gti

the Energy to Lead

REPORT

GTI PROJECT NUMBER 20206

Analysis of Cost-Effective Off-Board Hydrogen Storage and Refueling Stations

Report Issued:
November 14, 2008

Prepared For:
Mr. Jesse Adams
Project Manager
U.S., Department of Energy
Golden Field Office
Phone: 303-275-4954
Jesse.adams@go.doe.gov

Contract: DE-FG36-05GO15013

GTI Technical Contact:
Mr. Ted Barnes
Principal Engineer
End Use Solutions
847-544-3405
Ted.barnes@gastechnology.org

Gas Technology Institute
1700 S. Mount Prospect Rd.
Des Plaines, Illinois 60018
www.gastechnology.org

Legal Notice

This information was prepared by Gas Technology Institute ("GTI") for the U.S. Department of Energy ("Sponsor").

Neither GTI, the members of GTI, the Sponsor(s), nor any person acting on behalf of any of them:

a. Makes any warranty or representation, express or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately-owned rights. Inasmuch as this project is experimental in nature, the technical information, results, or conclusions cannot be predicted. Conclusions and analysis of results by GTI represent GTI's opinion based on inferences from measurements and empirical relationships, which inferences and assumptions are not infallible, and with respect to which competent specialists may differ.

b. Assumes any liability with respect to the use of, or for any and all damages resulting from the use of, any information, apparatus, method, or process disclosed in this report; any other use of, or reliance on, this report by any third party is at the third party's sole risk.

c. The results within this report relate only to the items tested.

Table of Contents

Table of Tables

Table of Figures

Introduction

Liquid fuels are widely popular in transportation applications for a clear reason: energy storage density. Liquid fuels have much greater energy density than gaseous fuels or other forms of energy storage like batteries or flywheels. They are also very easy to dispense and store.

During the past two decades, however, there has been steady international growth in the use of compressed gases in vehicles as alternatives to gasoline and diesel. This trend is being driven by various factors such as concerns over oil imports, balance of trade, energy security, ambient air quality, and greenhouse gas emissions. Compressed natural gas (CNG) vehicles have led this trend, with 5.7 million vehicles throughout the world – including 150,000 in the U.S. – and thousands of fueling stations[1]. CNG products even include home refueling appliances (HRA's) that allow consumers to conveniently refuel their vehicles at home.

The CNG vehicle experience is an informative analog to the growing interest in compressed hydrogen (CH_2) fueling stations and vehicles. Current estimates indicate there are 60 hydrogen fueling stations in the U.S. and 120 additional hydrogen stations in other parts of the world[2]. Hydrogen vehicles include "traditional" light-duty cars (albeit with proton exchange membrane fuel cell power plants), shuttle and transit buses, and off-road vehicles such as forklifts.

The requisite steps in a gaseous vehicle refueling station (Figure 1) used to deliver fuel are different than those needed to dispense liquid fuels. For gaseous fuels, issues such as hydrogen station sizing and delivery capacity are influenced by a number of factors. These include fleet size, the distribution of vehicle re-fueling events during the day (i.e., there is a high sensitivity to peak demand periods), vehicle fuel storage capacity, compressor size, cascade storage capacity, ambient temperature, and transient on-board vehicle hydrogen temperature during fast-fill operations.

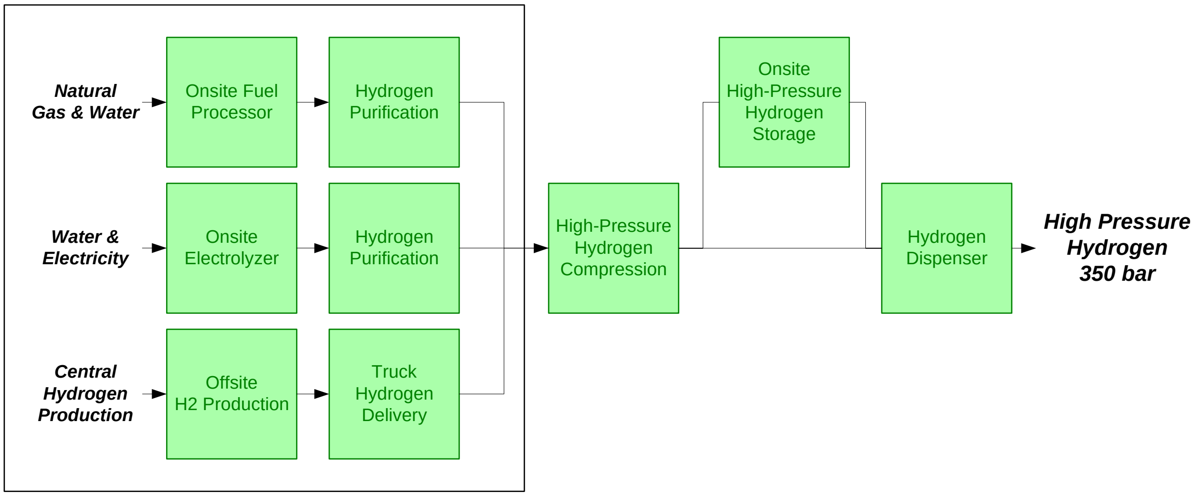


Figure 1: Hydrogen Fueling Station

---

[1] International Association for Natural Gas Vehicles (www.iangv.org)

[2] http://www.fuelcells.org/info/charts/h2fuelingstations.pdf

There are also a variety of considerations when evaluating the upstream hydrogen supply chain. For example, additional station design issues need to be assessed if there is onsite hydrogen production (e.g., natural gas reformation or water electrolysis) or truck delivery of compressed gas or cryogenic liquids. These considerations can be minimized under a more ideal scenario of large-scale centralized hydrogen production coupled with pipeline delivery. This is a desired future state for operating a network of hydrogen fueling stations.

Taken together, these factors make the sizing, fuel delivery performance, and economics of compressed gas hydrogen stations decidedly more complicated than a liquid fueling station.

Presently, hydrogen fueling stations are in a formative period, with uncertainty regarding even basic factors such as standardization of pressure levels. Will nominally 5000 psig (350 bar) stations suffice or will higher pressures such as 10,000 psig (700 bar) be needed to provide satisfactory range for hydrogen vehicles?

From a station design perspective, there are also real-world constraints in terms of product availability or having products in the desired size range. These considerations act to constrain the design approaches available for configuring and optimizing hydrogen fuel stations. Time and experience—similar to the multi-decade evolution of natural gas vehicles—will help shape hydrogen vehicle fuel station practices in the years to come.

This report highlights design and component selection considerations for compressed gas hydrogen fueling stations operating at 5000 psig or 350 bar. The primary focus is on options for compression and storage – in terms of practical equipment options as well as various system configurations and how they influence delivery performance and station economics.

Hydrogen Fueling Station Demand

Total fuel demand and the pattern of daily fuel dispensing is a critical consideration in designing a hydrogen fuel station. Fueling patterns can vary considerably, especially when examining – for example – a private, centrally fueled fleet versus a public access fueling station. As discussed in the GTI CNG Transit Fueling Station Handbook[3], there are three common fueling patterns:

- Random – vehicles come to refuel as needed.
- Regular – vehicles refuel according to a predictable pattern.
- Constant – vehicles pool together at a set time and refuel one after another.

The emphasis of this report is on the design of public access fueling stations. In these stations, the fuel demand pattern falls most generally into the random category – but will typically have a somewhat predictable (though unplanned) pattern.

To assist in formulating a demand profile, data were gathered and analyzed from a couple of key sources of information:

- Data on three different high-volume gasoline stations (courtesy of ConocoPhillips)
    - Hourly bin data showing daily demand ranging from 5000 to 15,000 gallons per day
- Fleet-oriented, public access CNG fueling stations
    - Hourly bin data ranging from 500 to 1000 gge per day

Figure 2 shows average daily demand profiles (gallons per hour) for three types of gasoline fueling stations – one located on an interstate, in a residential setting, and a truck stop station.

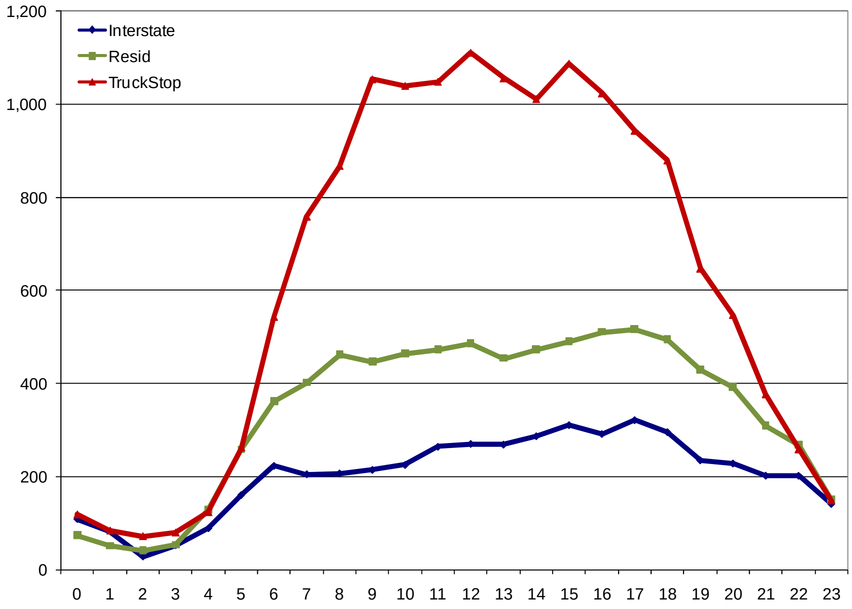


Figure 2: Representative Gasoline Demand Profiles

---

[3] GRI-97/0097, "CNG Transit Fueling Station Handbook," (www.gastechnology.org)

Figure 3 shows these same data normalized to hourly bin data as a percentage of total daily demand. On this basis, each of these stations has rather similar demand profiles. For analytical purposes, the demand profile for the residential location was used as a basis for estimating hourly demand.

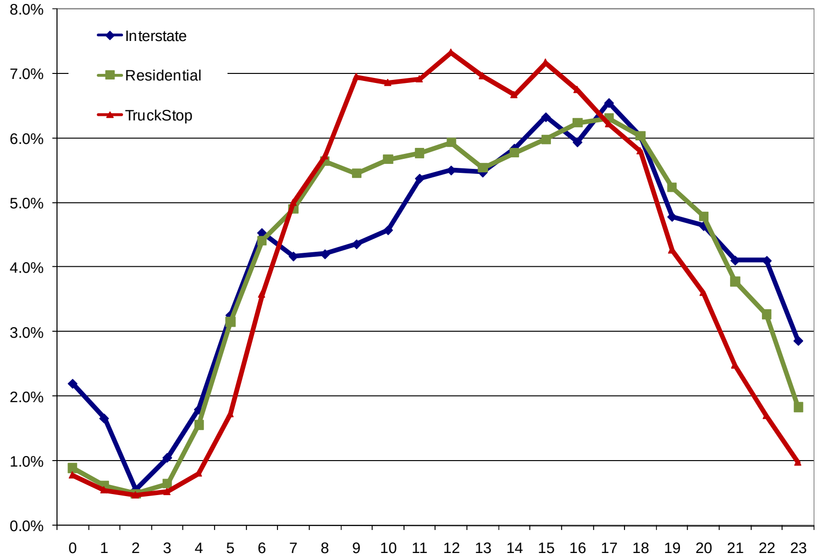


Figure 3: Normalized Gasoline Demand Profiles

For comparison, GTI analyzed CNG station demand data obtained from an operational public access station. This station was primarily catering to fleet vehicles. Figure 4 shows a comparison of an hourly bin demand data for a gasoline fueling station located in a residential setting, the CNG station fueling station, and a then-prevailing hydrogen demand profile included in the DOE H2A model.

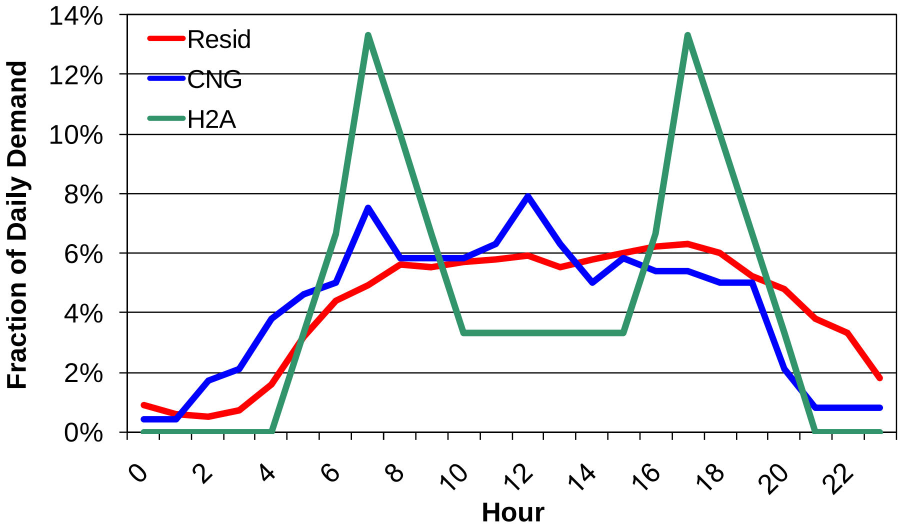


Figure 4: Daily Fuel Demand Profiles

The shape and amplitude of the demand profile has a very strong influence on the design and capital cost of a compressed gas fueling station. The gasoline demand profile and the CNG station data have a high degree of congruity. The H2A model, however, appears to have a significantly more severe profile in terms of the difference between the on-peak and off-peak demand during normal business hours. Since the level of fuel station capacity (i.e., compressors and storage) required is typically defined by the peak demand in a one or two-hour period, the H2A type of profile would require an over-investment in capital equipment (compared to the other two data sets) to properly satisfy customer demand.

The gasoline data were also analyzed to evaluate day-to-day variances in fuel demand over a weekly period. Figure 5 shows the variation in sales over the days of the week, indicating that peak demand occurs on Fridays.

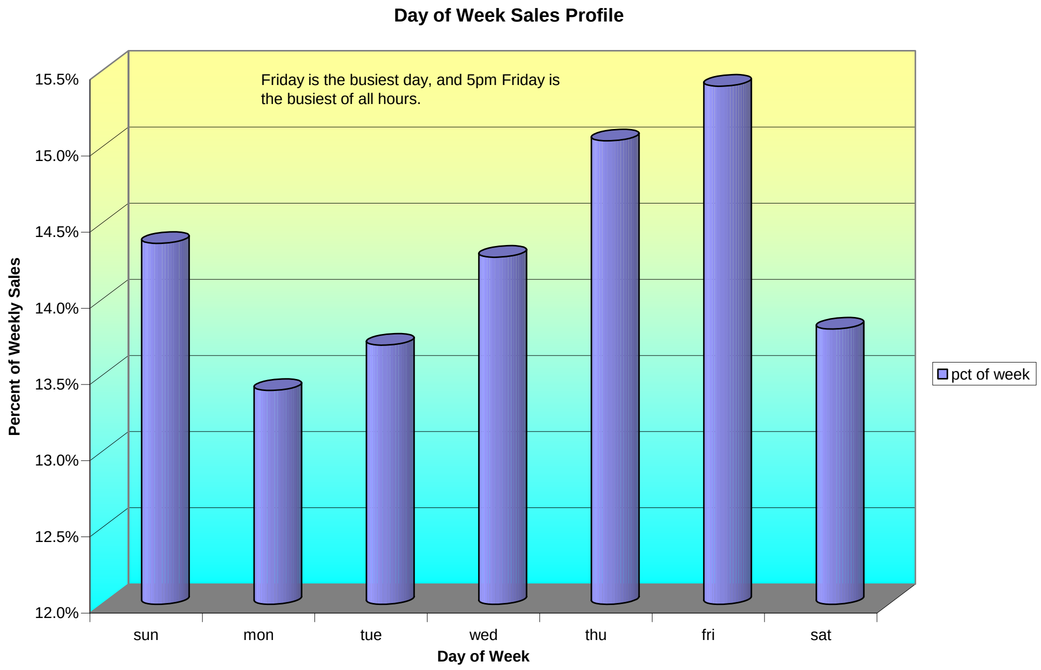


Figure 5: Variation In Fuel Demand During The Week

Further analysis was conducted to examine if there were day-to-day differences in hourly demand. Figure 6 shows a consistent pattern for mid-week fueling, featuring a slight peak early in the morning (around 8 am) followed by the highest level of demand around 5:00 pm.

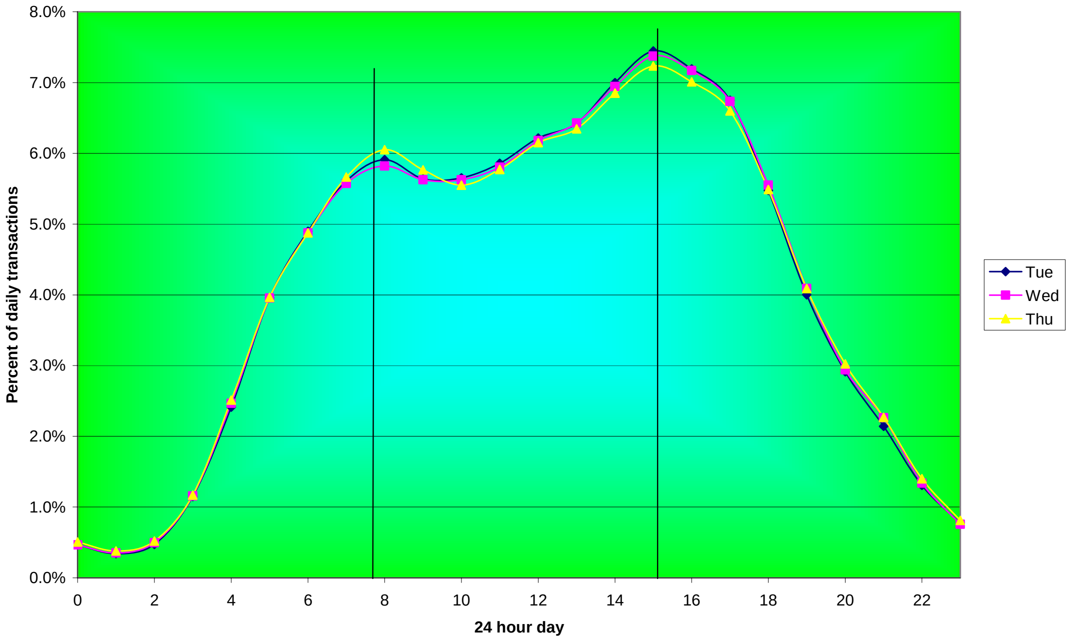


Figure 6: Mid-Week Fueling Profile

Figure 7 illustrates a level of consistent fueling demand between a typical Monday and Friday – bearing in mind that the total demand for Friday is greater than on Monday.

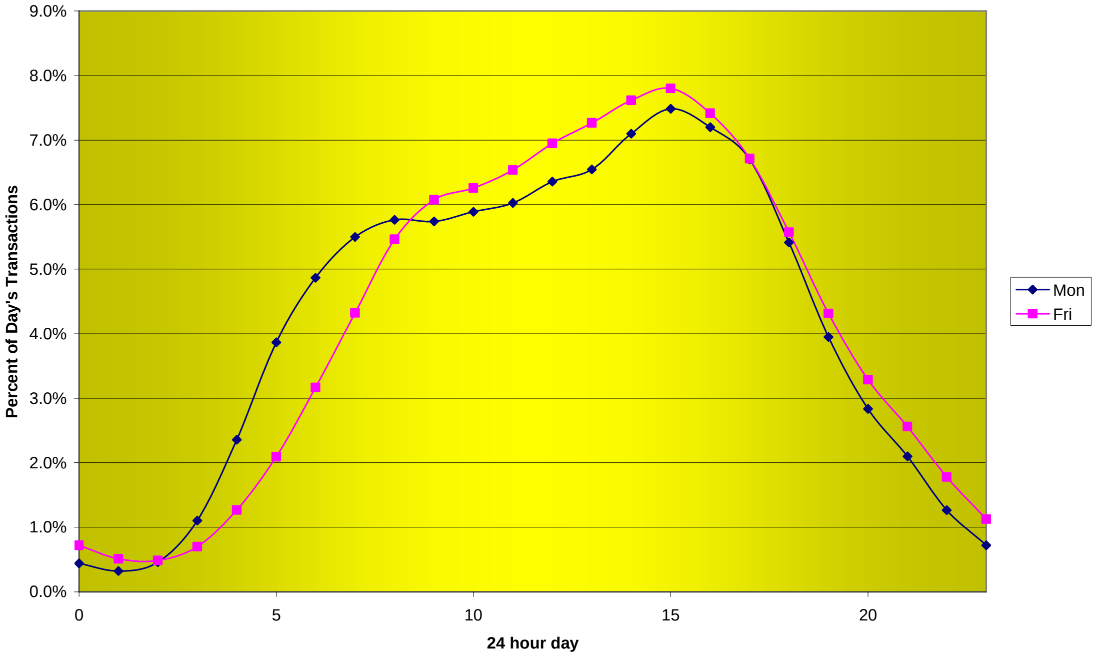


Figure 7: Monday/Friday Fueling Profile

Figure 8 shows the weekend demand profile for Saturday and Sunday.

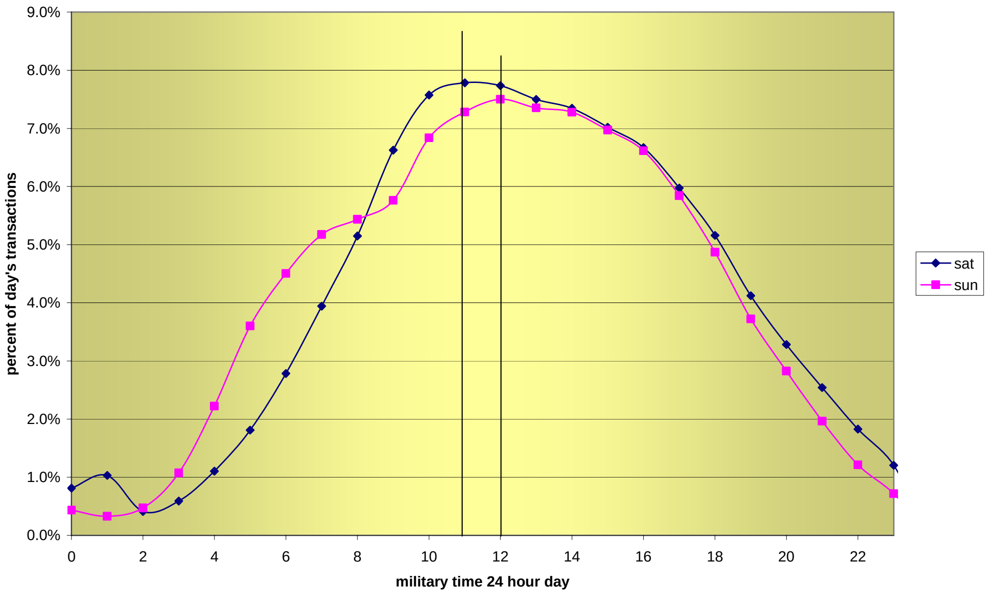


Figure 8: Saturday/Sunday Fueling Profile

These hourly data were used to develop fuel demand values over a 24 hour period for a 1200 kg per day hydrogen station (Table 1). The prototype vehicle had an on-board capacity of approximately 5.4 kg and required approximately 4.6 kg for a complete fill. These numbers are used to provide a rounded estimate of the number of vehicles filled per hour over the course of a typical day. Using this methodology, a total of 262 would be fueled in a 24-hour period.

Table 1: Table of Hourly Hydrogen Demand

Hour	Daily %	kg	# of Vehicles
1	0.7	8.4	2
2	0.6	7.2	2
3	0.5	6.48	1
4	0.6	7.32	2
5	1.2	14.4	3
6	2.1	24.6	5
7	3.1	37.2	8
8	4.3	51.6	11
9	5.5	66	14
10	6.0	72	16
11	6.3	75	16
12	6.5	77.4	17
13	7.0	84	18
14	7.3	87	19
15	7.7	91.8	20
16	7.9	94.8	21
17	7.5	89.4	19
18	6.8	81	18
19	5.6	67.2	15
20	4.3	51.6	11
21	3.3	39.6	9
22	2.6	31.2	7
23	1.8	21.6	5
24	1.1	13.2	3
	100	1200	262

Factory-Built Hydrogen Fueling Stations

Some of the challenges that need to be addressed in the evolution towards a cost-effective hydrogen fueling infrastructure include:

1. How to reduce the capital and installation costs for hydrogen stations in the short term to make the fuel cost ($/kg) attractive for early investors
2. As demand expands, how to move towards making larger fueling stations that can delivery larger quantities of hydrogen (1000-5000 kg/day)

Pre-packaged, factory-built and tested fast-fill hydrogen fueling stations are a key pathway for achieving a degree of standardization and cost-effectiveness in hydrogen fueling stations in the near term. For the foreseeable future, these will either need onsite hydrogen production (e.g., from natural gas or electricity) or truck-delivered hydrogen supplies. In the long-term, pipeline supply of hydrogen – similar to today's natural gas pipeline network – would simplify hydrogen fueling stations.

There are many design approaches that can (and will) be taken in the field of factory built hydrogen stations. One example design developed by GTI and GreenField Compression (part of Atlas-Copco) is shown in Figure 9. Figure 10 provides more details on the subsystems incorporated into this design. Not shown is a separate hydrogen dispenser that could be located on a fueling island.

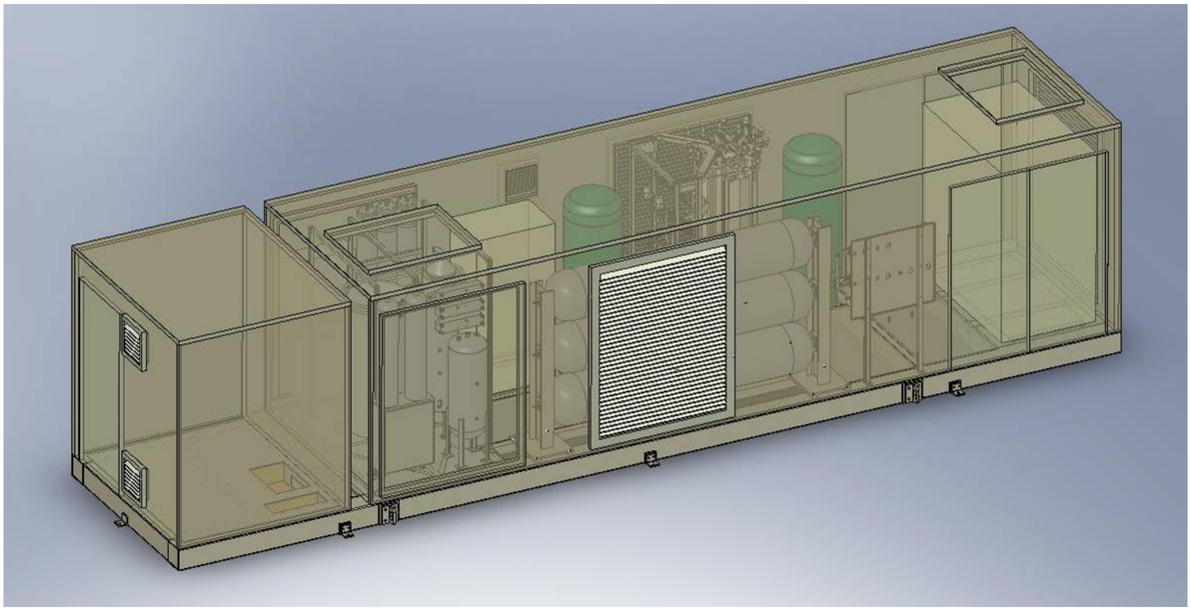
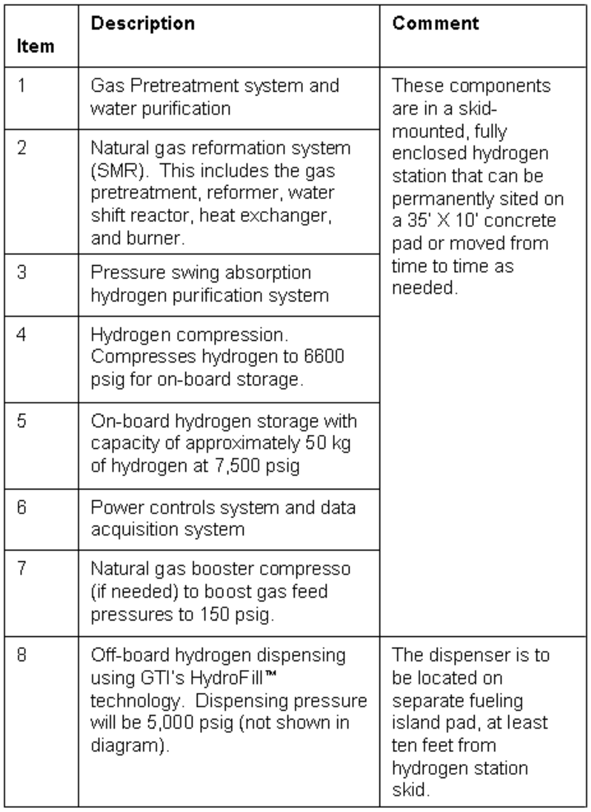
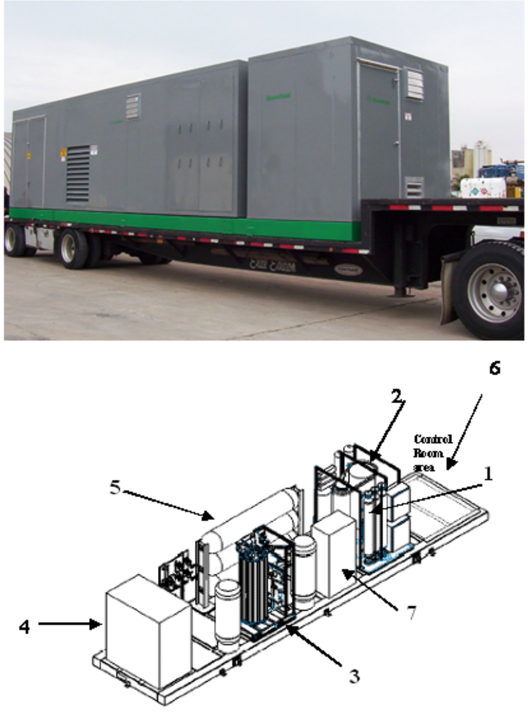


Figure 9: Factory-Packaged, Transportable Hydrogen Station Design



Item	Description	Comment
1	Gas Pretreatment system and water purification	These components are in a skid-mounted, fully enclosed hydrogen station that can be permanently sited on a 35' X 10' concrete pad or moved from time to time as needed.
2	Natural gas reformation system (SMR). This includes the gas pretreatment, reformer, water shift reactor, heat exchanger, and burner.	
3	Pressure swing absorption hydrogen purification system	
4	Hydrogen compression. Compresses hydrogen to 6600 psig for on-board storage.	
5	On-board hydrogen storage with capacity of approximately 50 kg of hydrogen at 7,500 psig	
6	Power controls system and data acquisition system	
7	Natural gas booster compresso (if needed) to boost gas feed pressures to 150 psig.	
8	Off-board hydrogen dispensing using GTI's HydroFill™ technology. Dispensing pressure will be 5,000 psig (not shown in diagram).	The dispenser is to be located on separate fueling island pad, at least ten feet from hydrogen station skid.



3-D view of station skid without the enclosure.
Major system components described in table.

Figure 10: Factory-Packaged, Transportable Hydrogen Fueling Station Details

The primary benefit of a factory-packaged hydrogen station is the ability to quickly transport the unit to the desired location and rapidly hook up the required utility connections and supplies to the dispenser. This is shown conceptually in Figure 11.

A couple of the key systems in a fast-fill hydrogen fueling station include compression and high-pressure gas storage. Together, these are a major capital investment that will heavily impact operating costs (i.e., for compression) and fuel delivery performance. In designing the system layout for a hydrogen fast-fill station, there are several tactical approaches that can be used to integrate compression and high-pressure gas storage in a manner that will have different implications on cost and delivery performance. These will be discussed in more detail in this report.

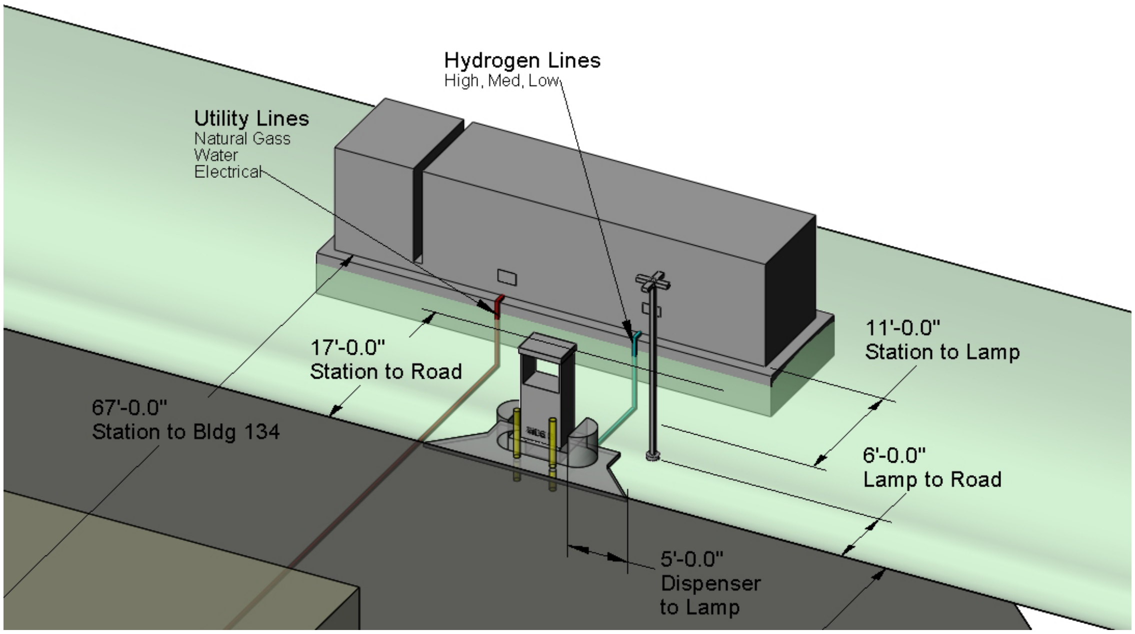


Figure 11: Transportable Hydrogen Station Installation Example

High-Pressure Hydrogen Fueling Systems

There are two high-level options for filling compressed gas vehicles:

- Time Fill – compressors provide steady overnight filling of vehicle(s) for periods as long as 8-10 hours.
- Fast Fill (or Cascade Fill) – compressors are coupled with compressed gas "ground storage" systems for fast filling vehicles typically within a period of 1-10 minutes.

Generally speaking, time fill systems are more specialized approaches that can be used by centrally fueled fleets or personal commuters who have an HRA device to fuel at home. Fast fill systems would be more typically applied in a public access fueling station.

In either case, whether the compressed gas fueling system is designed as a time fill or a fast fill approach, it is important to understand the demand profile for vehicles that will be refueling at the station.

Time-Fill Hydrogen Fueling Systems

Time fill systems can be used for "centrally fueled" fleets where vehicles are routinely parked overnight. A good example would be postal vehicles, utility vehicles, and school buses. Figure 12 shows a time fill CNG vehicle fleet, with individual fueling posts and fuel hoses that are typically connected to a vehicle at the end of the work day. Overnight, a compressor steadily builds pressure equally within all of the vehicle cylinders that are connected. In the morning, the vehicle driver disconnects the fuel hose before departing the central parking location.

Figure 12: Time Fill Station for Centrally Fueled Fleet

Time fill compressed gas systems (Figure 13) have several advantages:

1. Simplicity of design and control
2. Averting the cost of onsite ground storage.
3. Avoiding the temperature-rise phenomenon associated with quickly filling hydrogen cylinders.

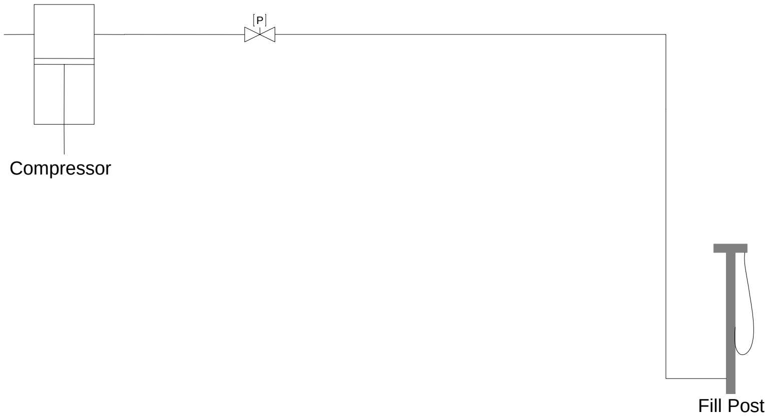


Figure 13: Basic Time Fill System Schematic

There are, however, downsides to time fill systems. They typically do not achieve utilization rates much higher than 30 percent – this can hinder the economic payback period. They also typically will not have an ability to quickly fill a vehicle (though hybrid time-fill/fast-fill systems with onsite storage are possible at additional cost). These systems are also exclusively meant for private fleet users – not public access – and will not have individual vehicle fuel management reporting information.

While time-fill systems are simple and avoid temperature-rise problems seen with fast-fill systems, they do require ambient temperature compensation. Figure 14 shows the relationship between hydrogen pressure and temperature for a nominal rating condition of 5075 psig and 59^{o}F. As ambient temperature varies above and below this temperature point, it is necessary to modify the final hydrogen fill pressure accordingly. Higher ambient temperatures will require higher levels of pressure to achieve a complete fill based on density.

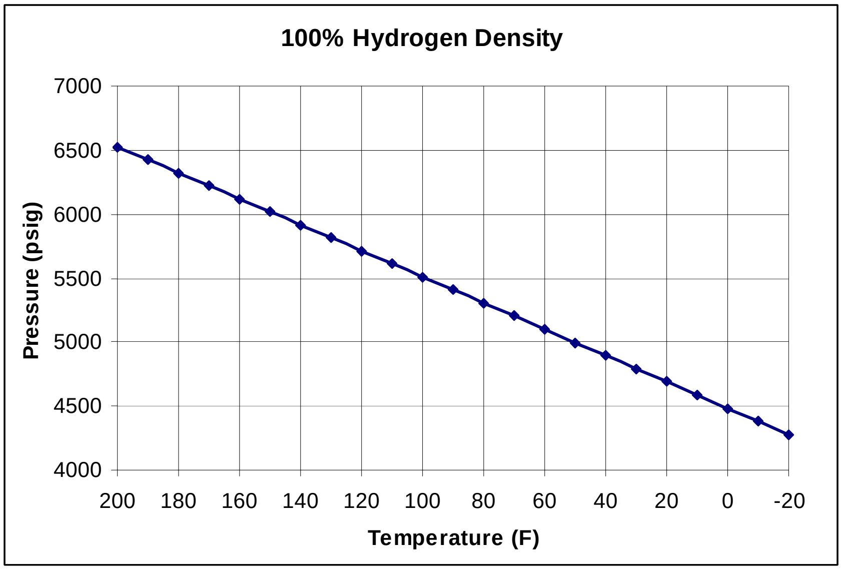


Figure 14: Hydrogen Temperature Compensation

Home Refueling Appliances

One attractive time fill concept is a home refueling appliance, or what is referred to as an HRA. The concept of a small, personal fueling appliance has been in existence (in various product configurations) for natural gas vehicles for nearly twenty years. Figure 15 shows the PHILL HRA product made for natural gas and available from FuelMaker Corporation. This unit compresses natural gas to 3600 psig and has a selling price in the range of $3500.

Figure 15: Natural Gas PHILL Home Fueling Appliance (Source: FuelMaker)

Several companies have reportedly been looking to develop hydrogen-based HRA devices. These may or may not include onsite hydrogen production – for example, a small electrolyzer. At the present time, though, there are no commercially available hydrogen HRA products.

Fast-Fill Hydrogen Fueling Systems

The primary emphasis of this report is on the design and performance of larger-scale fast-fill hydrogen stations – for example, stations that could dispense around 1200 kg/day. These systems include substantial compression and compressed gas storage capacities.

As noted, fast-fill systems for gaseous fueling stations are considerably more complicated than time fill systems. Operating a fast-fill system is analogous to manufacturing plants where production capacity and inventory need to be balanced with customer demand. Poor economic performance or frequent starts and stops can result from over-sizing production capacity (i.e., compressors), while inefficient capital use can result from excessive storage capacity. Conversely, unhappy customers – due to long delays in filling or from under-filling – can result if compressor or storage are undersized.

Careful analysis is needed to understand fuel demand patterns. This is critical to achieving a proper sizing and balance of compressor output capacity and high-pressure ground storage capacity. Demand profiles are needed that forecast expected hydrogen dispensing during the course of a typical day (diurnal) and over a typical weekly period. Just like forecasting demand and operations planning for a manufacturing facility, this can be a tricky endeavor.

There are two different types of fast-fill compressed gas station concepts:

- Buffer storage and dispensing – a specialized version of a fast-fill station used by some fleet customers (e.g., transit bus operators) wherein the ground storage is a single bank
- Cascade storage and dispensing – a more common fast-fill approach that features multiple compressed gas storage banks

The term “bank” is used to describe a discrete amount of high-pressure storage. A bank could be one cylinder or a collection of cylinders that are piped together in a manner that makes them appear to be one larger total volume.

Buffer Storage Fast-Fill Systems

Buffer fill systems use a single bank of storage with a direct-fill bypass circuit (Figure 16). This concept is used in some centrally fueled fleets where vehicles are fueled in a back-to-back manner. This approach is sometimes used in the transit bus industry, where common practice is to line up returning vehicles from their daily route for sequential fueling and cleaning on a nearly continuous basis. Each bus may have about 5-10 minutes total time to be simultaneously fueled and cleaned.

The sizing of a buffer fast-fill system requires assumptions about the short-run filling of one to two vehicles. From this, by induction, the designer can infer filling of subsequent comparable vehicles. The buffer-fill approach entails tight integration of the compressor, buffer storage capacity, vehicle fuel storage, and cycle time.

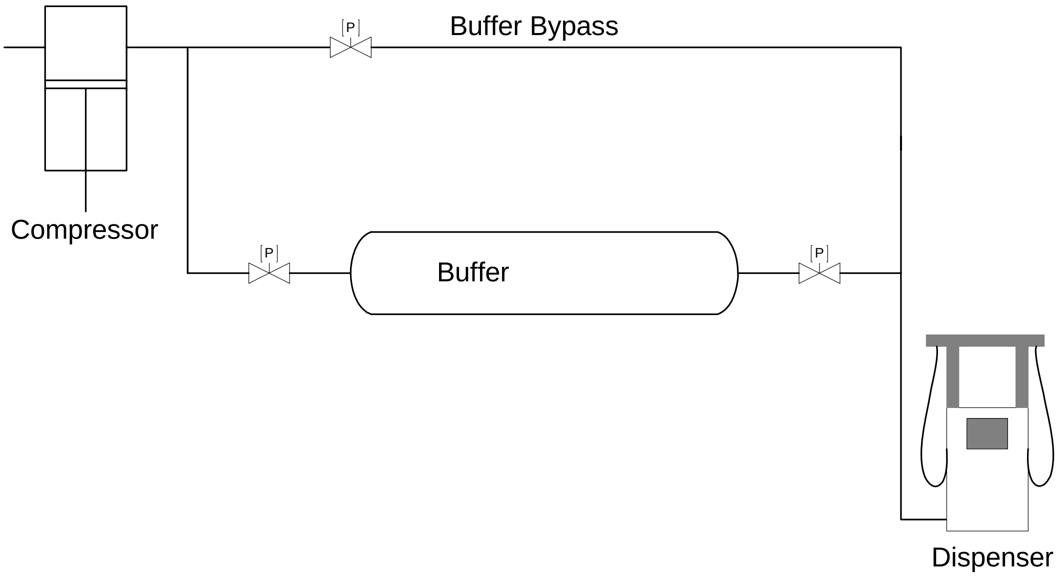


Figure 16: Buffer Fast-Fill Schematic

Cycle time in this case means the total process time for the following events to occur:

1. Bus pulls into fueling bay.
2. Fueler connects the dispenser to the vehicle and begins fueling.
3. The bus is cleaned and inspected.
4. The bus is filled with fuel and the dispenser is disconnected.
5. Bus pulls away from the fueling island (repeat step 1 with next vehicle).

The amount of fuel needed by the vehicle, the time spent fueling, the time spent not fueling, and the buffer storage capacity must be balanced to allow vehicle filling within, for example, a five minute window and time to refill the buffer storage before the next vehicle is connected.

When properly designed, these systems allow for continuous and rapid vehicle filling. The systems exemplify a distinct pattern in the change of buffer storage pressure (i.e., periodicity). Since the total time for the buffer filling of all fleet vehicles may only be four to six hours, compressor utilization rates in these systems tend to be low (e.g., 10 to 20 percent).

Figure 17 shows an idealized version of a buffer storage pressure system (using natural gas stored at 5000 psig to fill a 3600 psig vehicle). A similar operation could be used for hydrogen using buffer storage of 6000 to 7000 psig to fill a 5000 psig hydrogen vehicle. This figure shows the cascade pressure cycle with multiple buses being filled in succession.

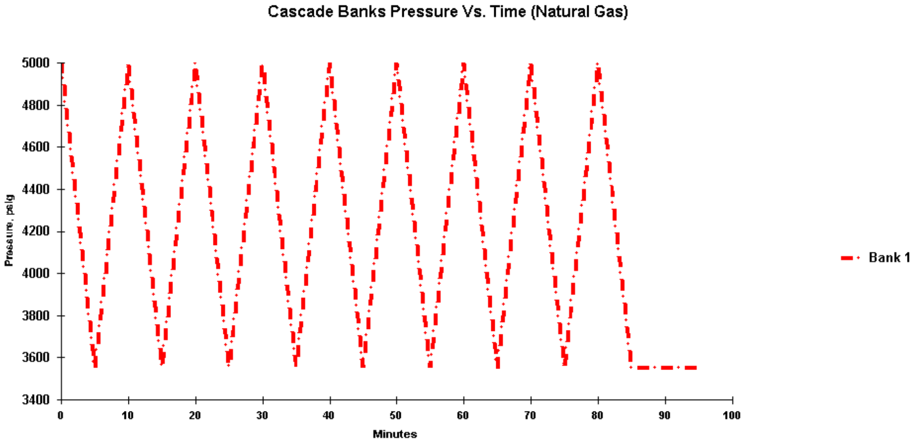


Figure 17: Buffer Storage Pressure Example

Figure 18 shows an actual fueling event using a buffer fill approach on a CNG bus. The initial flow rate into the cylinder is quite high using gas from the buffer storage system (note there is a deliberate intermediate pause in the fueling operation for control purposes). As the buffer storage pressure and vehicle cylinder pressure equalize, the filling rate is constant as gas is supplied directly from the compressors. In this example, the bus is filled in three minutes and the compressor flow is then redirected to recharge the buffer storage.

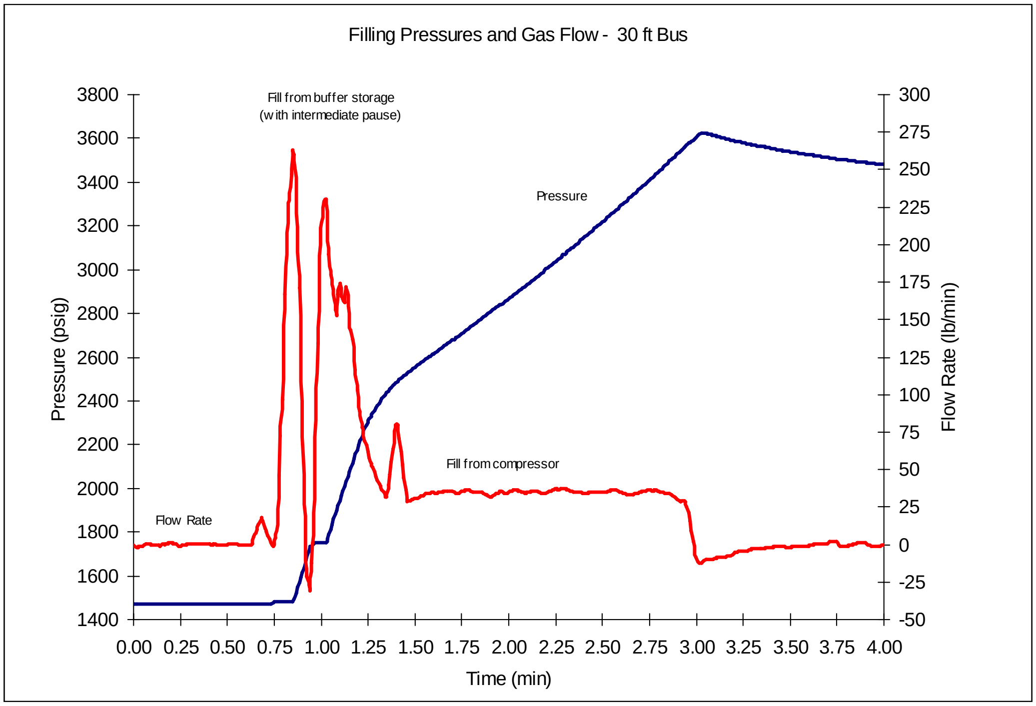


Figure 18: Example Transit Bus Buffer Storage Fast Fill Data

Compressors used in buffer fast-fill systems are relatively large and the amount of useable storage is low. While providing excellent fuel delivery rates on a sustained basis, there is a definite cost premium with the buffer fast-fill approach. Compressor utilization rates tend to be low – for example, 15 to 30 percent (3-7 hours). This is a relatively inefficient use of capital and helps explain why this is typically a niche industry practice.

Cascade Storage Fast-Fill Systems

The most common approach to designing a fast-fill compressed gas fueling station is to use a “ground storage” system referred to as a cascade. Figure 19 shows a schematic layout of a typical three-bank system. To guide the reader, a description of the terminology used in fast-fill systems may be appropriate.

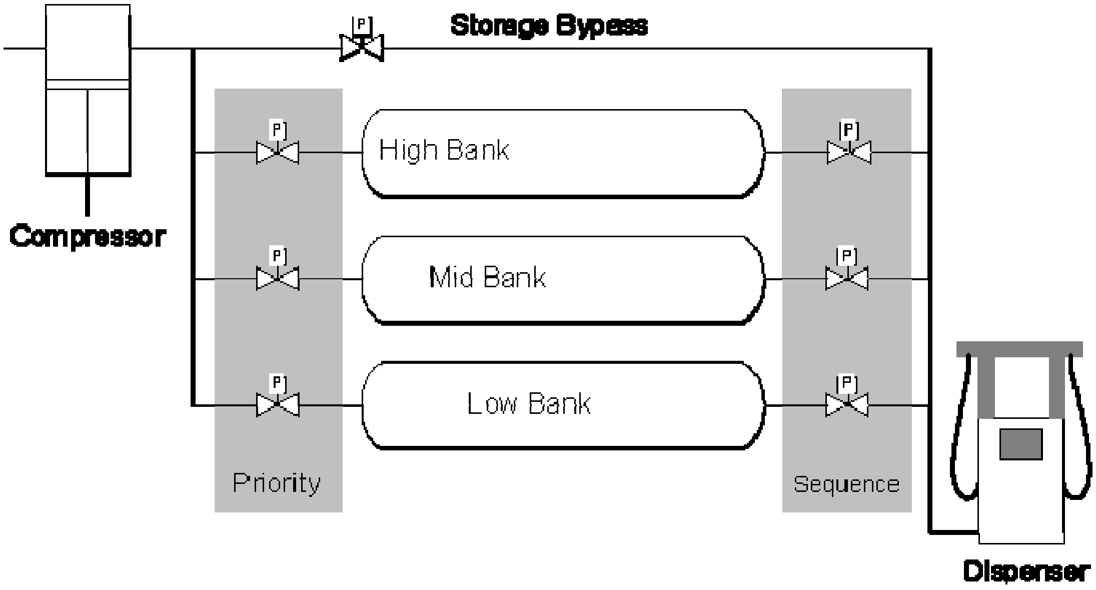


Figure 19: Three-Bank Cascade Storage Fast Fill System

The term “ground storage” refers to the fueling station high pressure storage system – typically located on the ground (though it could also be underground or located on top of a structure). The term is in contrast to the vehicle storage system.

The term “bank” is used to describe a discrete amount of high-pressure storage. A bank could be one cylinder or a collection of cylinders that are piped together in a manner that makes them act as one larger total volume.

The term “cascade” is used to describe two or more discrete banks of compressed gas storage. The most common version of a cascade storage system is comprised of three banks. These individual banks are typically referred to as the High, Medium, and Low Banks. Each of these banks can be independently filled or discharged.

“Priority controls” describe the equipment used to determine which of the banks are filled from the compressor, giving preference (or priority) to the High Bank first, followed by the Medium Bank and then the Low Bank. These may be electronic controls or passive devices that act based upon pressure differential.

“Sequencing controls” describe the equipment used to determine which of the banks are used to direct flow of gas from storage, through the dispenser, to the vehicle.

Figure 20 shows a typical three-vessel, three-bank cascade storage system using large steel ASME pressure vessels. On each side of this cascade are priority and sequencing controls. In some cases, sequencing controls may be located in the dispenser.

Figure 20: Three Bank Cascade With ASME Steel Pressure Vessels

For illustrative purposes, Figure 21 shows a typical approach when operating a three-bank cascade storage system that is fueling multiple vehicles over a time period of 75 minutes. In this example, the ground storage cascade system has three banks each with a maximum pressure of 7000 psig when full. Bank 1 could be also referred to as the “Low-Pressure” Bank, Bank 2 as the “Medium-Pressure” Bank, and Bank 3 as the “High-Pressure” Bank. This terminology is used – even though each bank starts at the same pressure.

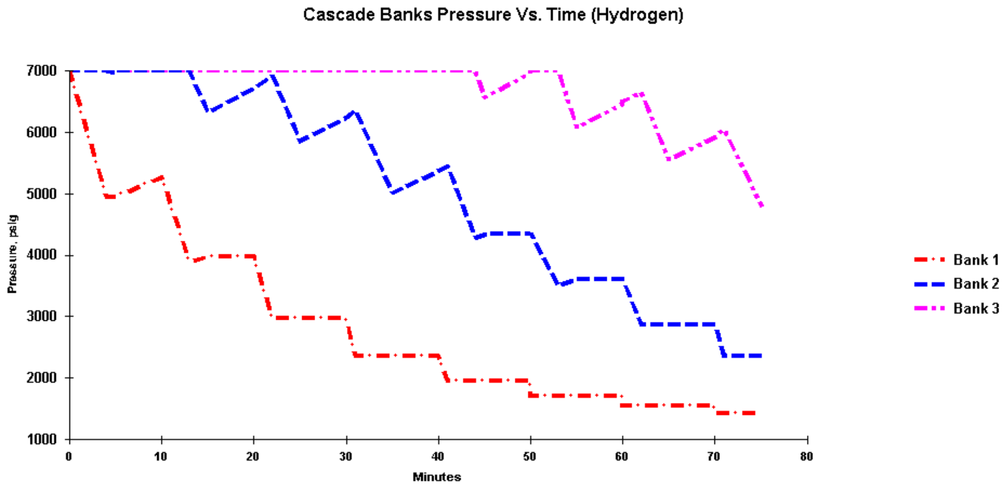


Figure 21: Hydrogen Cascade Fill Example

With each successive vehicle that takes fuel, there is a gradual decrease in pressure in Bank 1 (the first bank used for dispensing fuel) until it is virtually depleted because the residual pressure in the storage bank is not much greater than the next vehicle that pulls up. With time, Bank 2 becomes a more predominant source of hydrogen until this pattern is repeated and this bank is too low in pressure to be very useful. At that point, Bank 3 becomes a more significant source of gas for filling and completing the fill.

Note that in several instances all three banks will be used to fill one vehicle. The sequencing control panel senses either a minimum pressure differential between the bank and the vehicle storage – or uses the real-time hydrogen mass flow meter in the dispenser – to determine it is necessary to switch over to the next highest pressure bank to accelerate the filling process and to properly complete the fill.

At the end of this example, the cascade is essentially "empty." While Bank 1 has about 1200 psig, and Bank 2 has about 2500 psig, and Bank 3 has about 5000 psig – this is really not sufficient storage capacity to fill the next vehicle either in a timely or complete fashion.

It is important to note that throughout this process, a hydrogen gas compressor is running and producing compressed gas that is used to recharge the banks or, as a last resort, top off the vehicle fuel container(s) directly. The cascade priority controls will choose to recharge Bank 3 (the High Bank) first to 7000 psig, followed by Bank 2, and then Bank 1. The primary goal is to always have at least one bank that is able to complete the fill – necessitating a pressure over 5000 psig. Once all banks are brought back to full pressure, the compressor will either shutdown or go into a standby operating mode.

At the 75 minute point in the above example, the overall fuel system needs either an extended "time out" period to allow the compressors to begin recharging the cascade storage – or may need larger compressors that will extend the peak fueling window for this system if station demand is too great.

This example highlights the interplay of compression and storage as well as a couple of key concepts in a cascade storage system:

- Utilization rate
- Recovery time

Cascade Storage Utilization

Ground storage is generally the most common and cost-effective method to address peak demand issues in a compressed gas fueling station. The cost of storage – both in terms of capital and operating costs – is low compared to the cost of larger compressors (including the cost for power to run the compressors).

The cost and performance optimization of a station design however requires an understanding of the value derived from an investment in ground storage. Some key design questions to consider are:

- What is the maximum pressure desired for ground storage (or what practical limits are there in terms of available storage vessels and components)?
- What is the maximum vehicle pressure (including the influence of ambient pressure and the fast-fill temperature rise phenomenon in hydrogen cylinders)?
- How many banks of storage should be used?

As shown, common compressed gas fueling station practice has been to use a three bank cascade. But this is more a “rule of thumb” approach that captures good value from multiple banks without an excessive investment in controls. While this is accepted as a reasonably efficient number, there are no technical limitations to using other values such as one (as in buffer system), two, four, or five (or more). The question centers around the marginal benefits and costs of increasing the number of banks.

Generally speaking, increasing the number of banks increases ground storage utilization efficiency[4]. Figure 22 shows data developed by GTI that illustrates the effect of increasing the number of banks and increasing the pressure differential between the maximum cascade storage pressure and nominal vehicle pressure. Note that these specific curves were developed for a 3600 psig compressed gas vehicle. The curves would change slightly for a 5000 psig vehicle – but the overall trends are representative.

The two key parameters are the difference in pressure between the maximum ground storage pressure and the maximum vehicle pressure (the x-axis) and the number of cascade storage banks.

---

[4] Utilization efficiency measures the mass of gas that can be used to effectively fill vehicles divided by the total ground storage mass of gas.

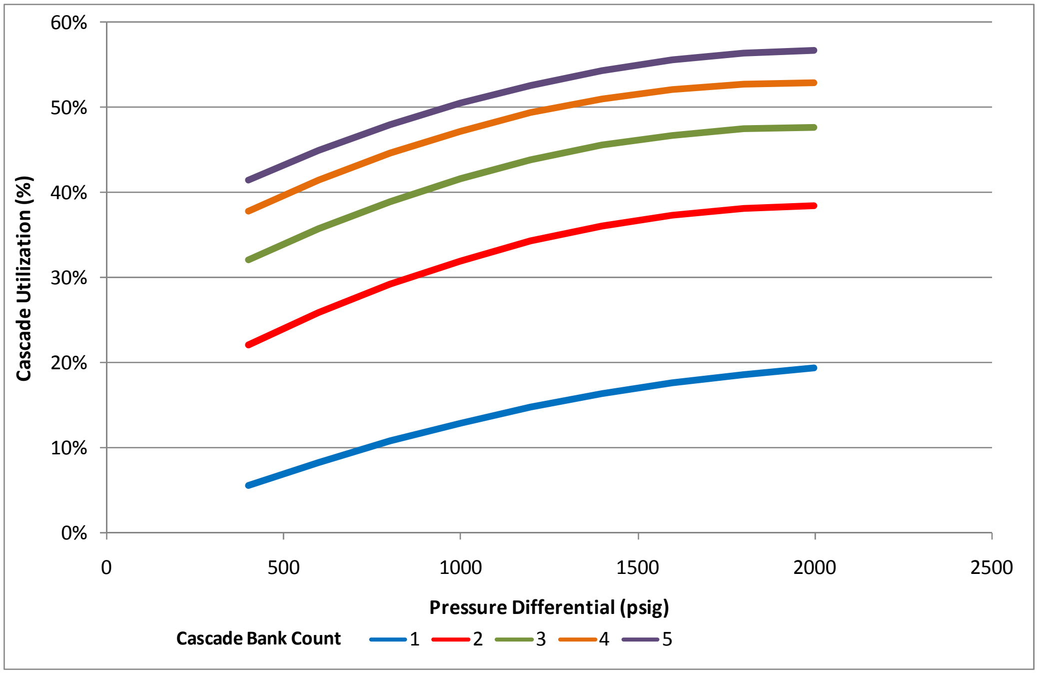


Figure 22: Cascade Utilization Rates

Referring to the prior discussion for a buffer storage system – that is, a bank count of 1 – the overall storage utilization rate is quite low at 10-20 percent.

For a multi-bank cascade system, there are distinct improvements in storage utilization by going from one to two and then to three storage banks. The increment of benefit decreases, however, with each added bank. Going from three to four and even further from four to five provides even smaller benefits. This is a classic example of "diminishing marginal benefits," while the cost for each increment (assuming equal amounts of storage for each bank) is fixed.

In some instances, it is potentially favorable to stagger the sizes of the cascade, with the "low bank" having a greater volume than the other two, and the "medium bank" being larger than the "high bank." For example, have a ratio of 3:2:1. In this approach, there is the potential to achieve improvements in cascade utilization efficiency along with rapid recovery of the high bank. The key is to have the high bank of sufficiently large capacity to meet peak demand (or, conversely, to have the recovery time of the high bank sufficiently fast due to the capacity of the compressor).

The cost of either adding more volume of storage for a given number of banks or adding additional banks needs to be weighed against the potential benefit of incrementally increasing compressor size. For a typical public access station, there is a need to have an appropriate ratio between the volume of storage and compressor capacity. This concept is captured in the phrase "cascade recovery time."

Cascade Recovery Time

An important consideration in sizing a fast fill fueling station is the time required to bring the cascade to a fully charged state. After the exhaustion of the cascade during peak fueling, the cascade must be replenished by an extended period of compressor operation (with much lower vehicle fuel demand than the peak period). The cascade recovery time is related to the amount of ground storage, the cascade utilization rate, and compressor size. The following shows this relationship:

$$\text{Cascade Recovery Time (min.)} = \frac{[\text{Cascade Volume (scf)} * \text{Cascade Utilization}]}{\text{Compressor Size (scfm)}}$$

For example take a hydrogen cascade with 30,000 scf of storage, a cascade utilization of 0.40, and compressor with a 100 scfm flow rate. The recovery time in this example is 120 minutes (two hours). A doubling of the compressor size would decrease this time to one hour.

The choice of storage volume, storage utilization, and compressor size requires a careful understanding of the fueling station fuel delivery requirements during peak periods (e.g., one hour). If there is a spurt of demand – for example, around 5 pm – that drops off in the next couple of hours there may be enough time for a smaller compressor to keep up. If the demand duration is longer, a larger compressor may be required. These “crunch periods” are the critical factors in sizing a fast-fill hydrogen fueling station.

Figure 23 and Figure 24 provide some illustrative graphs on the trade-offs that can be made between the sizing of hydrogen compressor capacity and total storage. The non-linear behavior of the cascade recovery relationship shown in Figure 24 reinforces the need to maintain a level of proportionality between these two factors. Over sizing cascade storage – or undersizing compressor size – can result in unacceptably long periods to recharge the cascade after a period of peak use.

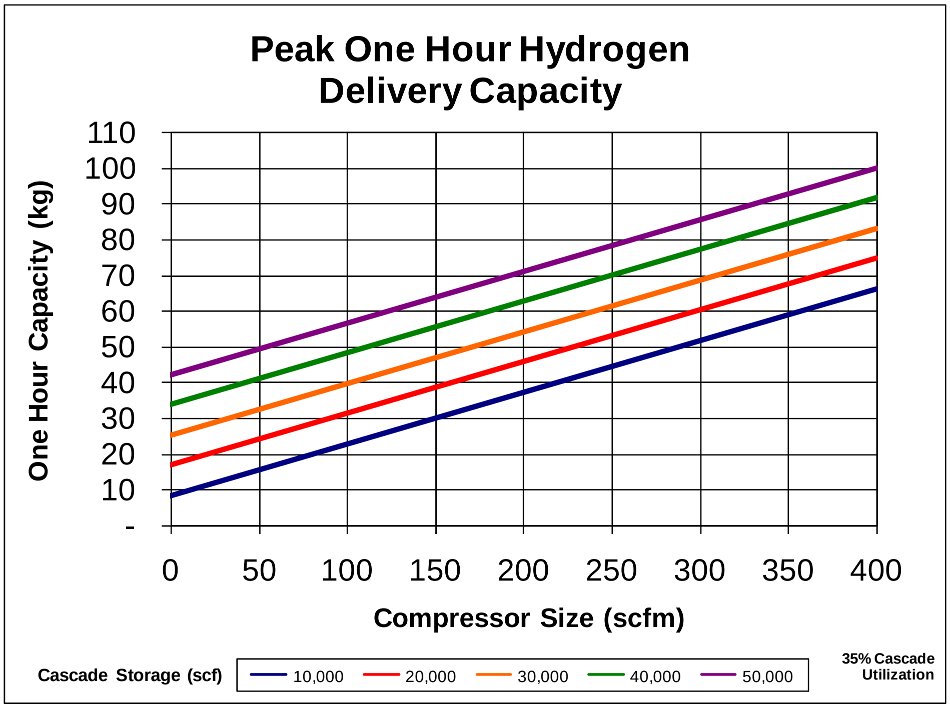


Figure 23: One Hour Hydrogen Delivery Capacity

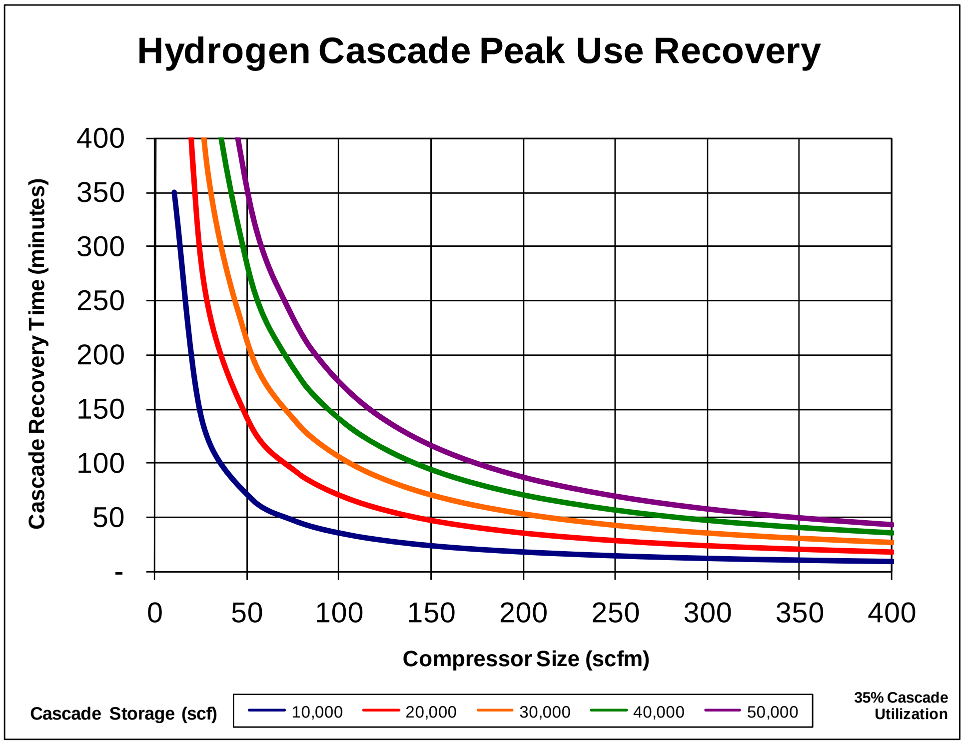


Figure 24: Hydrogen Cascade Recovery Times

Impact of Gas Temperature on Cascade Fill Performance

A factor that is often under-appreciated in sizing a compressed hydrogen dispensing station is the effect of ambient temperature and (more significantly) the fast-fill temperature rise phenomenon that occurs during vehicle cylinder filling.

Figure 25 shows an example temperature effects when fast filling a Type 3 hydrogen cylinder. From an ambient temperature of about 75°F, the temporal peak gas temperature rises to 160 to 180°F at the end of the fill.

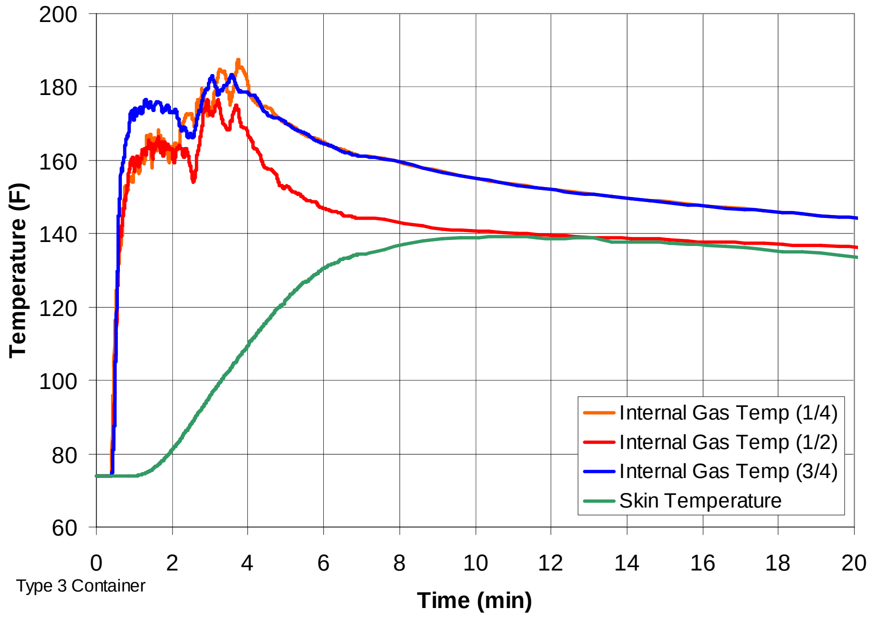


Figure 25: Example Hydrogen Fast Fill Temperature Rise (Type 3)

The implication of this is found by referring back to Figure 14 and Figure 22. The line in Figure 14 shows the constant density relationship between pressure and temperature that correlates to a completely filled hydrogen cylinder based on density. If the hydrogen gas temperature is 160 to 180°F at the end of the fill, the dispenser termination pressure needs to be in the range of 6200 or 6300 psig to achieve a full fill.[5]

Assuming the cascade storage pressure is 7000 psig, the pressure differential between the cascade storage and a nominal 5000 psig cylinder is 2000 psig. However, if the termination pressure for dispensing is actually closer to 6200 psig to compensate for the fast-fill temperature rise phenomenon, then the pressure differential is reduced to 800 psig. Assuming a three bank cascade and using Figure 22, the cascade utilization rate for the hydrogen station with fast-fill temperature rise is now reduced from about 39 percent to approximately 31 percent. In terms of useful storage, this is a 20 percent reduction in storage delivery capacity.

---

[5] U.S. Patent 7,059,364, issued to Gas Technology Institute, describes a hydrogen dispenser control methodology for fast-fill temperature rise.

Stationary Compressed Gas Storage

Compressed gas storage systems typically rely on ASME or DOT high-pressure storage vessels constructed of steel. Some of the more common approaches for making a cascade include:

- Three large individual ASME vessels (typically in a rack).
- Numerous small ASME vessels (typically in a pyramidal stack).
- Numerous small DOT vessels (typically in a basket).

Figure 26 shows examples of typical NGV cascade arrangements. Other options include high-pressure ASME spheres and integration of storage with the skid-mounted platform used to mount the compressor and other equipment on.

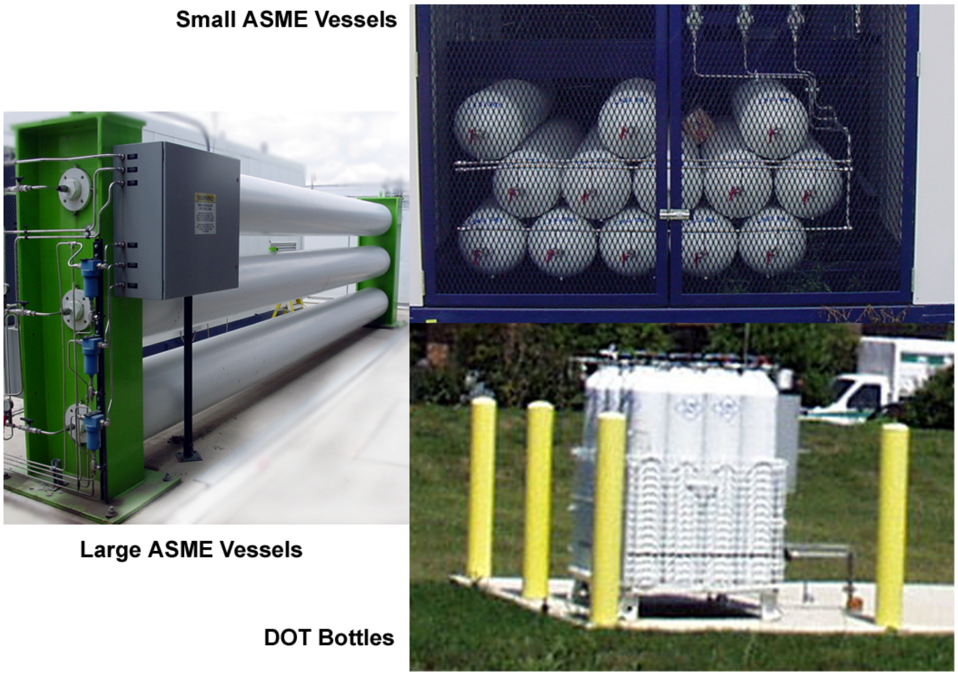


Figure 26: Common Cascade Storage Arrangements

A complete cascade system includes the pressure vessels as well as associated components for control and safety. The control is primarily the priority panel and possibly the sequencing panel as well as associated valves. The safety components include a pressure relief valve and vent lines that will allow safe discharge of hydrogen gas (if needed) to avoid an excess pressure condition within the container. Figure 27 shows an example of a very traditional three-bank cascade that uses ASME steel pressure vessels.

Figure 27: Traditional Three-Bank ASME Steel Vessels With Controls and Vent Line

In recent years, the use of composite pressure vessels for stationary storage has been gaining greater attention – driven in part by the increasing cost for steel. There are also packaging savings that can result since these lighter weight pressure vessels – due to their being a factor of 6-8 times lighter than steel containers. Areas of savings include lower cost for the support structure, reduced weight-bearing requirements for the concrete pad, and reduced structural requirements if they are used in either inside a containerized hydrogen station package or roof-mounted at a fueling station.

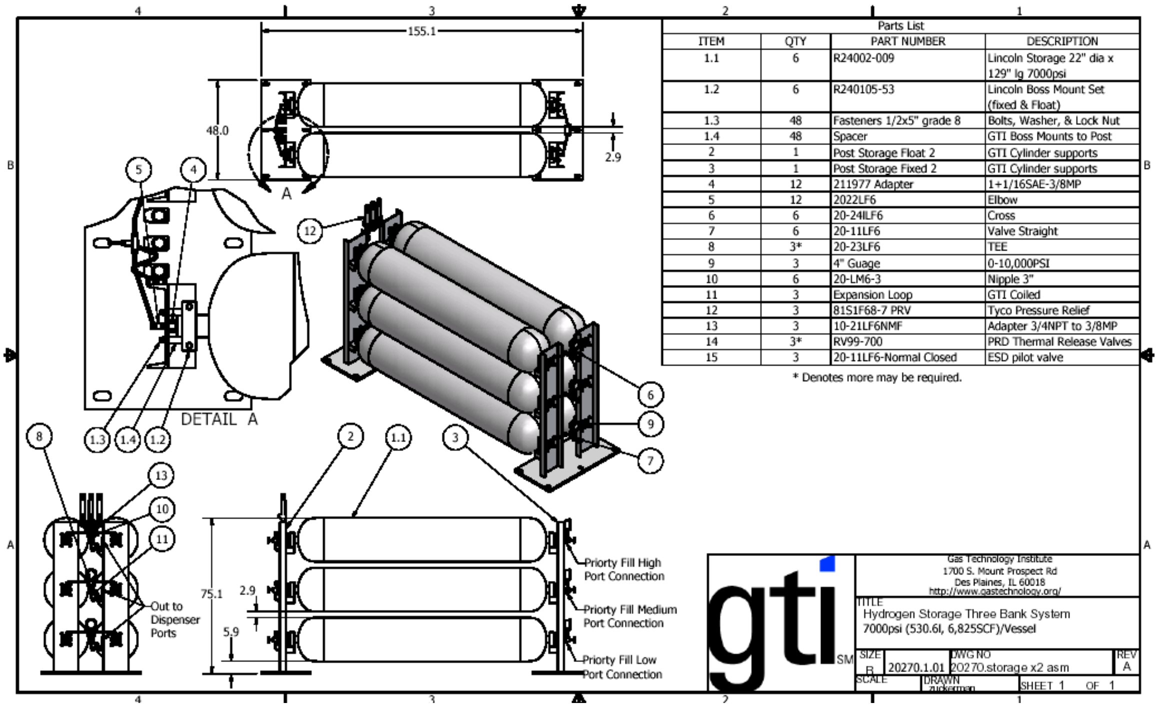
Figure 28 shows a three-bank storage cascade used by GTI at its Des Plaines, IL facility. These pressure vessels, produced by Lincoln Composites, each hold 15.2 kg at 7000 psig – or a total of 45.6 kg in a three-bank cascade. Using an estimate of 40% cascade utilization efficiency, the amount of useable hydrogen that could be dispensed to the vehicle would be around 18 kg. This would be suitable for fueling about 4-5 light-duty vehicles. The total weight of the cascade is approximately 2800 lbs. Comparable steel vessels, such as those shown in Figure 27, would likely weigh in the vicinity of 16,000 to 20,000 pounds.

Figure 28: GTI Three Bank Cascade With Composite Pressure Vessels

Figure 29 shows an interior photograph of the factory-packaged hydrogen fueling station design that was highlighted earlier in Figure 9 and Figure 10. In this design, the lightweight composite containers are mounted inside the station container. Their reduced weight compared to steel vessels lessens the requirement to stiffen or structurally reinforce the containerized structure.

Figure 29: Factory-Packaged, Transportable Hydrogen Station Cascade

Figure 30 shows the design for a six-cylinder, three-bank high-pressure hydrogen storage cascade using similar containers from Lincoln Composites. This approach would double the cascade capacity to over 90 kg gross and about 36 kg net taking into account utilization efficiency. This would provide short-term (e.g., one hour) filling capacity for about 8-10 light-duty vehicles.



Parts List			
ITEM	QTY	PART NUMBER	DESCRIPTION
1.1	6	R24002-009	Lincoln Storage 22" dia x 129" lg 7000psi
1.2	6	R240105-53	Lincoln Boss Mount Set (fixed & Float)
1.3	48	Fasteners 1/2x5" grade 8	Bolts, Washer, & Lock Nut
1.4	48	Spacer	GTI Boss Mounts to Post
2	1	Post Storage Float 2	GTI Cylinder supports
3	1	Post Storage Fixed 2	GTI Cylinder supports
4	12	211977 Adapter	1+1/16SAE-3/8MP
5	12	2022LF6	Elbow
6	6	20-24ILF6	Cross
7	6	20-11LF6	Valve Straight
8	3*	20-23LF6	TEE
9	3	4" Guage	0-10,000PSI
10	6	20-LM6-3	Nipple 3"
11	3	Expansion Loop	GTI Coiled
12	3	81S1F68-7 PRV	Tyco Pressure Relief
13	3	10-21LF6NMF	Adapter 3/4NPT to 3/8MP
14	3*	RV99-700	PRD Thermal Release Valves
15	3	20-11LF6-Normal Closed	ESD pilot valve

* Denotes more may be required.

Gas Technology Institute
1700 S. Mount Prospect Rd
Des Plaines, IL 60018
http://www.gastechnology.org/

TITLE Hydrogen Storage Three Bank System
7000psi (530.6l, 6,825SCF)/Vessel

SIZE B | 20270.1.01 | DWG NO 20270.storage x2 asm | REV A
SCALE | DRAWN zuckerman | SHEET 1 OF 1

Figure 30: Onsite Hydrogen Storage Cascade Design With Composite Containers

Referring back to the fuel demand profile in Table 1, the peak one-hour delivery requirements for a nominal 1200 kg/day station were identified as being in the range of 20-22 vehicles. This would require at least twelve pressure vessels of this size – or double the cascade configuration shown in Figure 30. This would result in a total storage capacity of 180 kg.

Large-Scale and Alternative Cascade Designs

Recently, Lincoln Composites introduced a very large composite pressure vessel – referred to as their Titan product line (Figure 31). These very large pressure vessels are 42.6 inches in diameter and 38 feet long. These were designed to compete with conventional steel tube trailers used in the industrial gas business. Currently these products are rated to 3600 psig and can be used for hydrogen service. A Titan pressure vessel would hold a substantial 150 kg of hydrogen at 3600 psig. Each tank has a gross weight of about 2087 kg.

In the future, a higher-pressure design (e.g., 7000 psig) could have even greater storage capacity. A multi-bank cascade with high-pressure Titan vessels could store in the range of 500 to 1000 kg of hydrogen and provide impressive short-term delivery capacity for traditional public access stations as well as larger fleet vehicles such as transit buses.

Figure 31: Extra-Large Composite Pressure Vessel (Source: Lincoln Composites)

A cascade of very large composite pressure vessel such as the Titan product may also be suitable for underground installation. This could provide a significant space savings. This conceptual approach helps one envision a “mega” hydrogen dispensing station producing, for example, 5000 kg/day or more with multiple dispensers. This would begin to approach the current practice with gasoline and diesel fuel tanks for fuel storage as well as the economies of scale seen in conventional liquid fuel stations.

With the light weight attributes of composite pressure vessels, they may also be used above ground by locating the storage vessels on top of portable hydrogen station containers, within fueling island canopy structures, or on top of buildings. For larger hydrogen stations located in land-constrained metropolitan markets, this can provide much needed space savings. Figure 32 shows a conceptual drawing developed by GTI with composite storage vessels built into the vertical supports and horizontal supports of a fueling island canopy. Other concepts could include placing cylinders on top of roof structures – for example, on top of a convenience store.

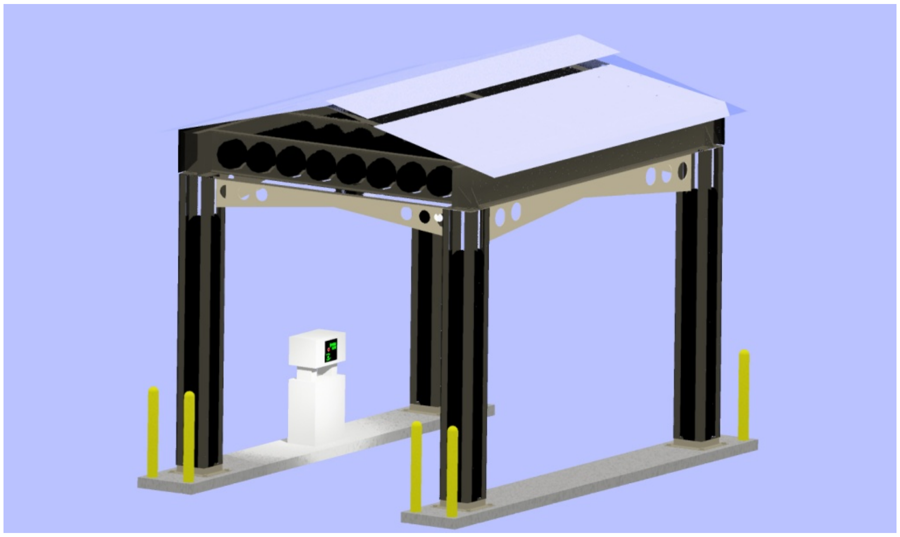


Figure 32: Drawing of Storage Within a Fuel Island Canopy

Cascade Storage System Costs

Figure 33 shows the total specific cost ($/kg) for three-bank hydrogen cascades. This includes the container costs (typically 85 to 90 percent of the total cost) as well as support structure, safety devices, and basic controls. There are relatively limited products to choose from. The graph indicates an expected benefit in terms of increasing the size of the cascade. The cost for very small cascades increases quickly due to higher specific costs for the containers and a relatively fixed cost for safety and control equipment. Higher volumes and increases in total production experience could help drive down the cost for larger cascade options.

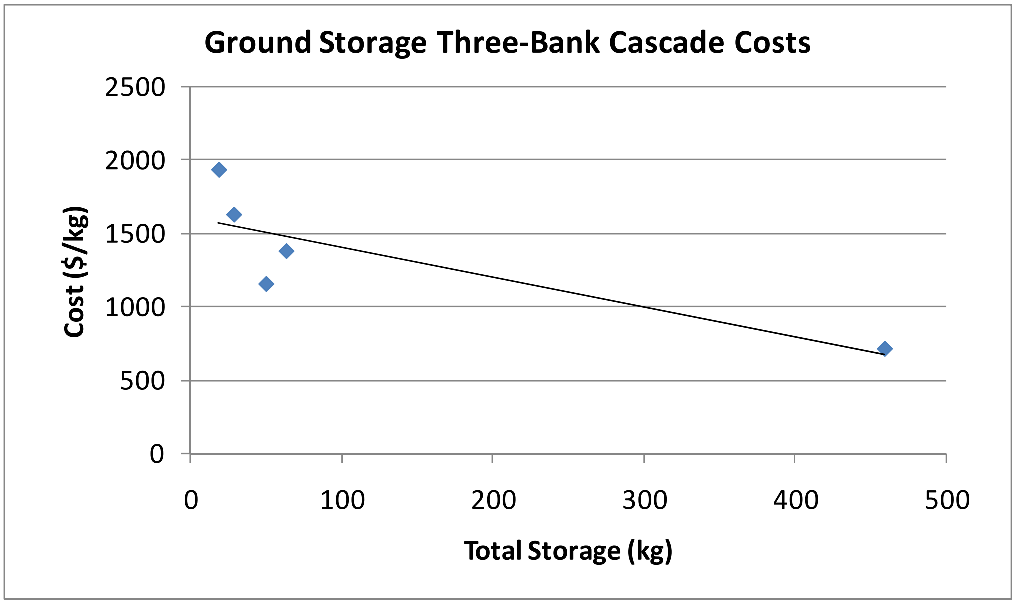


Figure 33: Three-Bank Hydrogen Cascade Costs

Hydrogen Compression

Compressor Overview

There are several theoretical options for compressing hydrogen to high pressure levels such as 5000 to 7000 psig (Figure 34). As a practical matter, the primary options are based on using multi-stage positive displacement machines to achieve an objective of going from low-pressure (below 200 psig) to vehicle or cascade storage pressures levels.

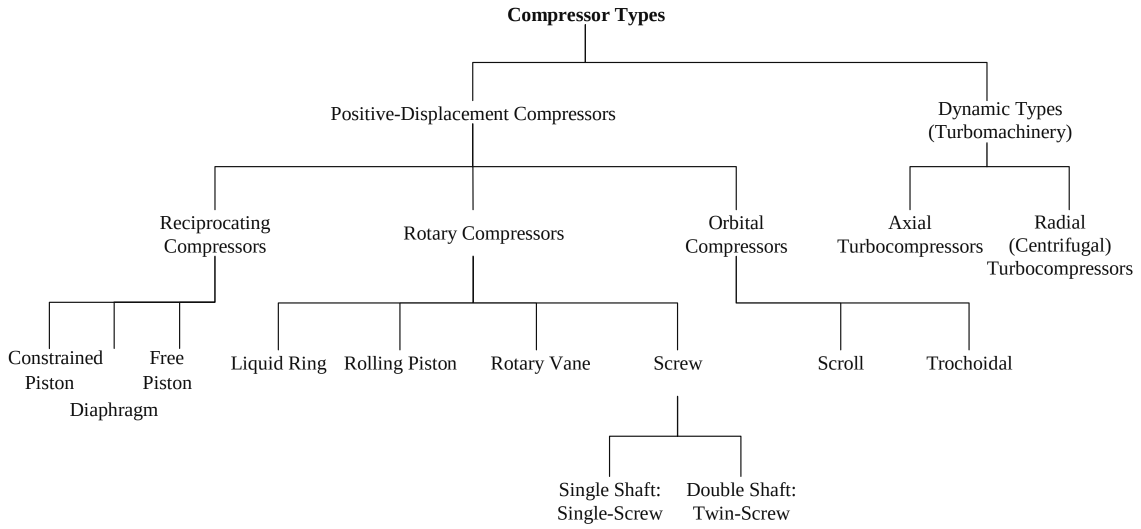
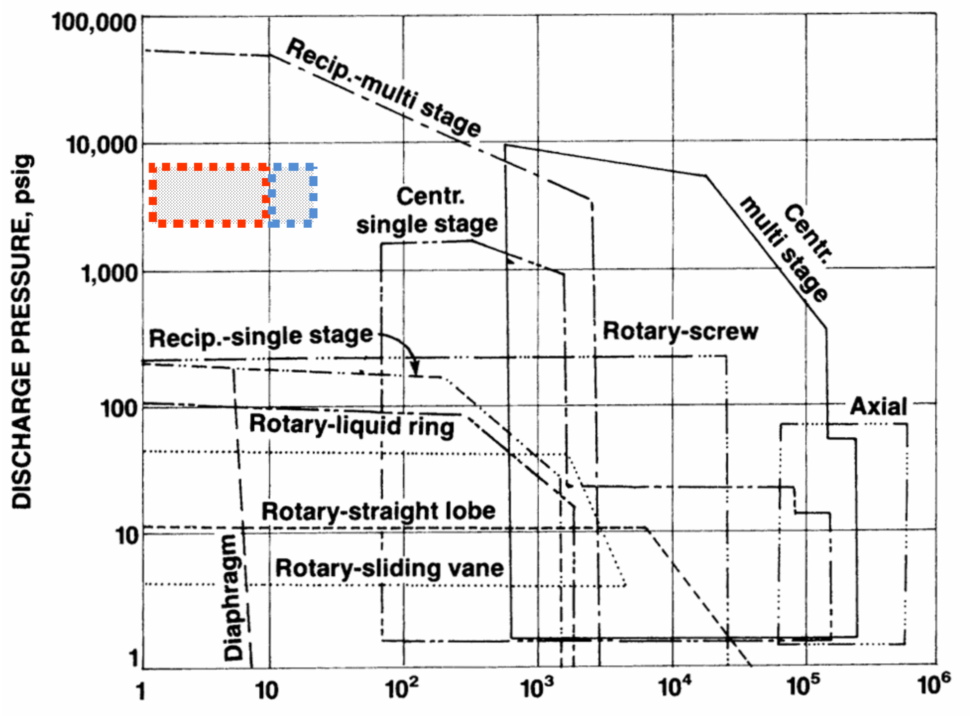


Figure 34: Compressor Types

Figure 35 shows a modified version of a graph produced by the Gas Processors Suppliers Association (GPSA). For reference, the volume throughput rates of 10 ACFM and 100 ACFM correspond to about 600 kg of hydrogen and 6000 kg of hydrogen per day at a suction pressure of 100 psig. The shaded area in red identifies the nominal ranges (flow and discharge pressure) where hydrogen stations are presently being designed and in blue the range for a 1200 kg/day station.

Multi-stage positive displacement machines are presently the most practical choice for satisfying this need. Specifically, most installations have used either a diaphragm compressor or a reciprocating piston compressor. At lower flow rates, diaphragm machines are available and used in several installations. To attain higher pressures, these units require at least two stages of compression.

Figure 36 shows a picture of a two-stage PDC Machines high-pressure hydrogen diaphragm compressor designed for service up to 7500 psig. This type of unit is viewed favorably by some in the fuel cell industry because the hydrogen does not come into direct contact with parts that may be exposed to lubricating oils or greases. The only concern is in the event of a diaphragm failure – such as a fatigue crack – that could result in hydrogen gas contamination.



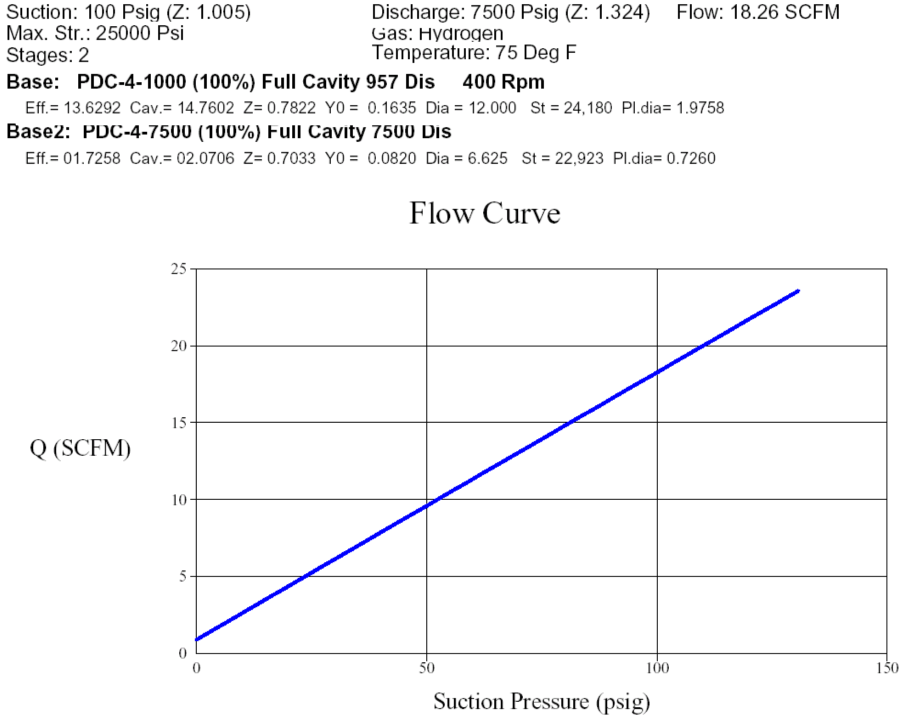
Source: GPSA

Figure 35: Flow Capacity and Discharge Pressure Map of Compressor Options

\

Figure 36: Two-Stage Hydrogen Diaphragm Compressor

Like all positive displacement compressors, the flow rate from a diaphragm compressor is a function of suction pressure. Figure 37 shows a suction pressure versus flow rate curve. At a suction pressure of 100 psig, this compressor would produce about 18 scfm. Operating at this rate over a 24 hour period would produce about 60 kg or hydrogen. This is a relatively small machine.



Suction: 100 Psig (Z: 1.005) Discharge: 7500 Psig (Z: 1.324) Flow: 18.26 SCFM
Max. Str.: 25000 Psi Gas: Hydrogen
Stages: 2 Temperature: 75 Deg F
Base: PDC-4-1000 (100%) Full Cavity 957 Dis 400 Rpm
Eff.= 13.6292 Cav.= 14.7602 Z= 0.7822 Y0 = 0.1635 Dia = 12.000 St = 24,180 Pl.dia= 1.9758
Base2: PDC-4-7500 (100%) Full Cavity 7500 Dis
Eff.= 01.7258 Cav.= 02.0706 Z= 0.7033 Y0 = 0.0820 Dia = 6.625 St = 22,923 Pl.dia= 0.7260

Figure 37: Hydrogen Compressor Performance Curve

While there are larger diaphragm compressors, often – at larger flow rates – it is more common to find multi-stage reciprocating machines in commercial use. There are several suppliers of high-pressure reciprocating compression equipment, with most employed for use in compressed natural gas or specialty process industries. These units may be designed to operate on a range of different gases, including hydrogen, oxygen, and other gases.

A concern when using reciprocating piston compressors is the potential for lubricating oil to become carried over with the compressed hydrogen. There are various approaches manufacturers use to minimize these concerns – including the design of so-called non-lubricated and oil-free machines.

One such reciprocating compressor is shown in Figure 38 and Figure 39 (the GreenField Compression DM compressor). This is a reciprocating design that is powered by electricity. The machine attributes include:

- Oil –free design
- Volume throughput up to 20 SCFM
- 4-stage design with inlet pressures down to 70 psi

- Discharge pressure of 6600 psig
- Low vibration scotch-yoke design
- Hermetically sealed, magnetically coupled, variable speed electric motor drive

Figure 38: Oil-Free Reciprocating Compressor

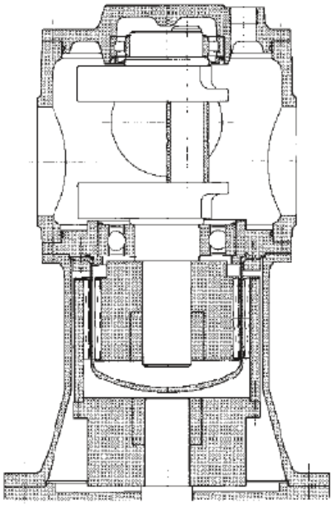


Figure 39: Oil-Free Compressor Hermetically Sealed Magnetic Coupling

This type of machine could compress hydrogen at a rate of 50 to 150 kg/day depending on machine selection and suction pressure. This is still comparably small when looking at hydrogen stations with daily demand of 1200 kg.

An example of a larger capacity reciprocating piston compressor is shown in Figure 40. This machine from Ariel Corporation is used for natural gas and process gas applications (including hydrogen).

Figure 40: Larger Hydrogen Reciprocating Piston Compressor

Figure 41 shows a cutaway depiction of a reciprocating piston compressor used for industrial process gas applications. These types of machines have a great deal of flexibility in terms frame and cylinder sizes to match output to specific applications. They can also be driven by an electric motor or engine drive. A consideration in these types of machines is managing the lubricating oils used in the crankcase. These types of units could be sized for application to a 1200 kg/day hydrogen station.

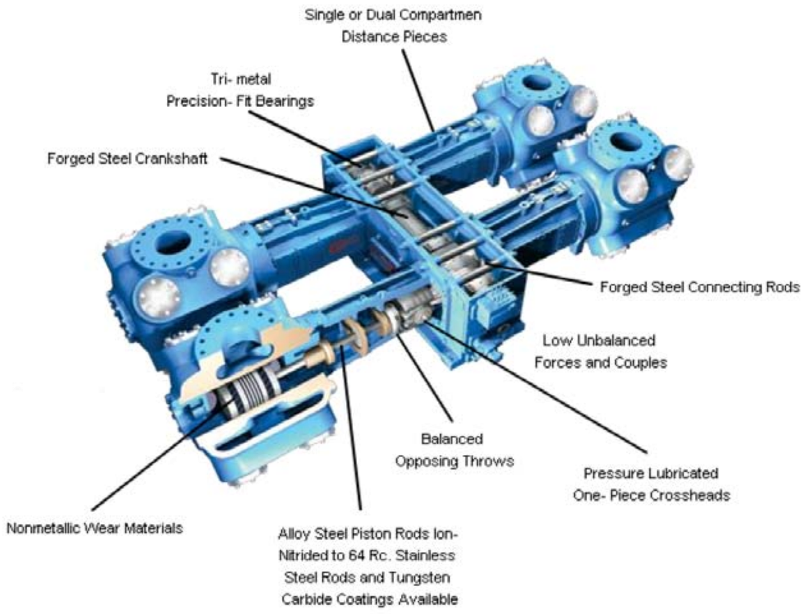


Figure 41: Cutaway of Multi-Stage Reciprocating Piston Compressor

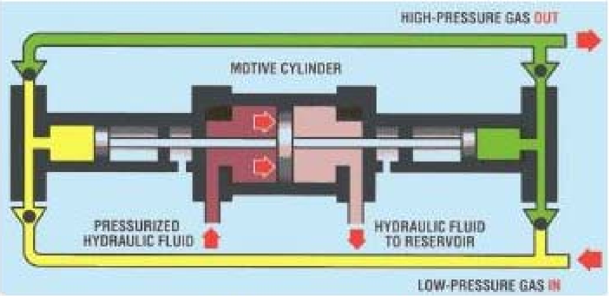
One new compressor coming to the market is called an Ionic Compressor – an approach developed by The Linde Gas Group. This unique machine works on the basis of ionic liquids, salts which are liquid in the desired temperature range. These liquids replace the metal pistons in conventional piston compressors, thus making compression possible at a virtually constant temperature and ensuring the ideal thermodynamic conversion of the electrical energy used into compression energy. This technology not only means lower maintenance costs, but also saves a substantial proportion of the energy required to compress the fuels. The first units are already in use at sites in Europe.

Booster Compressors and Intensifiers

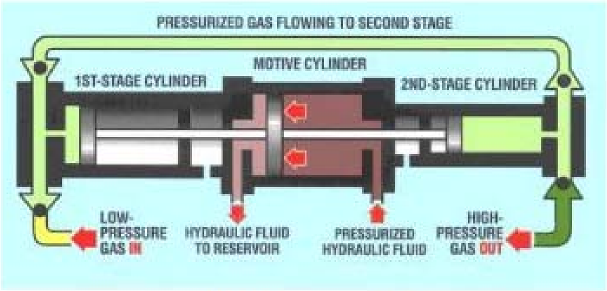
One area of consideration is the use of “booster” compressors in a hydrogen fueling station. These devices are sometimes also referred to as intensifiers. The units are often driven by a hydraulic liquid or in some cases pneumatically.

Figure 42 shows a cutaway that describes the motive cylinder – which in this case is driven by a liquid powered by a hydraulic pump – and the two working cylinders. The compression cylinders can be configured as a two-stage machine that takes hydrogen from low to high pressure in two separate compression steps. Alternatively, it can be configured as a “booster” compressor that would take hydrogen at high pressure – for example, between 1000 and 5000 psig – and booster the pressure to something greater than 5000 psig.

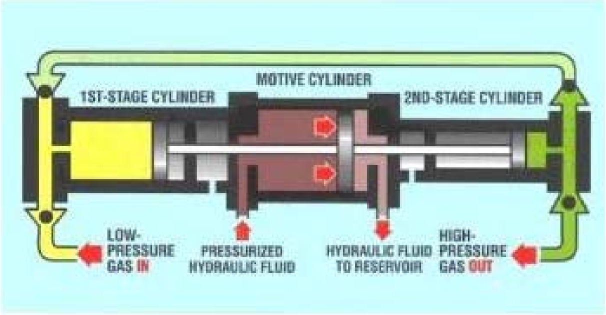
Figure 43 shows a packaged two-stage hydraulically driven compressor. Located on top is an electrically driven hydraulic pump that provides the high-pressure liquid that drives the motive piston. Bottom right is the larger, low-pressure cylinder that accepts and on the left is the high-pressure cylinder.



Single Stage Compressor



Stage 1 Compression

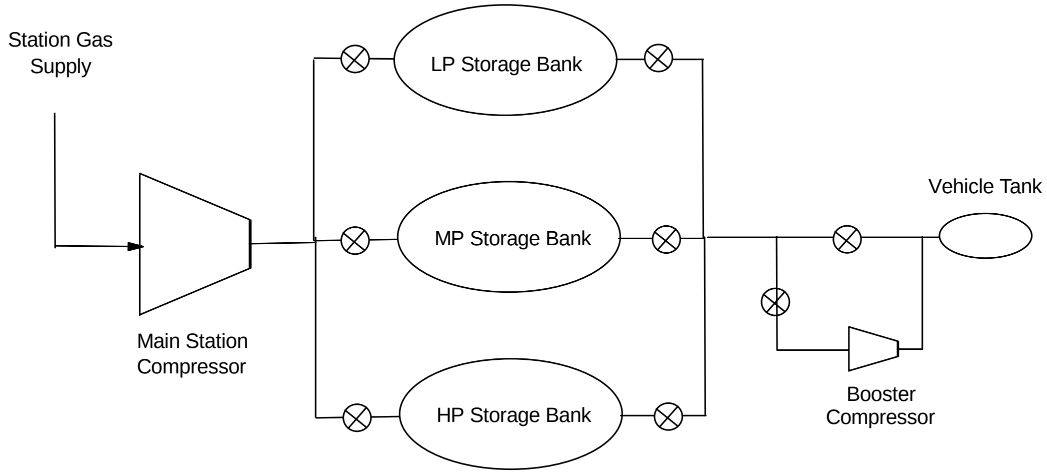


Stage 2 Compression
TWO STAGE COMPRESSOR

Figure 42: Example Hydraulically Driven Compressor (Source: Hydro-Pac)

Figure 43: Packaged Two-Stage Hydraulically Driven Intensifier Compressor

There are many ways a booster compressor could be deployed, but generally – as shown in Figure 44 – there would be a conventional main compressor that is primarily dedicated to filling the cascade storage system and a second single-stage booster compressor that takes hydrogen (when needed) from the cascade to directly fill the vehicle. The notion here is that when cascade pressure is too low to effectively fill a vehicle, then the booster compressor can raise that gas pressure to directly fill the vehicle.



:

Figure 44:Hydrogen Station With Booster Compressor

This approach can, theoretically, improve cascade utilization and enhance fuel delivery performance. Figure 45 shows an example of a booster compressor performance curve based on a relatively small machine. In the range of 4000 to 5000 psig, a booster compressor such as this could help "top off" a vehicle by transferring 0.5 kg in one to two minutes. Larger booster compressors could also be used to provide even higher flow rates to more rapidly complete a fill.

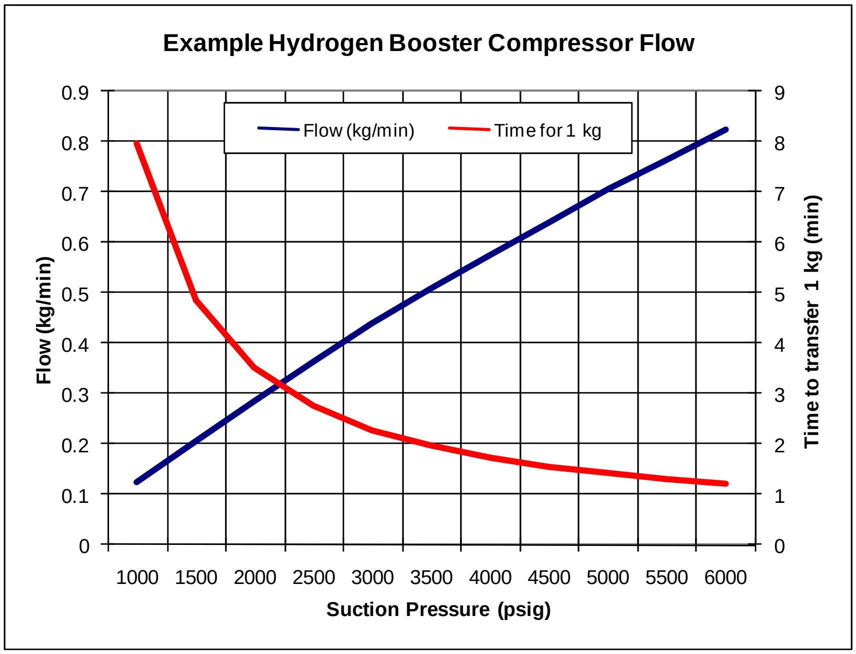


Figure 45: Hydrogen Booster Compressor Flow

Compressor Power Requirements

Power requirements to drive a high-pressure hydrogen compressor will vary depending on the mass throughput rate, suction pressure, discharge pressure, and other factors. Figure 46 was used to develop a correlation equation for specific compressor power requirements as a function of suction and discharge pressure differential. This is based on a nominal 50 scfm machine rated at 150 psig, having a compressor efficiency of 50%, and an electric motor efficiency of 95%.

Table 2 shows representative data on how increases in discharge pressure – going from 3000 to 7000 psia – will impact the compressor drive power requirements and specific power (kW/scfm) for compressing hydrogen.

Table 2: Impact of Discharge Pressure on Compressor Power

T1	P1	Density	P2	Compress.	El. Mtr. Input	SCFM	Spec Power
F	psia	lbm/cu.ft.	psia	kw	kw		kw/scfm
70	150	0.0529	7000	34.0	35.8	50.0	0.716
70	150	0.0529	6000	31.8	33.5	50.0	0.669
70	150	0.0529	5000	29.3	30.9	50.0	0.617
70	150	0.0529	4000	26.5	27.9	50.0	0.557
70	150	0.0529	3000	23.0	24.2	50.0	0.485

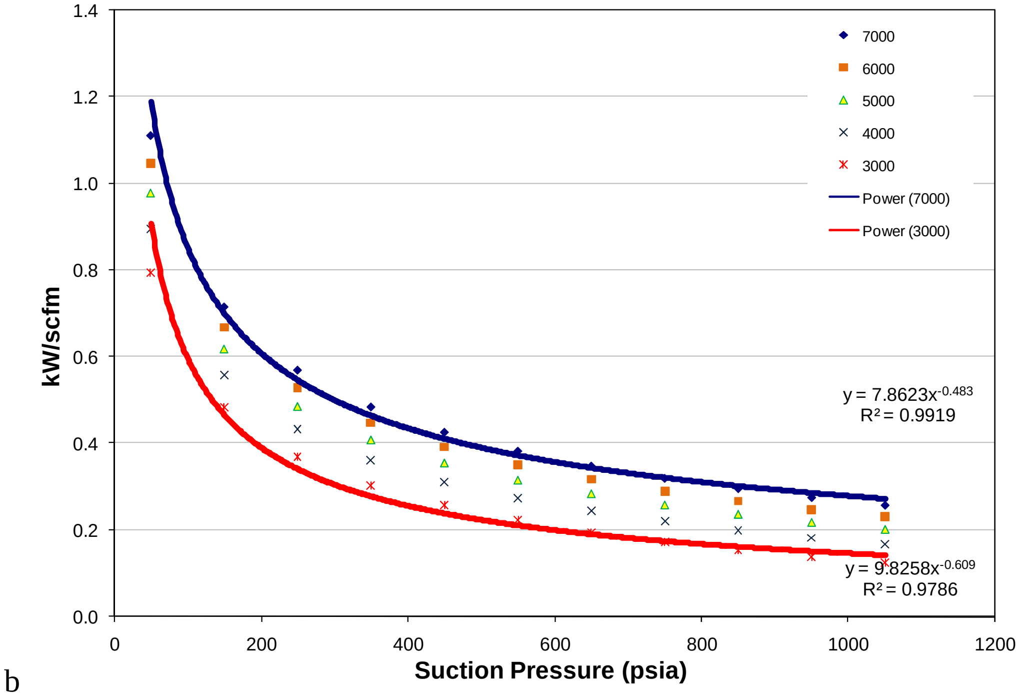


Figure 46: Specific Compression Power Requirements

High-Pressure Compressor Capital Costs

There is a wide range in the capital costs for high-pressure hydrogen compressors. Figure 47 shows data for units ranging in size from 25 to 150 kg per day. These data were used to estimate costs for a multi-unit compressor package suitable to 1200 kg/day.

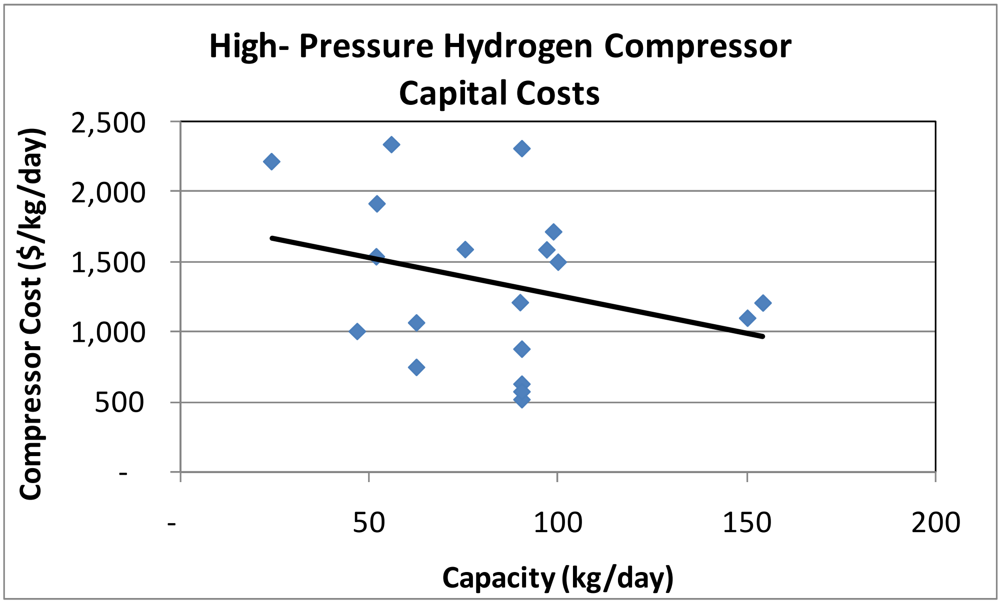


Figure 47: Specific Capital Costs for Hydrogen Compressors

Cascade Analysis Software

NATURAL GAS & HYDROGEN FUELING STATION SIZING SOFTWARE

To assist in the sizing of gaseous fueling systems, GTI developed the CASCADE Gaseous Fueling System Sizing Program. This was originally released in the 1990s for natural gas and upgraded in 2002 with enhancements that included hydrogen.

The CASCADE program is intended to allow for efficient characterization of fast-fill fueling operations using natural gas or hydrogen compressors and ground storage systems. CASCADE is a time-based, dynamic program that allows for simultaneous operations of vehicle filling along with the running of compressors and operation of a storage cascade. CASCADE software is available online at www.interenergysoftware.com.

In the program, the user defines a prototypical vehicle fleet composition, including on-board storage capacity, pressure, and number of vehicles. In addition, fueling station attributes like compressor size, cascade storage size, number of banks, and number of dispensers can be specified. Additional variables include the time for dispensing fuel and the time before a subsequent vehicle is connected for fueling. The program includes a visual representation of the vehicle fueling process.

To assist in the analysis of more sophisticated hydrogen fueling station configurations and station economics, an effort was undertaken in collaboration with this program to expand GTI's CASCADE software tool to incorporate new features and economic analyses functionality. The resulting program and its capabilities was renamed CASCADE H_2 PRO.[6]

The enhancements to CASCADE H_2 Pro were undertaken to allow a more expanded techno-economic assessment of hydrogen fueling station configurations. The following is a summary of the targeted analytical tool enhancements:

- Improved system flow representation
- Multiple, simultaneous vehicle fueling
- User selectable maximum dispenser flow rate
- Multiple vehicle types and flexible scheduling
- User definable compressor characteristics
- Compressor volumetric efficiency calculation
- Electrical and power consumption
- Time of day and seasonal rates
- Station life cycle cost analysis
- Net present value

---

[6] Presently, the CASCADE H_2 PRO has not been released for commercial use.

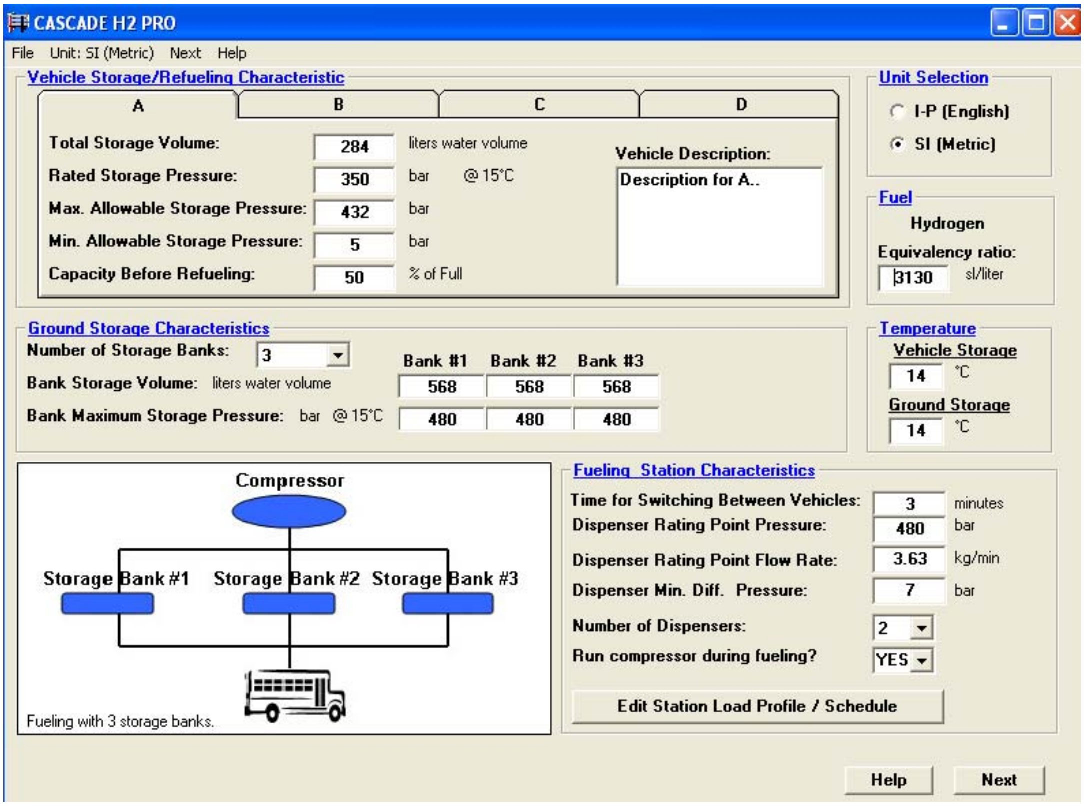
- Payback (simple and discounted)
- Rate of return solver
- Improved charting and reporting features

Table 3 provides a summary of the various input and output parameters and chart reports included in the CASCADE H2 Pro software program.

Table 3: Cascade H2 Pro Input and Output Parameters

	Parameters	English	SI
Input	Equivalency ratio:	scf/gge	sl/liter
	Vehicle Total Storage Volume:	cu. ft. water volume	liters water volume
	Vehicle Rated Storage Pressure:	psig	bar
	Vehicle Minimum Storage Pressure:	psig	bar
	Time for Switching Between	psig	bar
	Dispenser Rating Point Pressure:	psig	bar
	Dispenser Min. Pressure Difference:	psi	bar
	Dispenser Rating Point Flow Rate:	lb/min	kg/min
	Bank Storage Volume:	cu. ft. water volume	liters water volume
	Bank Maximum Storage Pressure:	psig	bar
	Compressor delivery rate used for analysis:	scf/min	liter/min
	Compressor Rated Suction Pressure:	psig	bar
	Compressor Rated Suction Temperature:	F	C
	Compressor Rated Discharge Pressure:	psig	bar
	Compressor Rated Moter Input Power:	kW	kW
	Station H2 Supply Pressure:	psig	bar
	Station H2 Supply Temperature:	F	C
Output	Vehicle Storage Full Fill Pressure	psig	bar
	Vehicle Storage Full Fill Temperature	F	C
	Vehicle Storage Capacity:	scf	liter
	Refueling Start Vehicle Gas Volume:	scf	liter
	Refueling Start vehicle Gas Pressure:	psig	bar
	Vehicle Gas Refueling Volume:	scf	liter
	Vehicle Gas Refueling Mass:	lb	kg
	Ground Storage Cylinder Capacity:	scf	liter
	Total Ground Storage Capacity:	scf	liter
	Total Daily Station Demand:	scf	liter
	Average Station Demandt:	scf	liter
	Estimated Maximum Station Demand:	scf	liter
Charts vs. Time	Cascade Pressure	psig	bar
	Cascade Capacity	scf	liter
	Compressor Output Capacity	scf/min	liter/min
	Compressor Power Input	kW	kW
	Compressor Electric Demand Profile	kW	kW
	Station Hourly Load Profile	lb	kg
	Disperser HourlyLoad Profile	lb	kg

Figure 48 shows an input screen for the CASCADE program. The user can select English or metric units. Up to four different types of vehicles can be defined (A, B, C, D) in terms of the on-board hydrogen storage features. Up to five different cascade storage banks can be defined, with the ability to alter the volume and maximum pressure for each cascade bank. The user can also describe the number of dispensers, pressure rating, maximum flow characteristics (if desired), and the time for switching between the end of one vehicle fill until the next vehicle is connected.



Vehicle Storage/Refueling Characteristic

Total Storage Volume: 284 liters water volume
Rated Storage Pressure: 350 bar @15°C
Max. Allowable Storage Pressure: 432 bar
Min. Allowable Storage Pressure: 5 bar
Capacity Before Refueling: 50 % of Full
Vehicle Description: Description for A..

Unit Selection

○ I-P (English)
● SI (Metric)

Fuel

Hydrogen
Equivalency ratio: 3130 sl/liter

Ground Storage Characteristics

Number of Storage Banks: 3

	Bank #1	Bank #2	Bank #3
Bank Storage Volume: liters water volume	568	568	568
Bank Maximum Storage Pressure: bar @15°C	480	480	480

Temperature

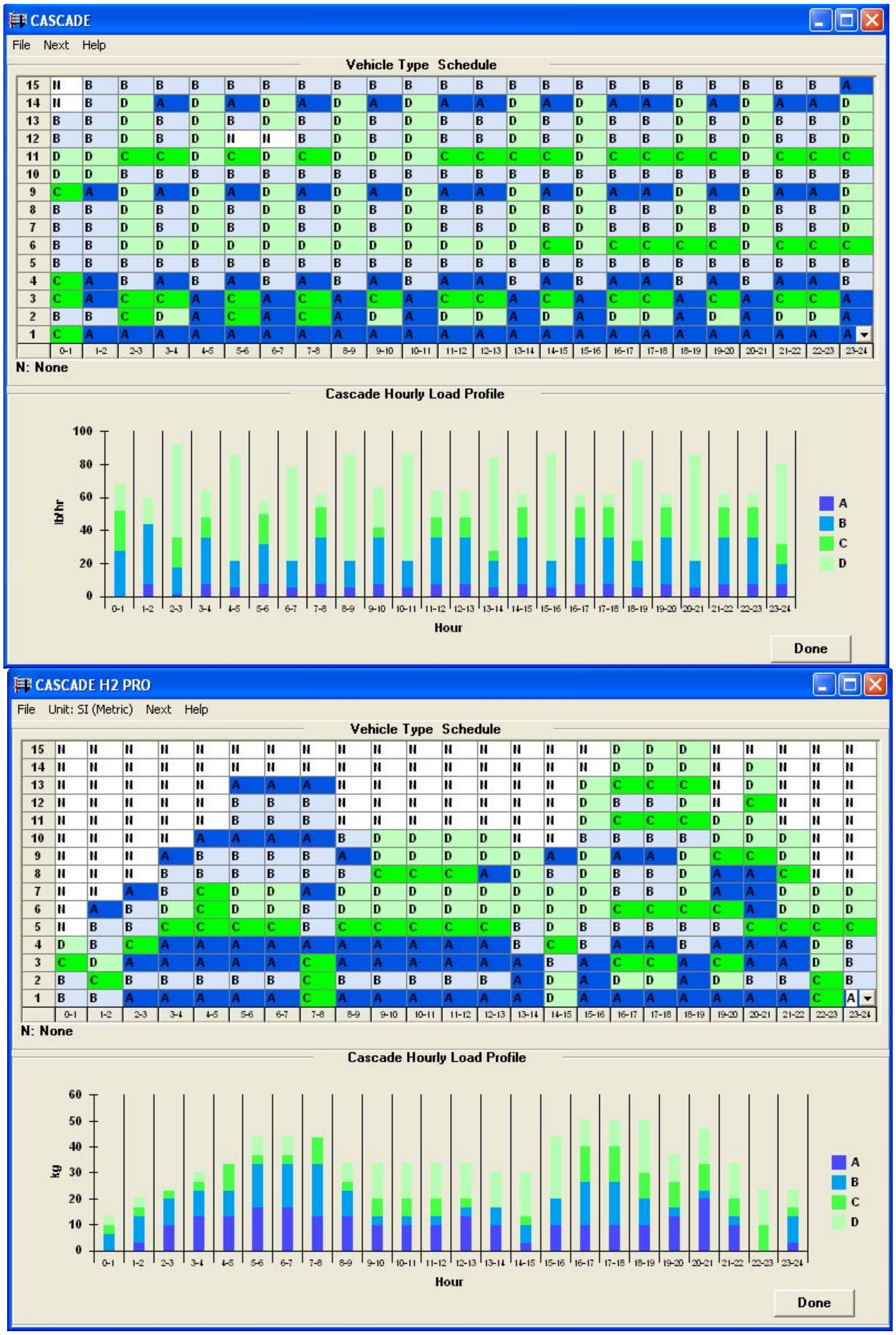
Vehicle Storage: 14 °C
Ground Storage: 14 °C

Fueling Station Characteristics

Time for Switching Between Vehicles: 3 minutes
Dispenser Rating Point Pressure: 480 bar
Dispenser Rating Point Flow Rate: 3.63 kg/min
Dispenser Min. Diff. Pressure: 7 bar
Number of Dispensers: 2
Run compressor during fueling? YES

Figure 48: CASCADE Software Fueling Station and Vehicle Configuration Set-up

By selecting the "Edit Station Load Profile/Schedule" button, the user is able to define specific fueling station full-day vehicle demand profiles over a 24 hour period (Figure 49). By assigning type (i.e., A, B, C, or D), number of vehicles, and priority of vehicles arriving at the station each hour, a full day-long demand profile can be built. This figure shows two different daily demand profiles (labeled a and b).



a)

Vehicle Type Schedule

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
15	N	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	A
14	N	B	D	A	D	A	D	A	D	A	D	A	A	D	A	D	A	A	D	A	D	A	A	D
13	B	B	D	B	D	B	D	B	D	B	D	B	B	D	B	D	B	B	D	B	D	B	B	D
12	B	B	D	B	D	N	N	B	D	B	D	B	B	D	B	D	B	B	D	B	D	B	B	D
11	D	D	C	C	D	C	D	C	D	D	D	C	C	C	C	D	C	C	C	C	D	C	C	C
10	D	D	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
9	C	A	D	A	D	A	D	A	D	A	D	A	A	D	A	D	A	A	D	A	D	A	A	D
8	B	B	D	B	D	B	D	B	D	B	D	B	B	D	B	D	B	B	D	B	D	B	B	D
7	B	B	D	B	D	B	D	B	D	B	D	B	B	D	B	D	B	B	D	B	D	B	B	D
6	B	B	D	D	D	D	D	D	D	D	D	D	D	D	C	D	C	C	C	C	D	C	C	C
5	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B	B
4	C	A	B	A	B	A	B	A	B	A	B	A	A	B	A	B	A	A	B	A	B	A	A	B
3	C	A	C	C	A	C	A	C	A	C	A	C	C	A	C	A	C	C	A	C	A	C	C	A
2	B	B	C	D	A	C	A	C	A	D	A	D	D	A	D	A	D	D	A	D	A	D	D	A
1	C	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

N: None

b)

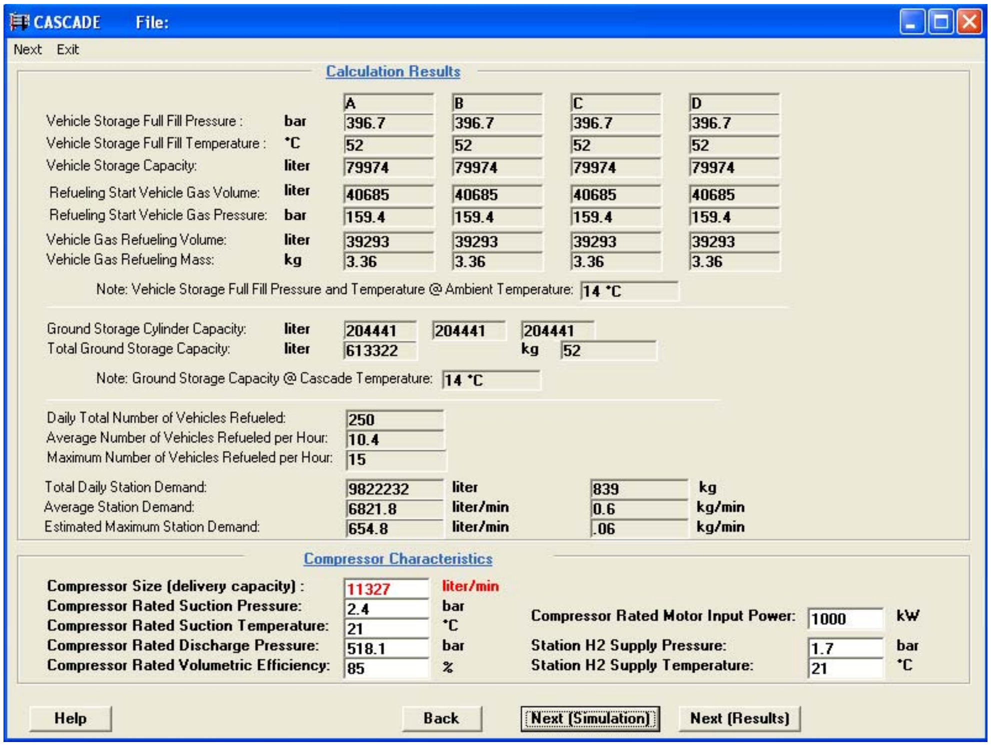
Vehicle Type Schedule

	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24
15	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	D	D	D	N	N	N	N	N
14	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	D	D	D	N	D	N	N	N
13	N	N	N	N	N	A	A	A	N	N	N	N	N	N	N	D	C	C	C	N	D	N	N	N
12	N	N	N	N	N	B	B	B	N	N	N	N	N	N	N	D	B	B	D	N	C	N	N	N
11	N	N	N	N	N	B	B	B	N	N	N	N	N	N	N	D	C	C	C	D	D	N	N	N
10	N	N	N	N	A	A	A	A	B	D	D	D	D	N	N	B	B	B	B	D	D	D	N	N
9	N	N	N	A	B	B	B	B	A	D	D	D	D	D	A	D	A	A	D	C	C	D	N	N
8	N	N	N	B	B	B	B	B	B	C	C	C	A	D	B	D	B	B	D	A	A	C	N	N
7	N	N	A	B	C	D	D	A	D	D	D	D	D	D	D	D	B	B	D	A	A	D	D	D
6	N	A	B	D	C	D	D	B	D	D	D	D	D	D	D	D	C	C	C	C	A	D	D	D
5	N	B	B	C	C	C	C	B	C	C	C	C	C	B	D	B	B	B	B	B	C	C	C	C
4	D	B	C	A	A	A	A	A	A	A	A	A	A	B	C	B	A	A	B	A	A	A	D	B
3	C	D	A	A	A	A	A	C	A	A	A	A	A	A	B	A	C	C	A	C	A	A	D	B
2	B	C	B	B	B	B	B	C	B	B	B	B	B	A	D	A	D	D	A	D	B	B	C	B
1	B	B	A	A	A	A	A	C	A	A	A	A	A	A	D	A	A	A	A	A	A	A	C	A

N: None

Figure 49 a) and b): Fueling Station Load Profile Configuration User Interface

Based on the previously described definition of fueling station/cascade configuration and station hourly load profile, a preliminary calculation of the station daily average and maximum demands are run to provide the user with information supporting station compressor sizing (Figure 50). The user can make adjustments to the compressor suggested delivery capacity.



Calculation Results

		A	B	C	D
Vehicle Storage Full Fill Pressure :	bar	396.7	396.7	396.7	396.7
Vehicle Storage Full Fill Temperature :	°C	52	52	52	52
Vehicle Storage Capacity:	liter	79974	79974	79974	79974
Refueling Start Vehicle Gas Volume:	liter	40685	40685	40685	40685
Refueling Start Vehicle Gas Pressure:	bar	159.4	159.4	159.4	159.4
Vehicle Gas Refueling Volume:	liter	39293	39293	39293	39293
Vehicle Gas Refueling Mass:	kg	3.36	3.36	3.36	3.36

Note: Vehicle Storage Full Fill Pressure and Temperature @ Ambient Temperature: 14 °C

Ground Storage Cylinder Capacity: liter 204441 204441 204441
Total Ground Storage Capacity: liter 613322 kg 52

Note: Ground Storage Capacity @ Cascade Temperature: 14 °C

Daily Total Number of Vehicles Refueled: 250
Average Number of Vehicles Refueled per Hour: 10.4
Maximum Number of Vehicles Refueled per Hour: 15

Total Daily Station Demand: 9822232 liter 839 kg
Average Station Demand: 6821.8 liter/min 0.6 kg/min
Estimated Maximum Station Demand: 654.8 liter/min .06 kg/min

Compressor Characteristics

Compressor Size (delivery capacity) : 11327 liter/min
Compressor Rated Suction Pressure: 2.4 bar
Compressor Rated Suction Temperature: 21 °C
Compressor Rated Discharge Pressure: 518.1 bar
Compressor Rated Volumetric Efficiency: 85 %
Compressor Rated Motor Input Power: 1000 kW
Station H2 Supply Pressure: 1.7 bar
Station H2 Supply Temperature: 21 °C

Figure 50. Interim Results Output Screen and Compressor Set-up

By pressing the "Next (Simulation)" button, the station's full-day operation can be run with a visualization tool enabled (Figure 51). This will present a dynamic process of switching between individual cascade banks to fill each successive vehicle that pulls up (based on the programmed demand schedule).

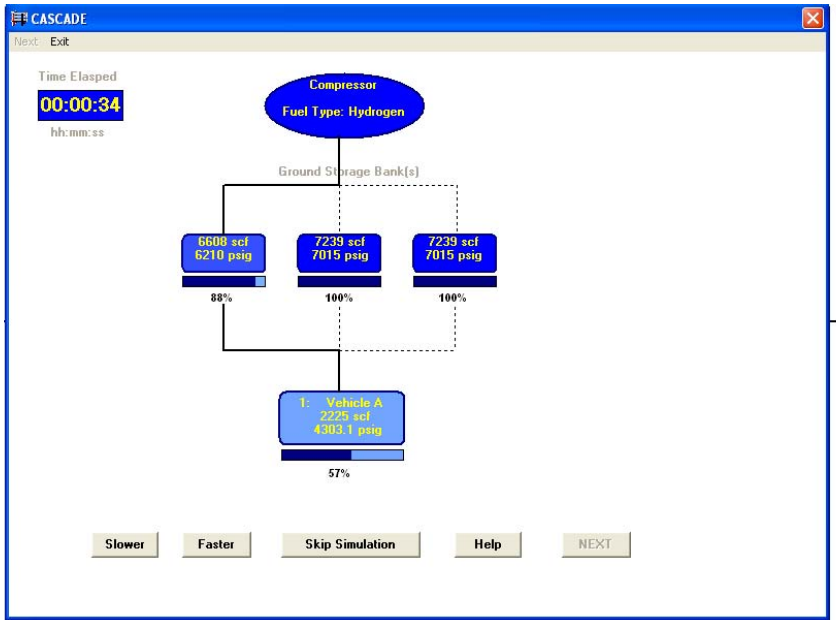


Figure 51. Process Visualization Tool

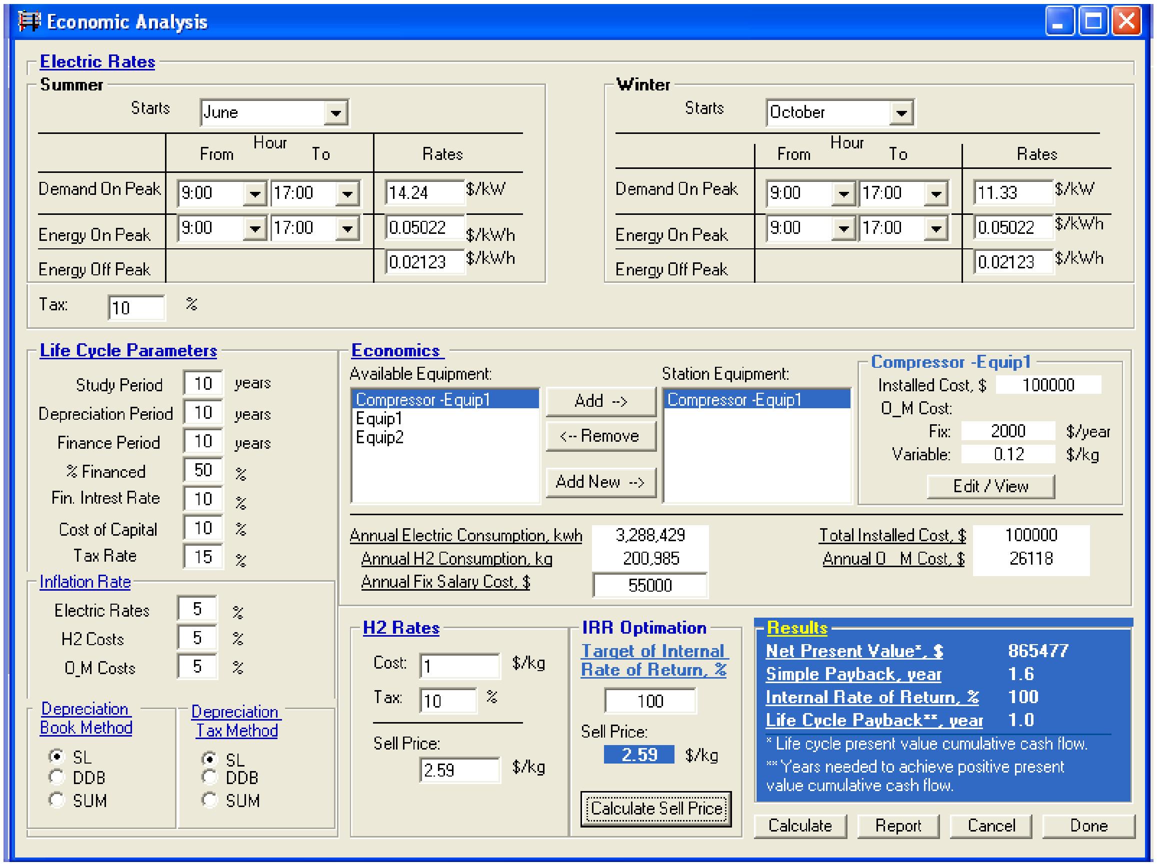
Figure 52 shows the economic analysis input screen. The following economic parameters can be defined by the user:

- Station/equipment first/installed cost
- Cost of hydrogen and sale price
- Local electric rate structure
- Life cycle parameters (7 independent parameters)
- Inflation rates
- Book and tax depreciation methods

The following economic parameters are calculated by the program:

- Project net present value
- Simple payback
- Internal rate of return
- Life cycle payback

The user can also calculate target selling price of hydrogen fuel generating target internal rate of return.



Electric Rates

Summer Starts: June

	Hour From	Hour To	Rates
Demand On Peak	9:00	17:00	14.24 $/kW
Energy On Peak	9:00	17:00	0.05022 $/kWh
Energy Off Peak			0.02123 $/kWh

Winter Starts: October

	Hour From	Hour To	Rates
Demand On Peak	9:00	17:00	11.33 $/kW
Energy On Peak	9:00	17:00	0.05022 $/kWh
Energy Off Peak			0.02123 $/kWh

Tax: 10 %

Life Cycle Parameters

Study Period	10	years
Depreciation Period	10	years
Finance Period	10	years
% Financed	50	%
Fin. Intrest Rate	10	%
Cost of Capital	10	%
Tax Rate	15	%

Inflation Rate

Electric Rates	5	%
H2 Costs	5	%
O_M Costs	5	%

Depreciation Book Method: ● SL ○ DDB ○ SUM

Depreciation Tax Method: ● SL ○ DDB ○ SUM

Economics

Available Equipment: Compressor -Equip1, Equip1, Equip2

Station Equipment: Compressor -Equip1

Compressor -Equip1

Installed Cost, $ 100000

O_M Cost:

Fix: 2000 $/year

Variable: 0.12 $/kg

Annual Electric Consumption, kwh 3,288,429

Annual H2 Consumption, kg 200,985

Annual Fix Salary Cost, $ 55000

Total Installed Cost, $ 100000

Annual O M Cost, $ 26118

H2 Rates

Cost: 1 $/kg

Tax: 10 %

Sell Price: 2.59 $/kg

IRR Optimation

Target of Internal Rate of Return, % 100

Sell Price: 2.59 $/kg

Results

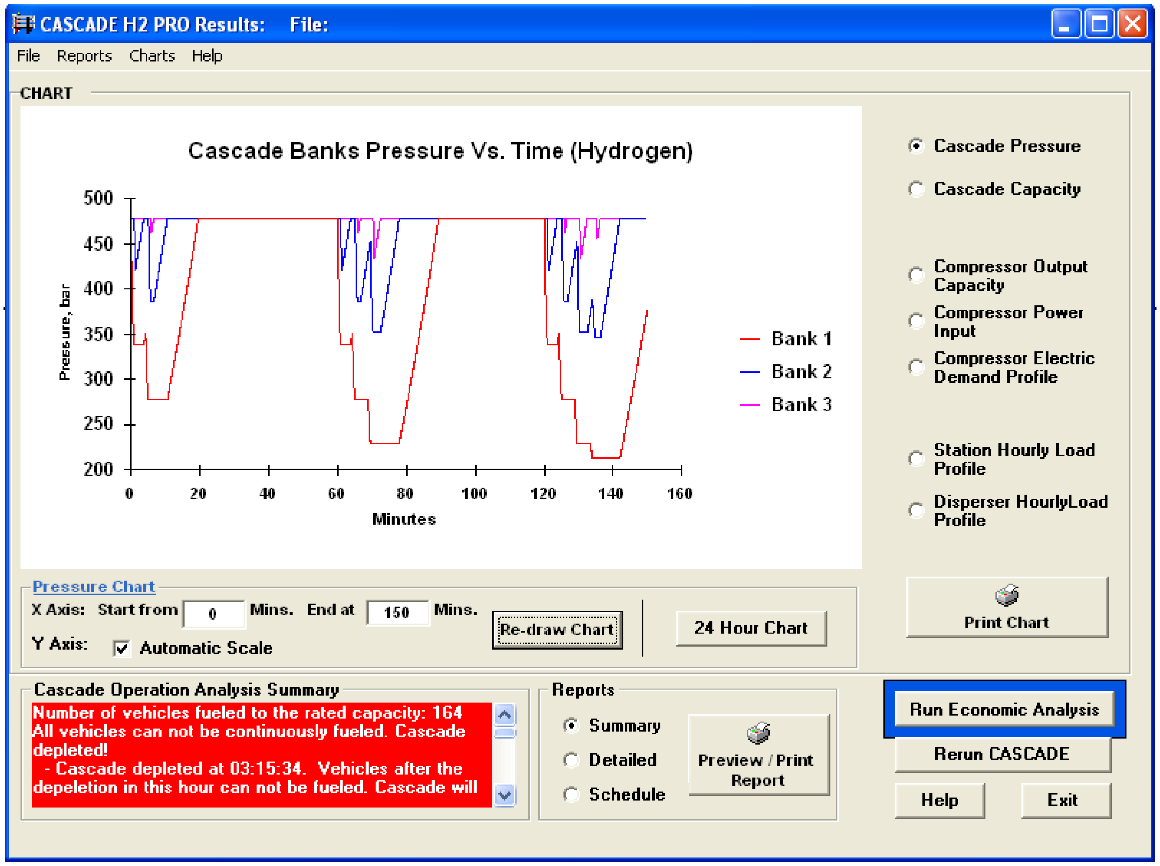
Net Present Value*, $	865477
Simple Payback, year	1.6
Internal Rate of Return, %	100
Life Cycle Payback**, year	1.0

* Life cycle present value cumulative cash flow.

** Years needed to achieve positive present value cumulative cash flow.

Figure 52. Economic Analysis Input/Output User Interface

Output results can be displayed printed in multiple formats of graphical and tabular reports (Figure 53). Figure 54 shows an example chart showing the dynamic change in compressor power with time.



● Cascade Pressure

X Axis: Start from 0 Mins. End at 150 Mins.

Y Axis: ☑ Automatic Scale

● Summary

Number of vehicles fueled to the rated capacity: 164
All vehicles can not be continuously fueled. Cascade depleted!
- Cascade depleted at 03:15:34. Vehicles after the depeletion in this hour can not be fueled. Cascade will

Figure 53. Output/Charting User Interface

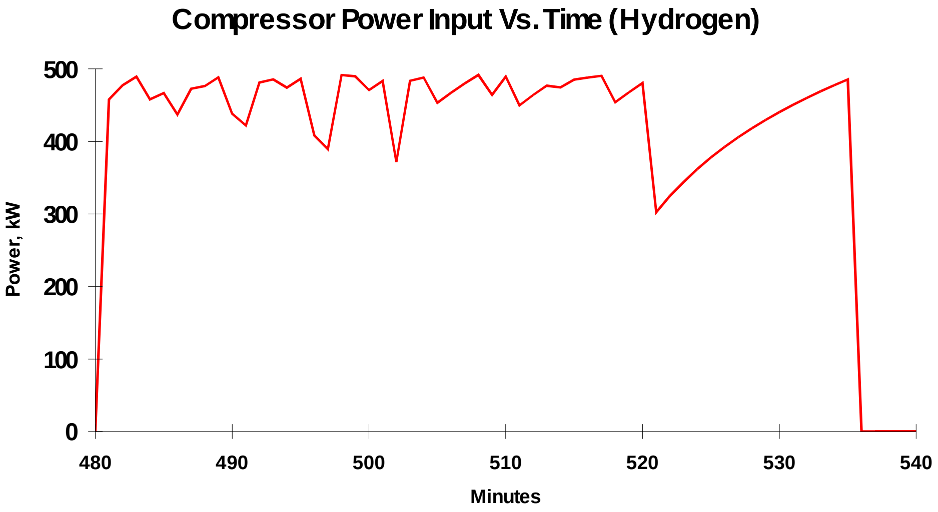


Figure 54: Compressor Power Timeline

Demand Profiles and the Impact of Compressor-Storage Sizing

Using the CASCADE program, a series of comparisons were made to determine the performance attributes of various choices of compression and storage needed to meet three distinct demand profiles (as shown in Figure 55). Each of these profiles had an equivalent daily demand of 1200 kg, but with differences in the hourly demand. Profile 1 is based on data for a gasoline station located in a residential setting, Profile 2 is based on a fleet-orient CNG station, and Profile 3 was derived from the H2A model.

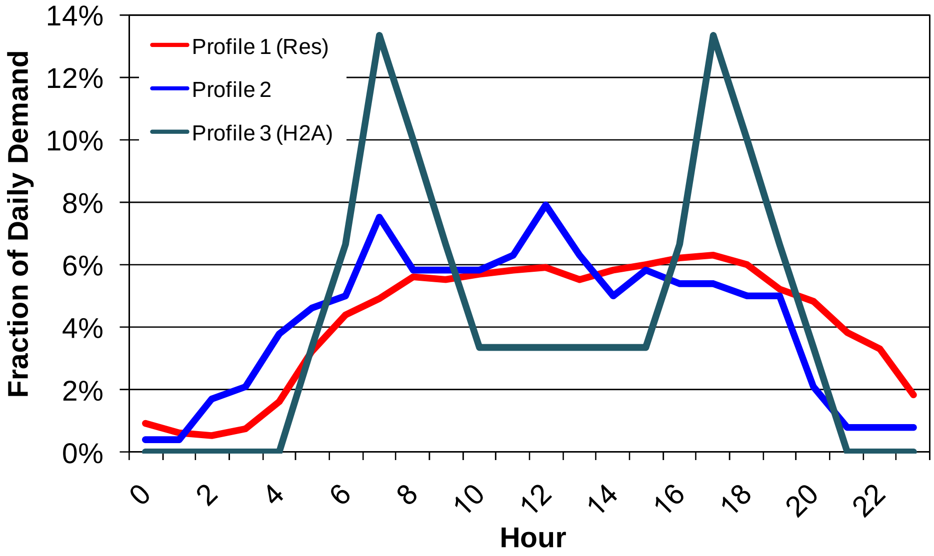


Figure 55: Fuel Demand Profiles

A series of relationships were used, going from a maximum compressor/minimum storage association towards a minimum compressor/maximum storage relationship for each profile (Table 4). The compressor is rated at 20 psig suction and 7500 psig discharge pressure.

Table 4: Compressor-Storage Results

Demand	Ambient	Min. Comp.	Cascade Ban	Cascade Bank Volume		
Profile	Temp	Rating*	Bank 1	Bank 2	Bank3	Total
	F	scfm	cu. ft.	cu. ft.	cu. ft.	cu.ft
Profile 1	59	800	10	0	0	10
	59	685	15	10	5	30
	59	500	30	20	10	60
	59	450	60	40	20	120
Profile 2	59	900	10	0	0	10
	59	700	30	20	10	60
	59	500	60	40	20	120
Profile 3	59	1350	30	20	10	60
	59	875	60	40	20	120
	59	785	90	60	30	180
	59	520	180	120	60	360

The minimum compressor rating of 450 scfm (with 120 ft^3 of storage) is achieved for the flat demand requirements of Profile 1, followed by an incrementally higher compressor needed to satisfy Profile 2 (500 scfm with 120 ft^3 of storage). Profile 3, with the very high peaks lasting over several hours, requires a larger compressor (520 scfm) but also requires a substantially larger amount of storage (360 ft^3). Profile 3 can be met with a more modest 120 ft^3 of storage, but with a much larger compressor size of 875 scfm. This comparison highlights the substantial sensitivity of hydrogen station sizing to the fuel demand profile. In particular, intraday peak demand periods of one to two hours will set the overall station capacity requirement.

Investing to meet a substantial peak like that shown in Profile 3 will drive up the compressor and storage cost in a meaningful fashion – while driving down utilization rates during off-peak periods. This can substantially impact overall station economics.

Investment Cost Comparison

Representative capital cost factors of $4500/kg-hr for larger compressors and $786/$ft^3$ of storage were used to develop a total capital cost for compression and storage for each scenario. Figure 56 reveals how the fuel demand profile can impact first cost. Note the bar labeled Profile 3-120 (this is the H2A profile with a 875 scfm compressor) and Profile 1-120 (with a 450 scfm compressor). Each of these are sized to delivery 1200 kg/day to meet their respective demand profiles. However, capital costs are nearly doubled to meet the challenging peak demand exhibited in Profile 3 (using the same amount of storage).

For the high peak demand scenario in Profile 3, further investment in storage can reduce the compressor capital cost (significantly) and the total investment moderately. Given that the operating costs are going to be lower with a smaller compressor, it would be prudent to add storage to meet the peak demand period. In this respect, an investment in 360 ft^3 of storage and a 520 scfm compressor would be a more cost-effective approach.

Note that this figure also contains a horizontal line showing the minimum compression required to meet this demand. This line signifies the smallest compressor size that would produce 1200 kg per day running for 24 hours (100% utilization). This is an idealized line that represents the minimum investment in compression capacity.

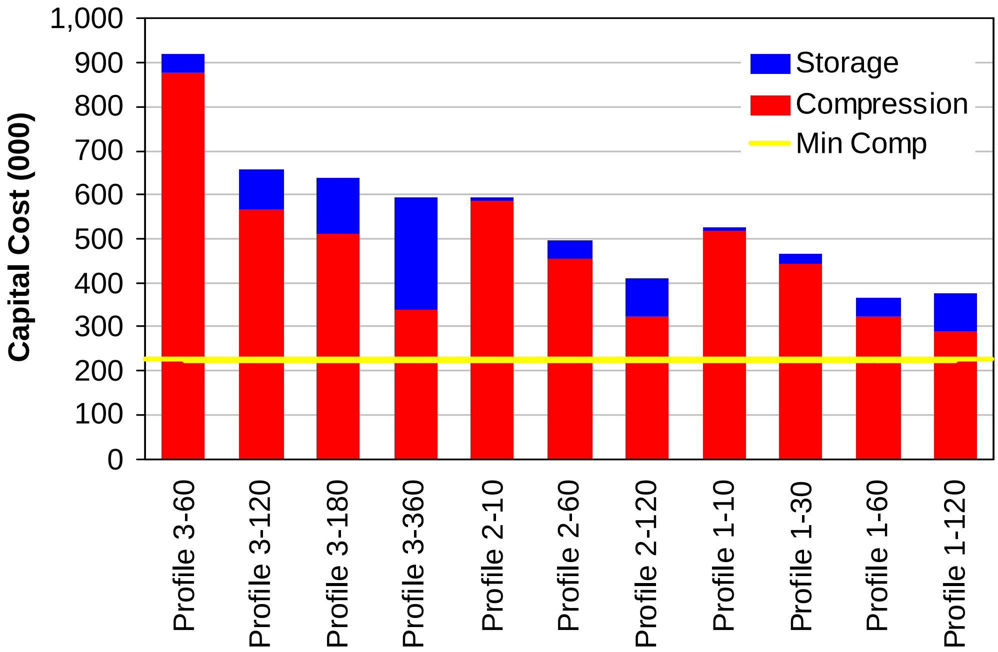


Figure 56: Compressor-Storage Cost Impacts

An important feature of this figure is the benefit of adding storage. This can provide a total capital cost benefit (and likely an operating cost benefit) – but this trend has a leveling off point. As shown in the Profile 1-120, adding storage can at some point just increase cost without adding any apparent benefit (holding the demand profile constant). Profile 1-60 is suitable for meeting the demand profile and the increment of additional storage going to the Profile 1-120 – while slightly reducing compressor capital cost – has a net increase in the total investment. Further investments in storage would continue to add to the total cost – indicating there is a minimum investment somewhere in the region of 60 ft^3 of storage for this demand profile.

Impact on Compressor Utilization

As discussed, it is important to look at the capital cost trade-offs as well as the operational efficiencies that result from a sizing decision. As illustrated in Table 5, adding storage has the benefit of reducing the size of the compressor while also increasing compressor on-time. Improved compressor on-time is a more cost-effective use of this investment[7]. It also has follow-on benefits by reducing the maximum connected power for the compressor – thus lowering monthly electric demand charges. As shown, by using storage effectively the compressor on-time can be increased substantially.

---

[7] The use of variable-speed drives and more sophisticated station demand and control models can also be used to increase compressor operating hours. This is often more efficient than frequently starting and stopping compressors.

Table 5: Impact Of Compressor-Storage Sizing On Compressor Utilization

Profile	Comp. Size scfm	On Minutes	Comp. Utilization
Profile 1-10	800	535	37.2%
Profile 1-30	685	681	47.3%
Profile 1-60	500	942	65.4%
Profile 1-120	450	1056	73.3%
Profile 2-10	900	486	33.8%
Profile 2-60	700	671	46.6%
Profile 2-120	500	950	66.0%
Profile 3-60	1350	338	23.5%
Profile 3-120	875	544	37.8%
Profile 3-180	785	606	42.1%
Profile 3-360	520	916	63.6%

Vehicle Fill Time Performance

Another factor to assess is hydrogen station performance. A couple of key station performance metrics are: (1) vehicle fill time and (2) completeness of fill[8]. Within this effort, we analyzed vehicle filling times on a dynamic basis for each scenario. The rate of transfer for hydrogen when filling a vehicle will be a function of the amount of gas stored in the cascade and its pressure level. In practice, the vehicle fill time – even if all vehicles required exactly the same amount of fuel – will vary depending upon the specific operating state of each of the individual cascade storage banks at that point in time of the vehicle fueling event.

The data in Table 6 provide evidence of the benefit of storage in terms of decreasing the time required to complete a fill. Compared to scenarios with large compressors and small storage, systems with larger amounts of storage tended to reduce the mean fill time while also generally reducing variability in the fill time (as indicated by the reduction in the standard deviation).

Table 6: Impact of Storage On Vehicle Fill Time (seconds)

Profile Scenario	Mean	Minimum	Maximum	Standard Deviation
Profile 2-10	243	116	312	34
Profile 2-60	136	102	234	22
Profile 2-120	144	95	215	24
Profile 1-10	264	129	271	28
Profile 1-30	173	130	331	42
Profile 1-60	149	110	185	19
Profile 1-120	145	96	184	20

---

[8] GTI has a patented hydrogen dispenser algorithm that targets achieving 100 percent fills on a mass density basis to compensate for the temperature rise during hydrogen filling.

Figure 57 and Figure 58 show time fill histograms for each of the fuel demand profiles with the different compressor-storage combinations modeled for each. These figures highlight the natural variability in fueling times that do occur. The addition of storage generally shortens the scenario fill times. One clear point is that fueling systems dominated by a large compressor and a small amount of storage (shown in blue in each chart) have considerably longer average fill times. These systems have a dominate mode value that correlates with the compressor output capacity.

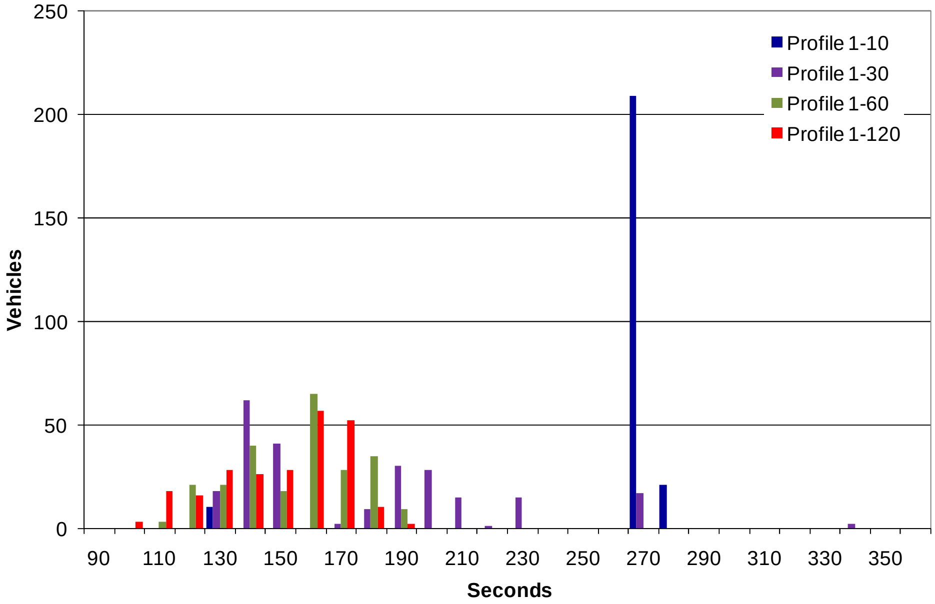


Figure 57: Profile 1 Vehicle Fill Time Histogram

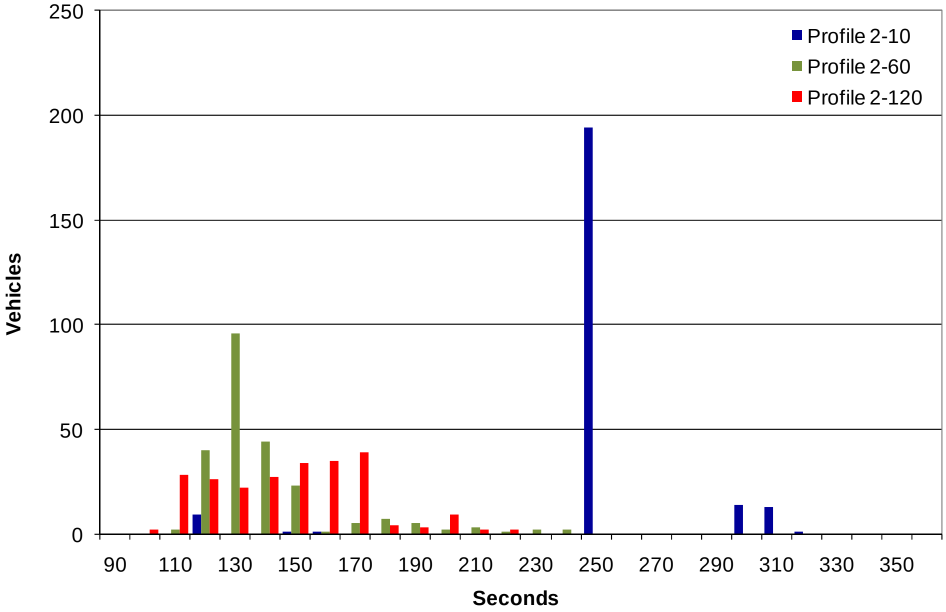


Figure 58: Profile 2 Vehicle Fill Time Histogram

Compressor Power and Energy

The new version of CASCADE enables a dynamic tracking of compressor power with time. Table 7 shows the maximum, average, and minimum power (in kW) for each of the scenarios that were analyzed. A couple of features that stand out are connected to Profile 3 (those with the greater peak demand requirements). The maximum power to meet this demand profile is greater and there is a larger differential between the maximum and minimum kW requirement.

Table 7: Compressor Power Statistics

Profile	scfm	Max kW	Avg kW	Min kW
Profile 1-10	800	786	718	674
Profile 1-30	685	673	616	567
Profile 1-60	500	492	431	302
Profile 1-120	450	443	385	270
Profile 2-10	900	885	811	747
Profile 2-60	700	687	640	517
Profile 2-120	500	492	431	302
Profile 3-60	1350	1328	1251	984
Profile 3-120	875	861	804	474
Profile 3-180	785	772	720	433
Profile 3-360	520	511	472	276

Figure 59 provides an interesting comparison of the compressor power requirements with individual cascade bank pressure levels. The varying power requirements on the compressor correlate with the upstream cascade pressures. Upward trends in power indicate a higher level of pressure in a bank over time as the compressor is filling that bank. Rapid changes in power indicate a shift in filling one cascade bank to the next. The final long duration increase in power starting around 520 minutes indicates the compressor is filling the low pressure bank from about 1500 psig to 7000 psig.

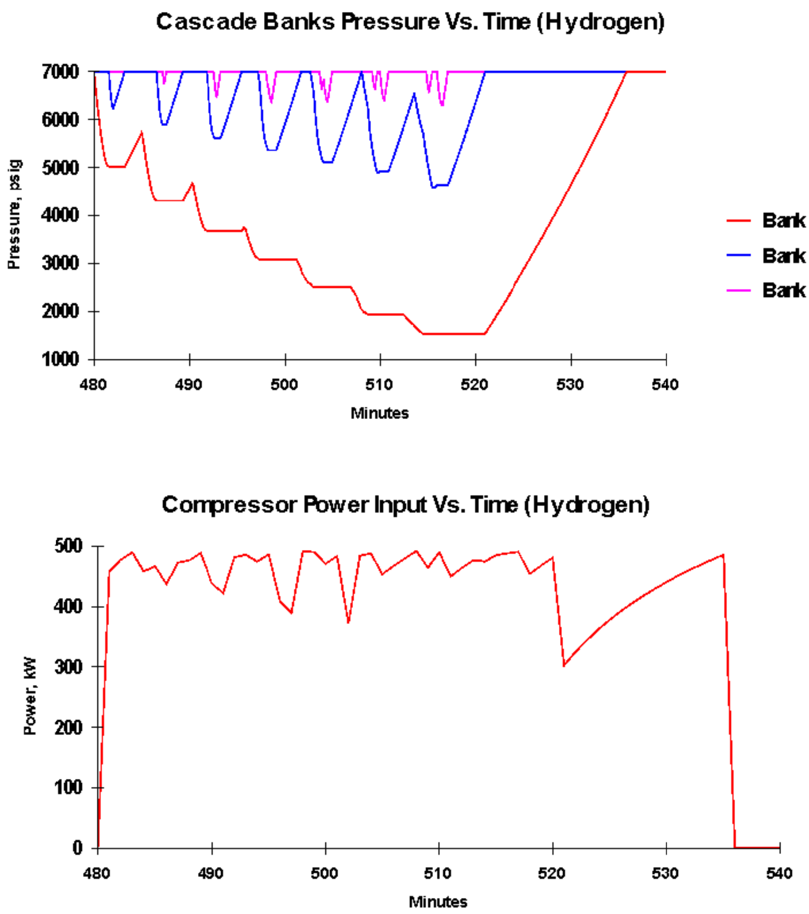


Figure 59: Dynamic Compressor Power Profile

Impact of Ambient Temperature

As noted in previous discussion, ambient temperature can have an influence on hydrogen fueling station operation and performance. This is due largely to the influence that temperature has on gas density. That is, at a given pressure, higher temperatures reduce gas density and conversely lower temperatures increase density.

Figure 60 provides an illustration of the impact elevated ambient temperatures can have on vehicle filling time. The higher 100^{o}F ambient temperature fills (shown in blue) show a shift toward longer fill times. On average, there was a twelve second increase in fill time. Importantly, the station was not able to fill two vehicles at the peak demand point during the day.

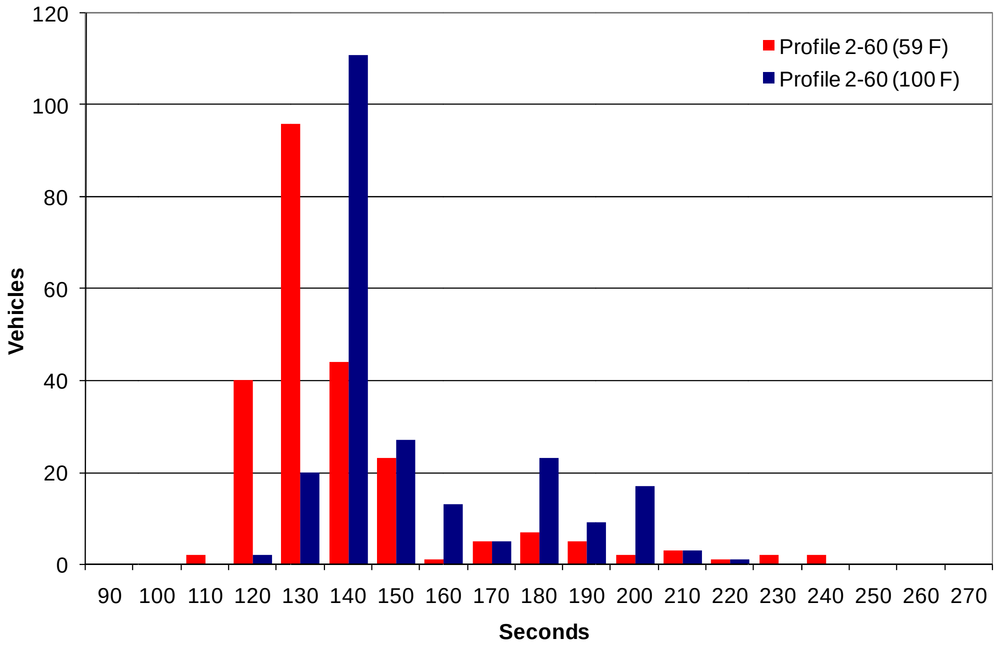


Figure 60: Impact of Elevated Ambient Temperature on Fill Time

Figure 61 shows the impact that ambient temperature can have on the minimum compressor requirements to meet demand Profile 2. At elevated ambient temperatures of 100°F, a 775 scfm compressor (compared to 700 scfm compressor at 59°F) to ensure the last two vehicles are filled during the peak period. At colder temperatures of 10°F, the compressor need only be sized at 525 scfm to meet the daily demand.

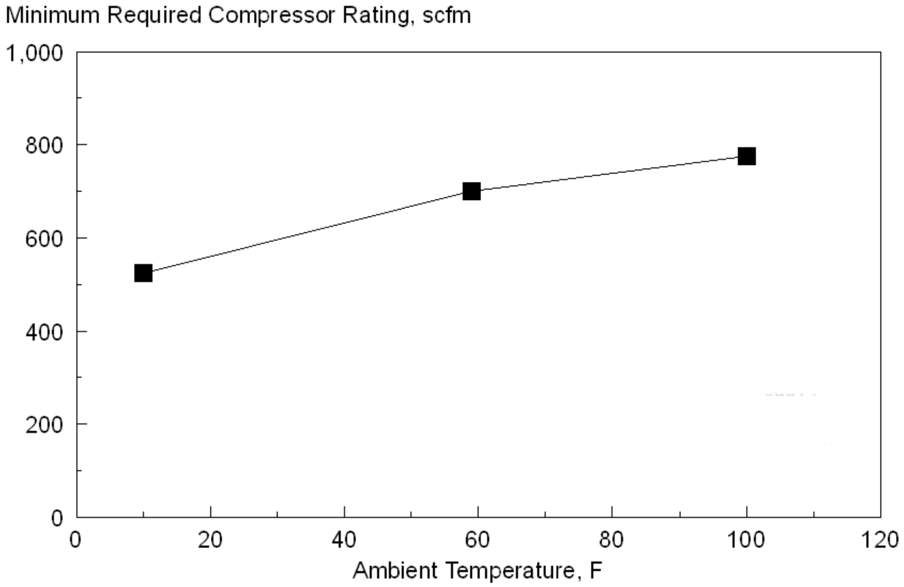


Figure 61: Impact of Ambient Temperature on Minimum Compressor Capacity

Booster Compressor Configuration Results

An area of interest in hydrogen stations are the potential benefits of booster compressors for aiding station fill performance and economics. These booster compressors can be sized to take, relatively speaking, low-pressure hydrogen from the cascade that otherwise may not be able to be used because it has such low pressure differential compared to the vehicle pressure. However, the gas pressure may still be at elevated levels such as 1000 to 5000 psig.

To illustrate, consider the three-bank cascade shown in Figure 62. At this point, this particular cascade is essentially “spent” and has limited ability to fill a vehicle. If a vehicle were to connect to this cascade with an initial pressure of 1000 psig, there would be virtually no gas transferred from the Bank 1, a modest amount from Bank 2 (with low flow rates due to the small pressure differential), and greater flow rates from Bank 3, but still low compared to if the Bank 3 pressure were over 6000 psig. In either case, because of the state of Bank 3 the vehicle cannot be completely filled. In this case, typically the completion of the fill would be done by directly charging from the compressor – which is typically a comparably low flow rate. The bottom line is a cascade in this situation has very poor fill time performance and is generally not going to completely fill the vehicle.

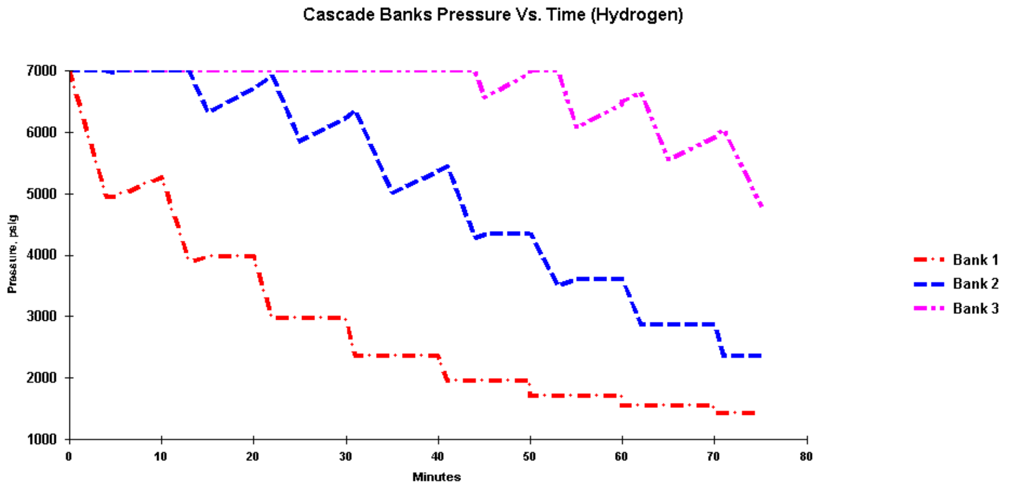


Figure 62: Hydrogen Cascade Fill Example

While the cascade pressures are relatively low, they are high compared to a station supply pressure of 100 psig. Taking hydrogen gas from, for example, 2000 psig to 5000 psig can be accomplished with less power, with a greater flow rate, and with a relatively compact compressor.

Figure 63 shows one example of how a booster compressor could be integrated into a hydrogen station. In this configuration, the control logic of the station could enable the inlet of the booster compressor to take gas from any of the three cascade banks. As shown previously in Figure 45, the compressor output will vary depending on the supply pressure to the booster compressor. This type of station configuration could provide improved ability to fill more vehicles, increased cascade utilization rates, and faster fills if the booster compressor capacity is sufficiently high to be able to transfer large amounts of hydrogen within a short time window (e.g., one to three minutes).

However, the addition of one more compressor to a hydrogen station does add capital, operating, and maintenance costs. Another booster concept that offsets the need for an additional compressor is shown in Figure 64. In this scheme, a split, two-stage main compressor is configured to be able to optionally take gas pressure from the cascade (flow path in blue) directly to the second-stage, high-pressure compressor. The discharge from this compressor stage (flow path in red) goes directly to the vehicle. A bypass from the outlet of the first-stage compressor goes to the hydrogen cascade and would normally only have sufficient pressure to fill the low-pressure (LP) cascade bank. This approach may have benefits if the gas going from the cascade to the second-stage compressor is sufficiently greater than the output pressure from the first-stage compressor. This would allow greater flow rates to the vehicle and speed up the completion of the fill process.

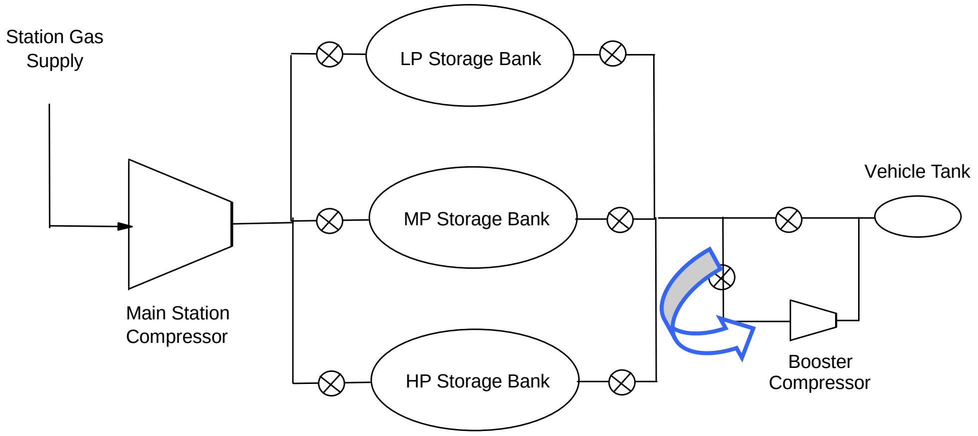


Figure 63: Main Compressor and Separate Booster Compressor

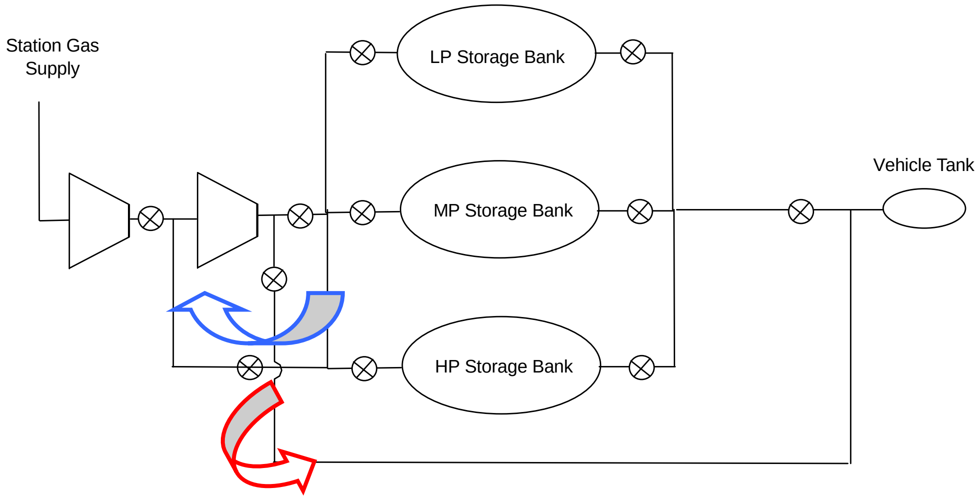


Figure 64: Split Two-Stage Compressor With Booster Capability

While the configuration in Figure 64 has the benefit of avoiding the cost of a second booster compressor, the downside is that there is no main compressor achieving a priority fill of the high-pressure cascade bank when it is in booster direct-fill mode. This is an important consideration because getting the high-pressure cascade bank up to high working pressure is generally a priority since it is the best option for ensuring the next vehicle that comes along can be quickly and completely filled. With electronic valving and controls, however, it is possible to operate this type of system where the second stage compressor – when it is not being used to directly fill a vehicle – could take gas from the medium pressure bank to help raise the pressure in the high bank while the first-stage compressor continues to fill the low-pressure bank (and other variations on this depending on the pressure levels in the cascades).

The GTI-developed CASCADE program does not presently have the programming enabled to account for the configurations and nuances that could be pursued by having a booster compressor interspersed between the cascade and the dispenser. Instead, a spreadsheet analytical technique was used to evaluate the peak one-hour performance of the above two configurations. Each scenario was tested by filling 15 vehicles using a two-dispenser station configuration.

Table 8 provides a summary of the results from this analysis. Using the configuration shown in Figure 63 with separate main and booster compressors, the station was able to fill the vehicles in a shorter period of time – just over 43 minutes compared to about 50 minutes for the base case. The alternative booster configuration (i.e., using the second stage compressor as a booster) also has a fill-time benefit, achieving fueling of the 15 vehicles in 44 minutes, but with less hydrogen in the cascade. This would increase the recovery time needed to rebuild the cascade pressure. The benefit of this option, though, is there is no incremental investment in compression.

Table 8: Booster Compressor Station Performance

Configuration	Main Compressor Capacity (scfm)	Booster Compressor Capacity (scfm)	Cascade Capacity At Start of Hour (scf)	Cascade Capacity At End of Hour (scf)	Total Vehicle Fill Time (min)
Base Case	520		39,248	35,634	50.5
Separate Main and Booster Compressors	520	1000	39,248	35,634	43.4
Booster Compressor is Last Stage of Main Compressor	520	1000	39,248	29,955	44.1

These results are also shown graphically in Figure 65.

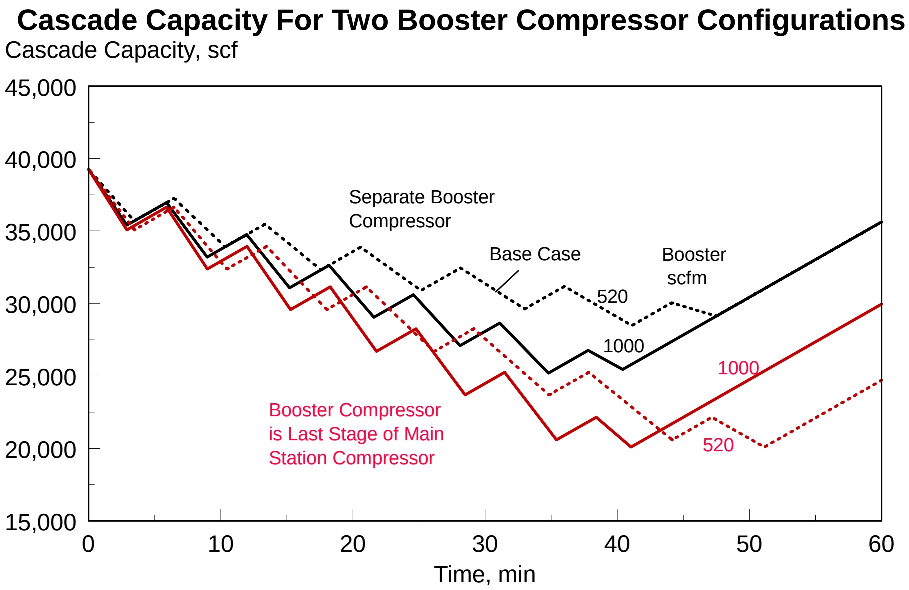


Figure 65: Booster Compressor Scenario Pressure Profile

A further analysis was done on the concept of using a separate main compressor and booster compressor (that is, two different compressors that can operate independently). Since this second compressor would require greater capital investment, the question to be addressed was whether less cascade storage could be required to offset the investment in a booster compressor. Table 9 provides a summary of the scenarios that were analyzed – including trade-offs in base case main compressor and cascade storage capacity.

Table 9: Booster Compressor – Cascade Storage Trade-off Analysis Parameters

Main Compressor Capacity (scfm)	Base Cascade Storage (scf)	Booster Compressor Capacity Options (scfm)
520	240	1040 and 1560
	180	
555		1110, 1665
	120	
635		1270, 1905

Figure 66 shows the overall results of this analysis. The lines in black correspond to a scenario with a 520 scfm compressor, the lines in green with a 555 scfm main compressor, and the lines in red with a 635 main compressor (with starting cascade storage as noted). There are many ways to view these data. One interpretation (❶) is to look at the improvement in fill time by using a booster compressor with the same amount of cascade capacity. In this case, a 1560 scfm booster compressor could reduce the peak time to fuel 15 vehicles by seven minutes. An alternative option is to look at having equivalent total fill performance, but identifying the potential to reduce cascade storage capacity (❷). In this case, adding a 1560 scfm booster compressor could achieve about a 25 percent reduction in storage cost.

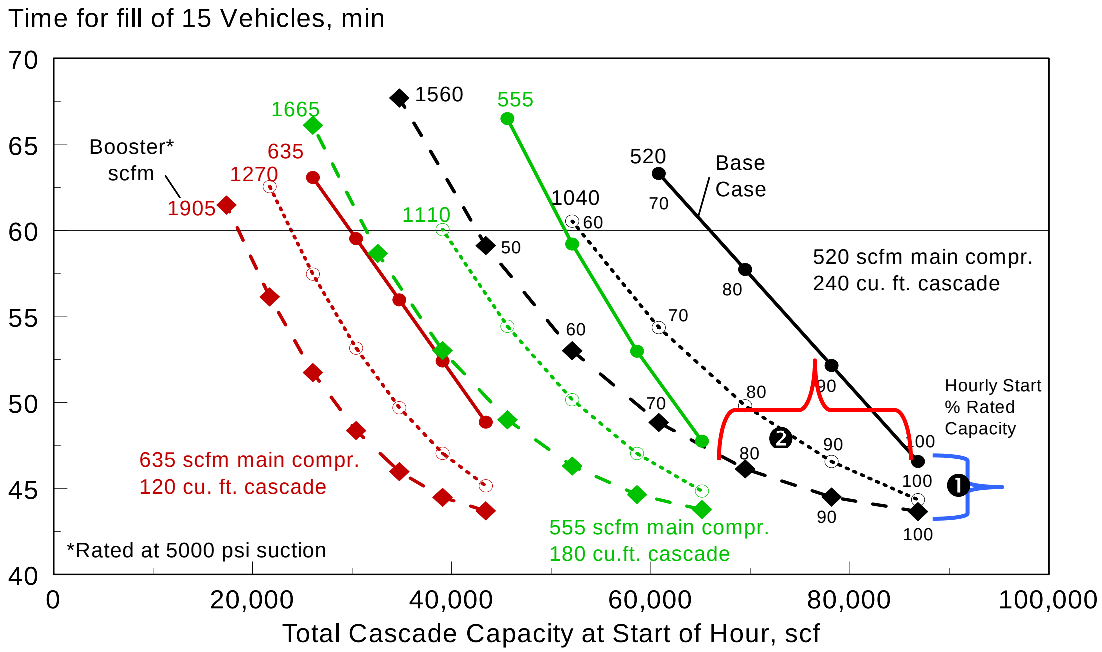


Figure 66: Booster Compressor – Cascade Storage Trade-offs

Generally speaking, from the previous analysis shown in Figure 56, system capital costs are more likely to be dominated by the investment in compression than storage. Presently, it would appear that adding a booster compressor has the potential for improving fueling station fill performance – but at a first cost premium. This configuration would also increase operating costs by increasing the total peak power requirement as well as maintenance costs by having two machines to maintain. From this analysis, it would appear that using a separate main and booster compressor would not be as cost-effective as having a more conventional main compressor and cascade storage configuration.

While this analysis does not positively support use of booster compressors, alternative high peak demand scenarios such as Profile 3 may indeed benefit from such devices. This scenario was not specifically analyzed in this program however.

In addition, there is a prospect for designing a purpose-built, high-pressure free piston or alternative approach that could be lower in cost and higher in performance. One example would be to have such a device that is solenoid driven as compared to using hydraulics. There may be a potential role for this type of product within a hydrogen fueling station – especially if vehicle systems move to higher pressure levels, opening up the potential for boosters to be "topping off" devices.

Summary and Recommendations

The development of high-pressure hydrogen fueling stations is progressing in the U.S. and throughout the world. Fueling station infrastructure developments are largely following a trend seen with compressed natural gas vehicles over the past two decades, with an emphasis placed on fast-fill stations that can fuel a vehicle in less than 5-10 minutes.

The design of a fast-fill hydrogen station will depend heavily on the type of daily demand profile that will occur. Station can use different approaches for high-pressure compression and storage to meet demand – with a focus needed on sizing the station to meet the most one to two hour demand window.

Different approaches to using storage can be considered, including the pressure level within the ground storage pressure vessels and the number of banks. Current analyses point to the use of storage as the most cost-effective means for satisfying peak demand requirements.

In sizing compressed gas stations, it is important to consider other factors that can influence overall fueling performance, average vehicle fill times, and completeness of fill. Gas temperature is one of these real-world considerations. Higher ambient temperature conditions will decrease station compressor capacity—that is, will result in a derating of daily delivery rates. The fast-fill hydrogen temperature rise that occurs when filling vehicles rapidly will also act to decrease the usable amount of gas stored in ground storage. Designers should factor in these considerations when evaluating a station sizing and configuration.

The concept of using booster compressors may be a viable option for improving hydrogen fueling station performance and average fill times. This would appear – at least for installations where a separate booster compressor is used – to be more expensive in many cases than adding storage. This, however, should not rule out the role of booster compressors as a viable component of a hydrogen fueling station. Stations with high peak demand may indeed be more cost-effectively designed with such a device. Also, the notion of having using a high-pressure stage of a two-stage compressor for sporadic booster operation may also be viable under certain demand situations.

GTI would also recommend DOE consider the potential for a purpose-built high-pressure hydrogen booster compressor that could provide a low-cost “topping off” capability. One approach could be based on a solenoid-driven, free-piston compressor or similar approach that could potential be sufficiently simple to achieve a low cost point.

There is also a need to explore the potential for reducing the cost of larger hydrogen compressors in the size range of 300 to 2000 scfm. This would position technology down the road for use in larger transit bus refueling operations as well as large public access fueling stations.

While only touched on briefly, there is market interest in a small refueling appliance that could be used either for home vehicle refueling or for specialty vehicles such as industrial lift trucks.

There are positive trends in composite pressure vessels, making them increasingly more attractive to use for ground storage. These high-pressure storage vessels may warrant further investigation for their application for underground storage or aboveground storage integrated into fueling station structures such as canopies or convenience stores. This may be important for urban areas with limited real estate.

Further research may also be warranted to develop intelligent station controls and operating procedures that could improve overall station performance and economics.