the total cost. The layout and physical footprint for the small, medium, and large design were estimated to be 20,020 ft^2, 62,920 ft^2, and 158,466 ft^2 respectively.

It is worth emphasizing that these designs may not be required to store these quantities of liquid hydrogen on-site. Aside from the significant cost of the on-site storage tanks, delivering that much liquid hydrogen by tanker truck may not be practical. The smallest system considered (multiple unit train refueling) could have a single liquid hydrogen tanker truck deliver the dispensing capacity for the entire day, while the next largest system (passenger locomotive refueling) needs 5 separate tankers each day. For the still-larger freight refueling systems, there would need to be tens or even hundreds of tanker deliveries every day. This illustrates some significant advantages to on-site production and liquefaction of hydrogen. Gaseous hydrogen can be produced on-site or delivered by pipeline. However, to utilize the gaseous hydrogen as a liquid, it would need to be liquefied on-site. Some rail yards may have sufficient space to have liquefaction facilities on-site or at least adjacent to the refueling site; doing so could avoid significant storage and delivery costs, but would introduce additional capital and operating costs for the liquefaction facility.

The selected option for each of the 5 base designs are shown in Table 4-1, along with the total hydrogen daily dispensing capacity, major component cost, and estimated physical footprint.

Table 4-1 Selected Base Designs Configuration, Dispensing Capacity, Cost, and Footprint

Design	Dispensed State	Capacity (kg/day)	Component Cost ($\times$\$1,000,000)	Lot Size ($\times$1,000 ft^2)
Multiple Unit Direct-Fill Cryopump 15-Minute	GH$_2$	2,600	1.7	12.8
Passenger Locomotive Direct-Fill Cryopump	GH$_2$	20,000	7.1	30.4
Small Freight	LH$_2$	37,500	4.6	20.2
Medium Freight	LH$_2$	375,000	30.1	62.9
Large Freight	LH$_2$	1,500,000	117.4	158.5

This analysis provides an assessment of the current commercially-available components to meet the needs of rail refueling in order to provide high-level technical guidance and to inform future assessments. The assumptions made in these designs are not meant to specify physical or practical limits, and the costs reported in this report reflect the approximate nature of commercially available components today, not what they might be in the future. Differences in component specification may lead to different costs, and many component costs do not scale linearly. Many commercially-available components were designed for industrial uses of hydrogen or for light-duty vehicles. It is reasonable to assume that as demand grows in the future, some if not all of the components identified here will be improved and scaled up to better fit the needs of rail refueling facilities. Additionally, these designs consider rail-only refueling infrastructure; systems may also refuel multiple modes of transportation, including maritime vessels, heavy-duty trucks, and even light-duty vehicles. Multi-modal refueling may allow for common use of shared equipment, which could benefit each of the different transportation modes.

Some of the liquid hydrogen components are not commonly available as standard commercially available components, particularly for the very large freight rail designs. Many of the designs identified here required the use of multiple evaporators, compressors, and cryopumps operating in parallel to meet required flow rates. While there are some operational reasons to have multiple components operating in parallel (e.g., increased resiliency and ability to operate at partial capacity during an outage on one component), larger capacity cryopumps could potentially reduce overall costs. Additionally, having multiple components in parallel just to meet an overall flow rate can be prohibitive from an operations and maintenance standpoint, since piping, valving, instrumentation, and safety would need to be considered for each component. That said, it should also be noted that the costs specified here are not the all-in cost for a system; this analysis only considered major system components. A real system would require much more detailed designs with much more exact cost estimates, including installation costs and operational costs. Additionally, the gaseous hydrogen dispensing designs were able to identify components that can nominally meet the desired refueling mass flow rates, but it is not clear if these flow rates are actually realizable. Both the gaseous and liquid hydrogen dispensing flow rates are much higher than typically used now, meaning that custom hardware may be needed. Tank heating and pre-cooling requirements for these high gaseous hydrogen mass flow rates will need to be

explored in more detailed. Finally, many of the designs would require significant amounts of liquid hydrogen, often similar to the capacity of existing liquefaction facilities. This analysis assumed that the liquid hydrogen was available through delivery, but likely dedicated on-site liquefaction will be needed.

The layout analysis done on selected designs is meant to inform future efforts on the rough scale of these types of facilities. However, these lot sizes are sensitive to many different design choices and the local environment in which they are installed. Storage tanks and even equipment can be stacked vertically, reducing the physical footprint required at the expense of structural support needs and more visibility to neighbors. Storage tanks could even be buried underground, which could be beneficial if equipment is able to be stored on top of the buried tanks. Improvements to component capacities (e.g., increased compressor/cryopump flow rate) would require fewer of these components, which could save space in the footprint. Additionally, the physical footprint of the equipment itself is important, but it is not the only factor for the siting of a facility. The NFPA 2 fire code requires setback distances to various types of exposures, which may or may not be present near the facility site. These exposures can be air intakes, people, parked cars, buildings, or other flammable materials. If these exposures are sufficiently far away, the siting would not be adversely affected; if the exposures are nearby, however, additional mitigations may need to be introduced and approved by the local fire marshal. The setback distances in this report only extend to lot lines by way of example; the required distance to other exposures could be more impactful, depending on what is nearby. It should also be emphasized that current fire code requirements may need to be assessed and modified to cover these types of designs; this was not a focus of this work, but will be critical for future deployment of safe refueling systems. Finally, this work highlights some of the gaps in dispensing nozzle sizes and pre-cooling requirements that will need to be addressed in future fueling protocols, which can allow for better specifications for these heavy-duty fills.

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APPENDIX A. CASCADE DESIGN METHODOLOGY

Cascade pressure systems can be designed in a variety of ways. This is a simplified method in order to determine the number of tanks needed for the cascade system, and not an in-depth analysis of all flows and operating states during the dynamic cascade-fill process. This methodology assumes that there are three "tiers" of cascade tanks: some that end at a low pressure, some that end at a medium pressure, and some that end at a high pressure. The overall process is to quantify the mass of hydrogen transferred to the on-board vehicle storage in order to raise the pressure to each of these intermediate pressures, then determine the number of tanks required to transfer that much mass.

First, the effective volume of on-board rail vehicle storage tank(s) is calculated using Equation 2, in which $V_{eff,v}$ is the effective total volume for the on-board vehicle storage [m^3], $m_{d,total}$ is the total dispensed mass of hydrogen during a fill [kg], $\rho_{T,P}$ is the density of hydrogen at a given temperature and pressure, T_0 is the ambient temperature [K], $P_{v,0}$ is the initial on-board vehicle pressure (empty tank) [Pa], and $P_{v,f}$ is the final on-board vehicle pressure (full tank) [Pa].

$$V_{eff,v} = \frac{m_{d,total}}{\rho_{T_0,P_{v,0}} - \rho_{T_0,P_{v,f}}} \tag{2}$$

Here, ambient temperature (T_0) is assumed to be 20°C (293 K); this temperature is used for all density calculations. The on-board vehicle tank is assumed to be at 5 bar (500,000 Pa) when empty and 350 bar (35,000,000 Pa) when full. Note that the total dispensed mass during a fill varies between designs.

All cascade tanks have an initial pressure of 450 bar (45,000,000 Pa). The final pressures are assumed to be 35% of the initial pressure for the low tier ($P_{c,low}$ = 157.5 bar), 65% of initial pressure for the medium tier ($P_{c,medium}$ = 292.5 bar), and 85% of initial pressure for the high tier ($P_{c,high}$ = 382.5 bar); these tiers and final relative pressures are taken from the HDRSAM software [23].

The usable mass in each cascade tank is calculated using Equation 3, in which $m_{use,c}$ is the usable mass in the tank [kg], V_c is the hydraulic volume of the cascade tank [m^3], $P_{c,0}$ is the initial pressure of the cascade tank [Pa], and $P_{c,f}$ is the final pressure of the cascade tank (low, medium, or high) [Pa]. For all the cascade designs, the hydraulic volume of the cascade tank is 765 L (0.765 m^3) based on the identified example tank in this study.

$$m_{use,c} = V_c \left(\rho_{T_0,P_{c,0}} - \rho_{T_0,P_{c,f}} \right) \tag{3}$$

Next, the amount of dispensed hydrogen at each pressure tier is determined using Equation 4, in which $m_{d,tier}$ is the dispensed mass for the pressure tier in question [kg] and $P_{v,tier,0}$ and $P_{v,tier,f}$ are the initial and final pressures (respectively) for the on-board vehicle storage for the pressure tier in question [Pa].

$$m_{d,tier} = V_{eff,v} * \left(\rho_{T_0,P_{v,tier,0}} - \rho_{T_0,P_{v,tier,f}} \right) \tag{4}$$

The initial and final pressures of the on-board vehicle tank for the tier in question are given in Table A-1.

Table A-1 Initial and Final On-Board Vehicle Storage Pressures for Each Pressure Tier

Tier	$P_{v,tier,0}$	$P_{v,tier,f}$
Low	$P_{v,0} = 5$ bar	$P_{c,low} = 157.5$ bar
Medium	$P_{c,low} = 157.5$ bar	$P_{c,medium} = 292.5$ bar
High	$P_{c,medium} = 292.5$ bar	$P_{v,f} = 350$ bar

The cryopump or compressor is sized such that it can re-fill the cascade over the non-filling hours of the day through a constant mass flow rate. During the fill, the cryopump or compressor continues to provide mass flow into the cascade. In order to account for this mass flow, the amount of hydrogen that is supplied by the cascade can be reduced. This is done by calculating the time it takes to refuel the on-board vehicle storage for a given pressure tier using Equation 5, in which t_{tier} is the time it takes for the on-board vehicle storage to go from the initial pressure of the tier to the final pressure of the tier [min], $m_{d,tier}$ is the dispensed mass for the pressure tier in question [kg], and $\dot{m}_{d,total}$ is the total dispensing mass flow rate [kg/min]. Note that the total dispensing mass flow rate varies between designs.

$$t_{tier} = \frac{m_{d,tier}}{\dot{m}_{d,total}} \tag{5}$$

Then the amount of mass that needs to be supplied by the cascade can be calculated using Equation 6, in which $m_{d,c,tier}$ is the dispensed mass from the cascade for the given tier [kg], $m_{d,tier}$ is the total dispensed mass for the given tier [kg], $\dot{m}_{c,in}$ is the mass flow rate into the cascade [kg/min], and t_{tier} is the time it takes for the on-board vehicle storage to go from the initial pressure of the tier to the final pressure of the tier [min]. Note that the mass flow rate into the cascade varies between designs.

$$m_{d,c,tier} = m_{d,tier} - \dot{m}_{c,in}t_{tier} \tag{6}$$

The number of cascade tanks needed for the given tier is calculated using Equation 7, in which N_{tier} is the number of cascade tanks needed for the given tier, $m_{d,c,tier}$ is the mass that must be dispensed by the given tier [kg], and $m_{use,tier,c}$ is the usable mass per cascade tank for the given tier [kg]. Note that the number of tanks is then rounded up to the nearest integer.

$$N_{tier} = \frac{m_{d,c,tier}}{m_{use,tier,c}} \tag{7}$$

Finally, the total number of cascade tanks is then calculated by adding the number of cascade tanks for each tier, as shown in Equation 8, in which N_{total} is the total number of cascade tanks needed, N_{low} is the number of cascade tanks needed for the low tier, N_{medium} is the number of

cascade tanks needed for the medium tier, and N_{high} is the number of cascade tanks needed for the high tier.

$$N_{total} = N_{low} + N_{medium} + N_{high} \qquad (8)$$

Once the total number of cascade tanks to refuel a given rail vehicle are known, the number of tanks can be multiplied by the number of simultaneous and back-to-back fills that the station requires.

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