

# **SIZING AND OPERATING CONSIDERATIONS FOR NATURAL GAS AND HYDROGEN FUELING SYSTEMS**

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## **ABSTRACT**

The ability of a gaseous refueling station to deliver fuel to a vehicle is uniquely different than fueling with liquid fuels. For gaseous fuels, fast-fill station sizing and delivery capacity is influenced by a variety of factors such as fleet size, vehicle-filling dispersion throughout the day, vehicle fuel capacity, compressor size, and cascade storage capacity.

Cascade storage systems are commonly used in gaseous fueling stations to balance investment in compressors. The gaseous fuel station designer strives to match cascade storage and compression capacity to satisfy peak fuel demand. Satisfaction of this objective is constrained, however, by the need to keep up-front capital costs low while also minimizing system operational and maintenance costs.

This paper highlights work by Gas Technology Institute (GTI) to develop information and tools—such as the CASCADE™ station-sizing program—to allow designers, developers, and fleet operators to better understand the operation of natural gas and hydrogen fuel stations under a variety of scenarios. The paper highlights principles for cascade system operation and key gaseous fueling station design decisions.

## **INTRODUCTION**

During the past two decades, there has been growth in the U.S. and internationally in the application of natural gas as an alternative to gasoline and diesel-powered vehicles. In recent years, interest has also been expanding in looking at the potential for hydrogen fuel cell vehicles as the ultimate low-emission vehicle.

Liquid fuels are popular in transportation applications for obvious reasons: energy storage density. Liquid fuels have much greater energy density than gaseous fuels or other forms of storage like batteries or flywheels. Unlike gasoline or diesel, natural gas or hydrogen are gases at ambient temperature and can only be converted to a liquid at cryogenic conditions. For natural gas, liquefied natural gas (LNG) is normally at  $-240^{\circ}\text{F}$  ( $-151^{\circ}\text{C}$ ) while liquid hydrogen ( $\text{LH}_2$ )

exists at  $-423^{\circ}\text{F}$  ( $-253^{\circ}\text{C}$ ). LNG is making some in-roads in the U.S., but still is a small portion of the market<sup>1</sup>. Liquid hydrogen, or  $\text{LH}_2$ , is being evaluated as a transportation fuel<sup>2</sup>.

As a practical matter, nearly all NGVs use high-pressure natural gas storage. While this may not represent a technically optimal solution (in terms of energy storage density), high-pressure gas storage is a practicable method of increasing the energy density of natural gas to a level that can meet vehicle customer needs. Typical NGV storage pressures are either 3000 psig (200 bar) or 3600 psig (250 bar)—the latter is mainly in the U.S.

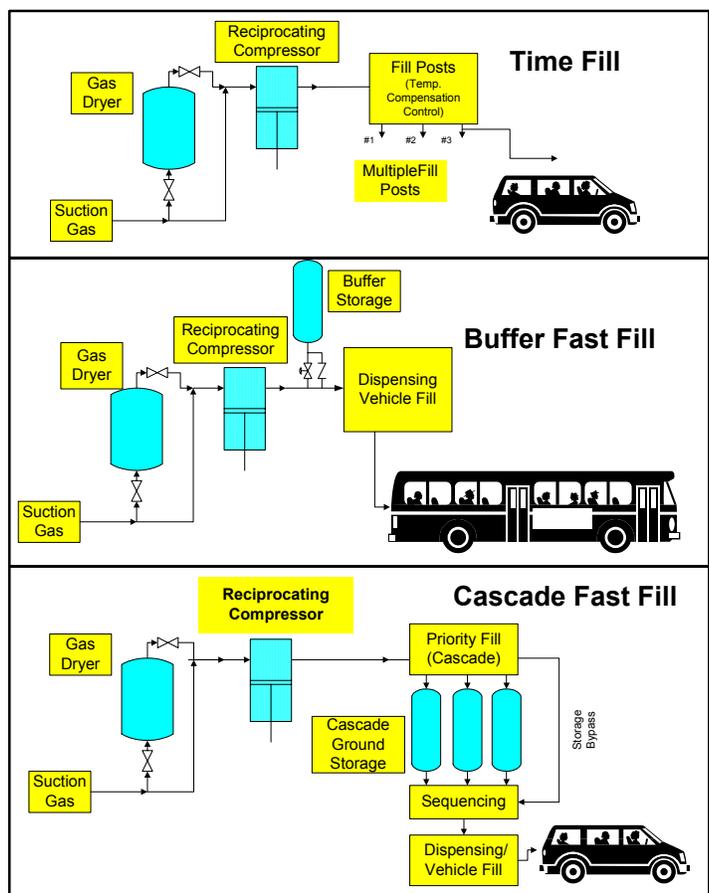
Hydrogen is still in its infancy, with uncertainty on standardization of pressure levels. There is growing interim consensus around 5000 psig (345 bar). Time and experience—similar to the two-decade evolution of NGVs—will help shape hydrogen vehicle industry practice.

There are several pathways for making high-pressure gas, including:

- TIME FILL – compressors provide overnight filling of vehicle(s).
- BUFFER FILL – compressors are coupled with a single-bank storage system for continuously fast filling vehicles<sup>3</sup>.
- CASCADE FILL – compressors are coupled with multi-bank cascade storage systems for fast filling vehicles.

Figure 1 is a depiction of these approaches. Generally speaking, system complexity increases from time fill, to buffer fill, to cascade fill system operation.

The sizing of a time-fill system is simple. The designer makes assumptions about the time that vehicles will be hooked up to the operating compressor (Operating Hours) and the amount of fuel required for all vehicles that are connected (Fuel, scf). The size of the compressor is easily found:



**Figure 1: Gaseous Fuel Station Approaches**

<sup>1</sup> Approximately two percent of the NGVs in the U.S. are LNG vehicles. Most are heavy-duty vehicles such as transit buses, refuse trucks, and Class 8 trucks.

<sup>2</sup> Some vehicle manufacturers are investigating  $\text{LH}_2$  storage; most notable is BMW with their hydrogen engine 7 Series and Mini vehicle prototypes.

<sup>3</sup> Fast fill in this paper means less than five minutes, or generally comparable to liquid refueling times.

$$\text{Compressor Size (scfm)} = \frac{\text{Fuel (scf)}}{[\text{Operating Hours} * 60 \text{ (min./hour)}]}$$

For example, assume a need to supply 100 gasoline gallon equivalent (gge<sup>4</sup>) to multiple vehicles being fueled overnight (for example, for ten hours):

$$\text{Compressor Size (scfm)} = 100 * 124 / [10 * 60] = 20.7 \text{ scfm}$$

This requires about a 20 to 25 scfm natural gas compressor. For hydrogen, this value would be about 69 scfm (found by replacing 124 with 416 in the above equation). Compressor utilization—a key economic consideration—may be up to 40 percent in a time fill system (operating hours divided by total hours, e.g., 10/24). The annual utilization number may be lower depending on differences between weekday and weekend fueling patterns.

## **GASEOUS GROUND STORAGE SYSTEMS**

Fast-fill systems for gaseous fueling stations are 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 against customer demand. Over sizing production capacity can result in inefficient operation (e.g., frequent system starts and stops) or excessive inventory and warehousing expenses. Under sizing can result in long delays in delivery of product to fill orders and dissatisfied customers.

To help in properly balancing production capacity (i.e., compressor size) and inventory (i.e., high-pressure ground storage<sup>5</sup>) in a gaseous fueling station, GTI developed the CASCADE sizing program. This program simulates vehicle fleet fueling, taking into account the characteristics of vehicles to be fueled and key fueling station attributes such as compression capacity, ground storage, number of dispensers, fueling pattern, and ambient conditions.

The issue of fueling pattern is an important consideration. As noted in the GRI CNG Transit Fueling Station Handbook, three of the common fueling patterns include:

- 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.

### **Buffer Storage Concept**

Buffer fill systems use a single bank of storage. This concept is used in fleets where vehicles are constantly fueled in succession—as is often done in the transit bus industry. Common practice in this industry is to line up returning vehicles for sequential fueling and cleaning on a nearly

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<sup>4</sup> A gasoline gallon equivalent for natural gas is about 124 scf/gallon. For hydrogen, this conversion factor is about 416 scf/gallon. These numbers will vary depending on the specific fuel composition.

<sup>5</sup> Ground storage is a term used to define the use of ASME or DOT high-pressure storage vessels at the fueling station.

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.

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

1. Bus pulls into fueling bay.
2. Fueller 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 in such a manner 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 rapid vehicle filling and a pattern in the change of buffer storage pressure (i.e., periodicity). Since the total time for the buffer filling of all buses may be four to six hours in total, compressor utilization rates in these systems tend to be low (e.g., 10 to 20 percent).

The results show that for the buffer volume and compressor size selected, the station should have sufficient capacity to repetitiously fuel the bus fleet.

### **Cascade Storage Concept**

The most common approach for gaseous fuel station storage is the cascade system. This typically entails three segments of storage that hold high-pressure gas. Each of these banks can be independently filled or discharged. Figure 2 shows a typical three-vessel, three-bank cascade storage system using large ASME pressure vessels. On each side of this cascade are control panels that designate which of the three banks are filled first (priority fill panel) and which will be drawn from first to fill the vehicle (sequencing panel).



**Figure 2: Three Bank Cascade With ASME Vessels**

The term “bank” is used to designate a segmented amount of high-pressure gas that can be controlled for priority fill or sequencing. The number of pressure vessels may differ from the number of banks by manifolding several individual pressure vessels together so they behave as one integrated unit. Figure 3 shows an example of a small NGV fast-fill station that uses a bundle of DOT bottles grouped into three banks by high-pressure tubing. In the background is a small compressor and to the right is a fuel dispenser.



**Figure 3: Three Bank Cascade With Multiple DOT Vessels**

## **GASEOUS FUEL SYSTEM SIZING**

As noted, there are several considerations to keep in mind when sizing an NGV or hydrogen fueling system. Chief among these is customer demand. How much fuel is needed and when? The pattern by which vehicles will refuel at this type of station has tremendous influence on station sizing and economics. This is a direct result of the need for fixed investment in ground storage or larger compressors to satisfy periods of peak demand<sup>6</sup>. To understand the value of an

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<sup>6</sup> Peak demand problems are common in many industries, but not of much significance for liquid fuel stations.

investment in ground storage, it is important to quantify the amount of useful storage available for filling vehicles.

### Cascade Storage Utilization

Ground storage is the most cost-effective and common technique to address peak demand issues in an NGV or hydrogen fueling station. Common NGV industry practice is to use a three bank cascade. While this is accepted as an efficient number, there are no technical limitations to using other values such as one (as used in buffer systems), two, four, or five (or more). At issue are the marginal benefits of varying the number of banks against the cost (taking into account more valves and other parts and system controls) and convenience (e.g., time spent switching among banks during the fueling operation).

Increasing the number of banks has the primary benefit of increasing ground storage utilization efficiency<sup>7</sup>. Figure 4 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.

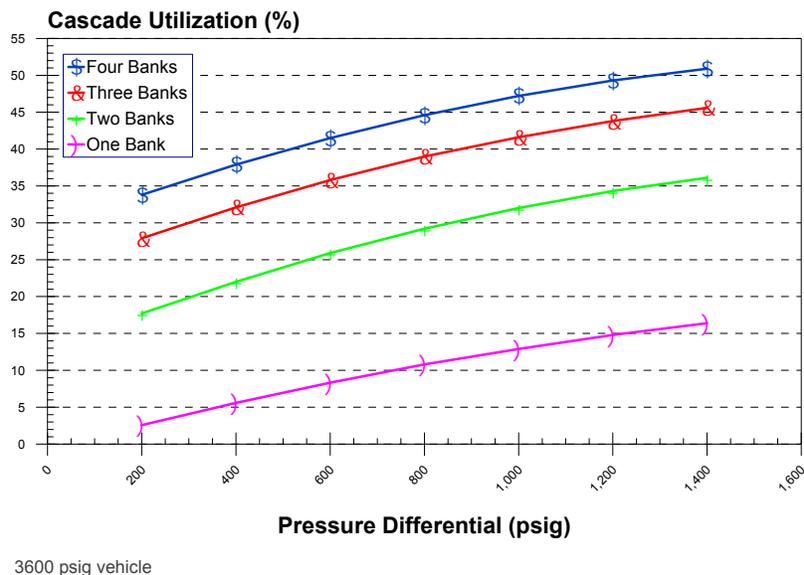


Figure 4: Cascade Utilization Rates

### Cascade Recovery Time

An important consideration in sizing this type of fueling system 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 the size of the compressor. The following shows this relationship:

<sup>7</sup> Ground storage systems can only work down to some minimum pressure level. Utilization efficiency measures the amount of gas that can fill vehicles divided by the total ground storage.

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

For example take a natural gas cascade of 14,800 scf, cascade utilization of 0.536, and compressor of 40 scfm. The recovery time is about 198 minutes. This would be appropriate for systems that may have peak demand in the morning, around lunch, and in the late afternoon.

### Fast-Fill Station Sizing Examples

To assist in the sizing of gaseous fueling systems, GTI developed the CASCADE Gaseous Fueling System Sizing Software. CASCADE allows for efficient characterization of fast-fill fueling operations using natural gas or hydrogen compressors and ground storage systems.

The CASCADE program 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. The user defines a prototypical vehicle profile and fleet composition, including on-board storage capacity, pressure, and number of vehicles along with fueling station attributes like compressor size, cascade storage size, number of banks, and number of dispensers. 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 fleet fueling process.

### Buffer Fill Example

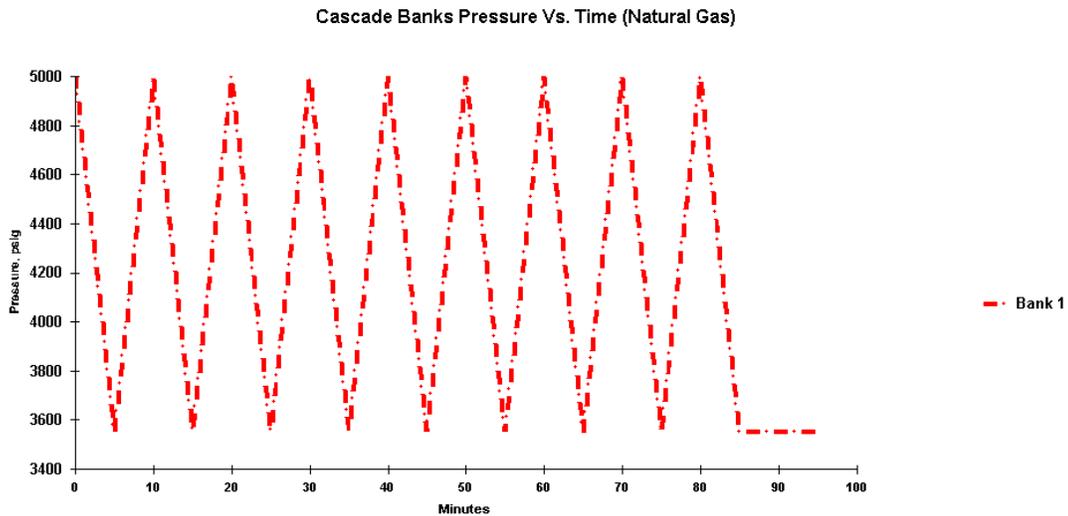
The following illustrates buffer fill system operation for a transit bus fleet. Figure 5 shows the input screen from CASCADE. The example is a 10-vehicle fleet with 30 ft<sup>3</sup> of storage at 3600 psig and driving range of 175 miles. The station is a buffer system with single 40-ft<sup>3</sup> bank at 5000 psig. The vehicle is filled in five minutes with five additional minutes for moving the vehicle out and pulling up the next vehicle (for a total cycle time of ten minutes). A subsequent screen defines the compressor size, which was set at 600 scfm for this example.

The screenshot shows the CASCADE software interface with the following settings:

- Fuel:** Natural Gas (selected), Methane, Hydrogen. Equivalency ratio: 124 scf/gge.
- Fleet/Vehicle Characteristics:**
  - Fleet Size: 10 vehicles/day
  - Vehicle Fuel Efficiency: 4 mpg
  - Daily Vehicle Route: 175 miles
  - Dual Fuel Operation?: NO
- Vehicle Storage/Refueling Characteristic:**
  - Total Storage Volume: 30 cu. ft. water volume
  - Max. Storage Pressure: 3600 psig @70 °F
  - Refueling Min. Diff. Pressure: 100 psi
- Ground Storage Characteristics:**
  - Number of Storage Banks: 1
  - Bank #1: 40
  - Bank Storage Volume: cu. ft. water volum
  - Bank Maximum Storage Pressure: psig 5000
- Fleet Refueling Characteristics:**
  - Maximum Allowable Refueling Time: 5 minutes/vehicle
  - Time for Switching Between Vehicles: 5 minutes
  - Refueling Operation Time: 4 hours per day
  - Number of Dispensers: 1
  - Run compressor during fueling?: YES
- Temperature:**
  - Vehicle Storage: 60 °F
  - Ground Storage: 60 °F

Figure 5: Buffer Example Input

Figure 6 shows the cycling of the buffer system as it subsequently discharges to fill the vehicle and is recharged by the compressor. The CASCADE software program has additional summary and detailed reports to permit more system analysis.



**Figure 6: Buffer Storage Pressure Profile**

Cascade Fill Example – Natural Gas

The following is an example for a fast fill NGV station. Figure 7 shows the input screen. The example covers a fleet of 45 vehicles with 7 ft<sup>3</sup> of storage on each vehicle at 3000 psig. There is a three-bank cascade with each bank having 14-ft<sup>3</sup> water volume rated at 5000 psig. The compressor in this example was sized at 40 scfm.

<b>CASCADE</b>												
File Next Help												
<b>Fuel</b> <input checked="" type="radio"/> Natural Gas <input type="radio"/> Methane <input type="radio"/> Hydrogen		Equivalency ratio: 124 scf/gge										
<b>Fleet/Vehicle Characteristics</b> Fleet Size: 45 vehicles/day Vehicle Fuel Efficiency: 15 mpg Daily Vehicle Route: 150 miles Dual Fuel Operation? NO		<b>Vehicle Storage/Refueling Characteristic</b> Total Storage Volume: 7 cu. ft. water volume Max. Storage Pressure: 3000 psig @70 °F Refueling Min. Diff. Pressure: 100 psi										
<b>Ground Storage Characteristics</b> Number of Storage Banks: 3 Bank Storage Volume: cu. ft. water volume Bank Maximum Storage Pressure: psig		<table border="1"> <tr> <th>Bank #1</th> <th>Bank #2</th> <th>Bank #3</th> </tr> <tr> <td>14</td> <td>14</td> <td>14</td> </tr> <tr> <td>5000</td> <td>5000</td> <td>5000</td> </tr> </table>		Bank #1	Bank #2	Bank #3	14	14	14	5000	5000	5000
Bank #1	Bank #2	Bank #3										
14	14	14										
5000	5000	5000										
<b>Fleet Refueling Characteristics</b> Maximum Allowable Refueling Time: 5 minutes/vehicle Time for Switching Between Vehicles: 5 minutes Refueling Operation Time: 20 hours per day Number of Dispensers: 1 Run compressor during fueling? YES		<b>Temperature</b> <b>Vehicle Storage</b> Temperature: 60 °F <b>Ground Storage</b> Temperature: 60 °F										

**Figure 7: Natural Gas Cascade Example Input**

Figure 8 shows the pressure profile of the three-bank cascade system. The first bank completely fills the first vehicle (and the compressor begins to run). Subsequent vehicles tap into the second bank and third banks. After 95 minutes, the cascade storage system is essentially exhausted as Bank 3 has dropped down to nearly 3000 psig. Cascade recovery time is about 198 minutes.

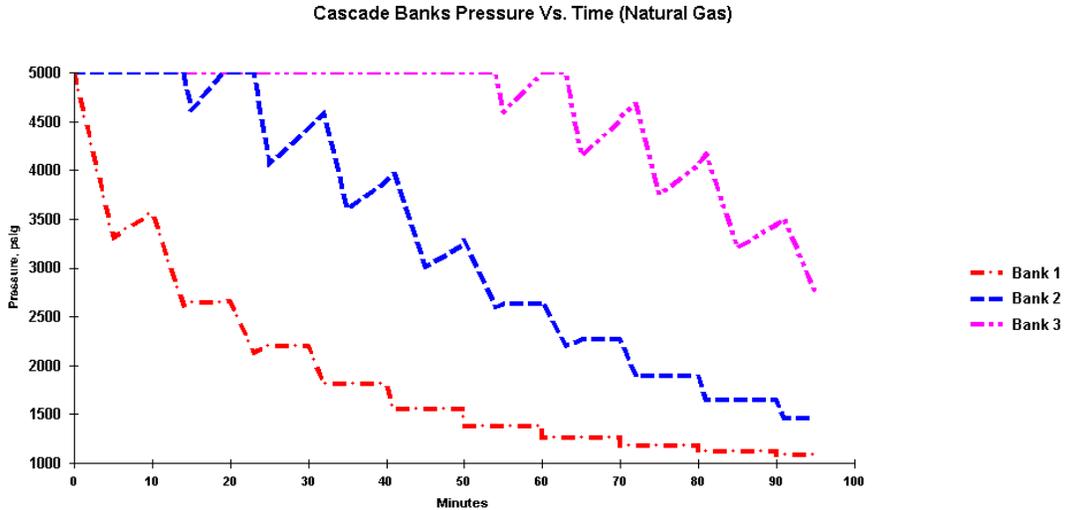


Figure 8: Cascade Storage Pressure Profile

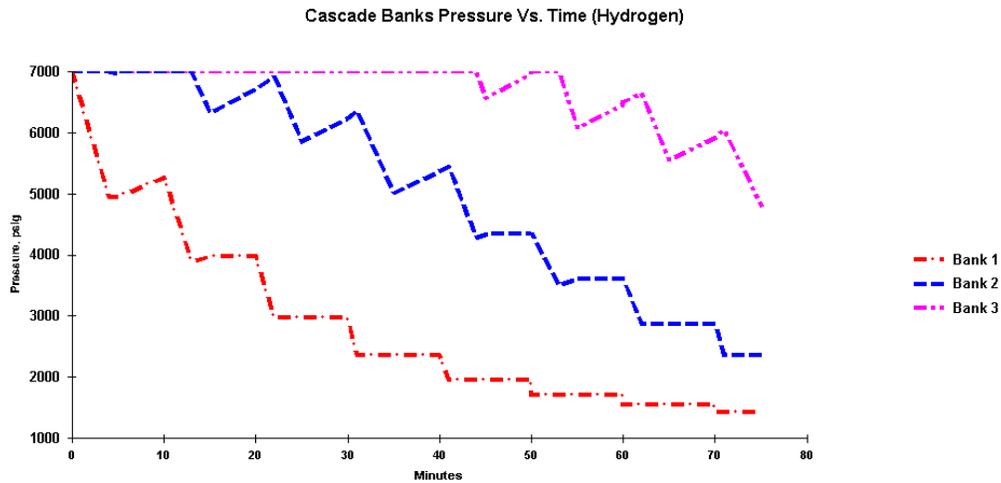
Cascade Fill Example – Hydrogen

This example uses similar input to the natural gas cascade system, but with hydrogen. Changes include nominal vehicle pressure of 5000 psig, cascade storage pressure of 7000 psig, and twice the fuel economy. Figure 9 shows the input values. The compressor size remains 40 scfm.

Category	Parameter	Value
Fuel	Fuel Type	Hydrogen
	Equivalency ratio	416 scf/gge
Fleet/Vehicle Characteristics	Fleet Size	45 vehicles/day
	Vehicle Fuel Efficiency	30 mpg
	Daily Vehicle Route	150 miles
	Dual Fuel Operation?	NO
Vehicle Storage/Refueling Characteristic	Total Storage Volume	7 cu. ft. water volume
	Max. Storage Pressure	5000 psig @70 °F
	Refueling Min. Diff. Pressure	100 psi
Ground Storage Characteristics	Number of Storage Banks	3
	Bank Storage Volume	14 cu. ft. water volum
	Bank Maximum Storage Pressure	7000 psig
Fleet Refueling Characteristics	Maximum Allowable Refueling Time	5 minutes/vehicle
	Time for Switching Between Vehicles	5 minutes
	Refueling Operation Time	20 hours per day
	Number of Dispensers	1
	Run compressor during fueling?	YES
Temperature	Vehicle Storage Temperature	60 °F
	Ground Storage Temperature	60 °F

Figure 9: Hydrogen Cascade Example Input

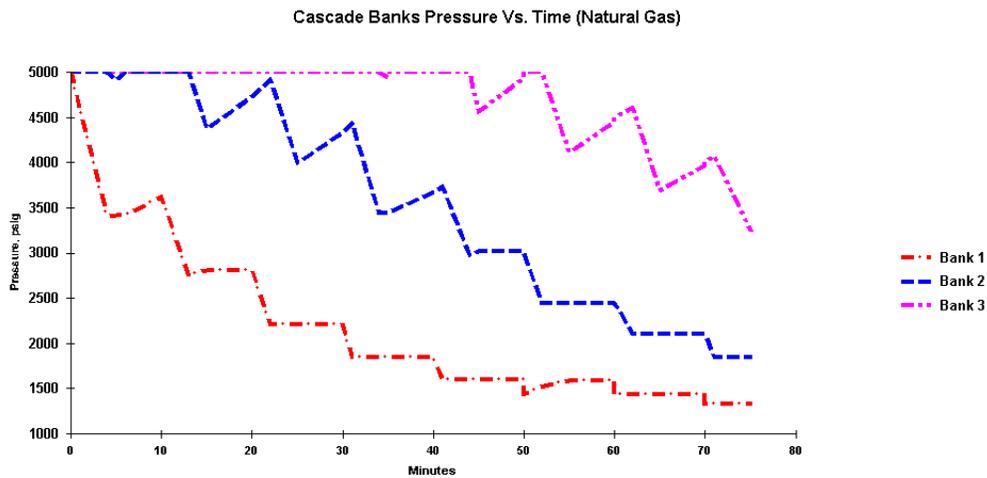
Figure 10 shows the operation of the hydrogen three-bank cascade. Unlike the natural gas example that was able to fuel 10 vehicles before depletion in 95 minutes, this example shows the hydrogen station can fuel about 8 vehicles in 75 minutes before the cascade is exhausted. The cascade recovery time in this example is 159 minutes (compared to 189 minutes).



**Figure 10: Hydrogen Cascade Fill Example**

**Impact of Ambient and Fast Fill Temperature Rise**

A factor that is often under-appreciated is the effect of ambient temperature as well as the temperature rise phenomenon that occurs during fast filling of natural gas or hydrogen vehicles. Figure 11 shows the prior natural gas cascade example with an ambient temperature of 100°F (rather than 60°F). At this temperature, the temperature-compensated fill pressure is 3,575 psig. This results in an earlier cascade depletion pressure. In this example, the station can fill about nine vehicles—not ten—during the peak period.



**Figure 11: Natural Gas Cascade Example at 100°F Ambient**

Similar derating of gaseous fuel system performance will also occur in systems that use pressure compensation to address temperature rise effects that occur during fast filling of natural gas or hydrogen vehicles. For example, the GTI-patented AccuFill system allows for more complete filling of vehicles through appropriate use of mass-based filling and pressure. AccuFill is a dispenser control algorithm based on a proprietary GTI-developed program called CHARGE that permits prediction of temperature rise effects using first-principle thermodynamic principles and extensive empirical test data. This has been developed for natural gas and is now being validated by GTI for hydrogen in a cooperative program with the U.S. Department of Energy.

### **Future CASCADE Enhancements**

Several software enhancements are planned to further expand the capabilities of the CASCADE program to simulate real-world gaseous fueling operations. In particular, GTI is modifying the program to:

- Expand the user's ability to define the vehicle-refueling pattern, using a more deterministic approach that permits a specified time of day for each fueling event for each vehicle.
- Expanded ability to define the fleet profile, including definition of a variety of vehicle types.
- Incorporation of optional temperature-rise effects to more accurately represent end of vehicle fill pressure and cascade utilization for both natural gas and hydrogen.

### **CONCLUSIONS**

There is growing interest in the U.S. and internationally in using gaseous-fueled vehicles powered by natural gas or hydrogen. High-pressure gas storage is the most common and practicable method of storing fuel on these vehicles.

Providing fuel to a natural gas or hydrogen vehicle on a fast-fill basis entails a more complicated fueling system than needed for liquid fuels. Fast fill NGV and H<sub>2</sub> fueling systems require an integrated approach to the design and operation of a compressor and ground storage system. Properly balancing these subsystems can help in managing up-front capital costs as well as ongoing operating and maintenance costs. Under or over designing either compression or ground storage can result in poor fuel station operation, customer dissatisfaction, and/or reduced economic returns.

To help in designing these stations, GTI developed the CASCADE software program (Version 2). This software tool permits efficient sizing and scenario analysis for fleet and public access fueling operations. Recent upgrades to this software include the provision of a hydrogen fueling option and other design enhancements. Development efforts are underway to further CASCADE to enable users to analyze a range of vehicle fueling patterns and vehicle types. In addition, modifications are underway to include "heat of compression" effects that occur when fast-filling a natural gas or hydrogen vehicle. This work builds on efforts by GTI to fully characterize this phenomenon on both fuels. A Version 3 release of CASCADE is planned in 2003.

## **ACKNOWLEDGEMENTS**

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More information about the CASCADE software program is available at [www.interenergysoftware.com](http://www.interenergysoftware.com).