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REFUELING STATIONS FOR NATURAL GAS VEHICLES

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FOR NATURAL GAS VEHICLES

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ABSTRACT

The unavailability of natural gas vehicle (NGV) refueling stations constitutes one of the major barriers to the wide spread utilization of natural gas in the transportation market. The purpose of this paper is to review and evaluate the current technical and economic status of compressed natural gas vehicle refueling stations and to identify the components or design features that offer the greatest potential for performance improvements and/or cost reductions. Both fast-fill- and slow-fill-type refueling systems will be discussed.

INTRODUCTION

Natural gas vehicle refueling stations differ significantly from their conventional liquid fuel counterparts. As opposed to the relatively simple task of storing a liquid fuel at near atmospheric pressure and pumping that liquid fuel to the vehicle, natural gas refueling stations must be able to take a relatively low pressure gas and compress that gas to high pressures for storage at the refueling station and/or on the vehicle. Older NGV refueling stations were typically designed to deliver gas for on-board storage applications up to 2400 psig. Newer refueling stations typically operate at pressures greater that 3600 psig to service vehicles with maximum on-board storage pressures of 3000 psig. Hundreds of these NGV refueling stations have already been constructed in North America, primarily by natural gas distribution utilities. A partial listing of refueling stations operated by utilities is presented in Table 1. A number of other private refueling stations are being operated by organizations such as bus fleets, the U.S. Post

Office, and delivery service operators such as Federal Fxpress and UPS. Large fleet operators are a particularly attractive and growing market for NGVs. In addition to fleet operators, traditional liquid fueling station operators such as Amoco, Unccal and Texaco have opened public NGV refueling stations in the U.S.

Table 1. Partial Listing of Refueling Stations Operated by Gas Utilities.

Refueling Station Operator	Number of Stations
Alabama Gas Corp.	5
Southwest Gas Corp.	4
Pacific Gas & Electric	14
KN Energy	10
Atlanta Gas Light Co.	12
Northern Illinois Gas Co.	5
People's Gas Light & Coke Co.	6
Northern Indiana Public Service Co.	23
Washington Gas Light Co.	3
Columbia Gas of Kentucky, Inc.	2
Minnegasco	8
Brooklyn Union Gas Co.	5
The East Ohio Gas Co.	12
Oklahoma Natural Gas Co.	9
Northwest Natural Gas Co.	4
The People's Natural Gas Co.	8
Philadelphia Electric Co.	3
Entex	4
Washington Natural Gas Co.	4
Wisconsin Gas Co.	10

REFUELING STATION CONFIGURATION

Typical NGV refueling stations consist of a compressor, ground (station) storage, and a dispenser. In actuality the NGV refueling station configuration will be dictated by the application. For instance, a refueling station for a large urban bus fleet will be configured and look substantially different from that of a small light duty vehicle fleet or a public refueling station. Components for an NGV refueling station include the compressor(s), drives (either electric motor or internal combustion gas engine), unloading tank, all piping, fittings, valves, gas conditioning, control elements, ground storage and the refueling dispenser. A more complete components list for a typical NGV refueling station is presented in Table 2. A typical medium duty refueling station layout is presented in Figure 1.[2]

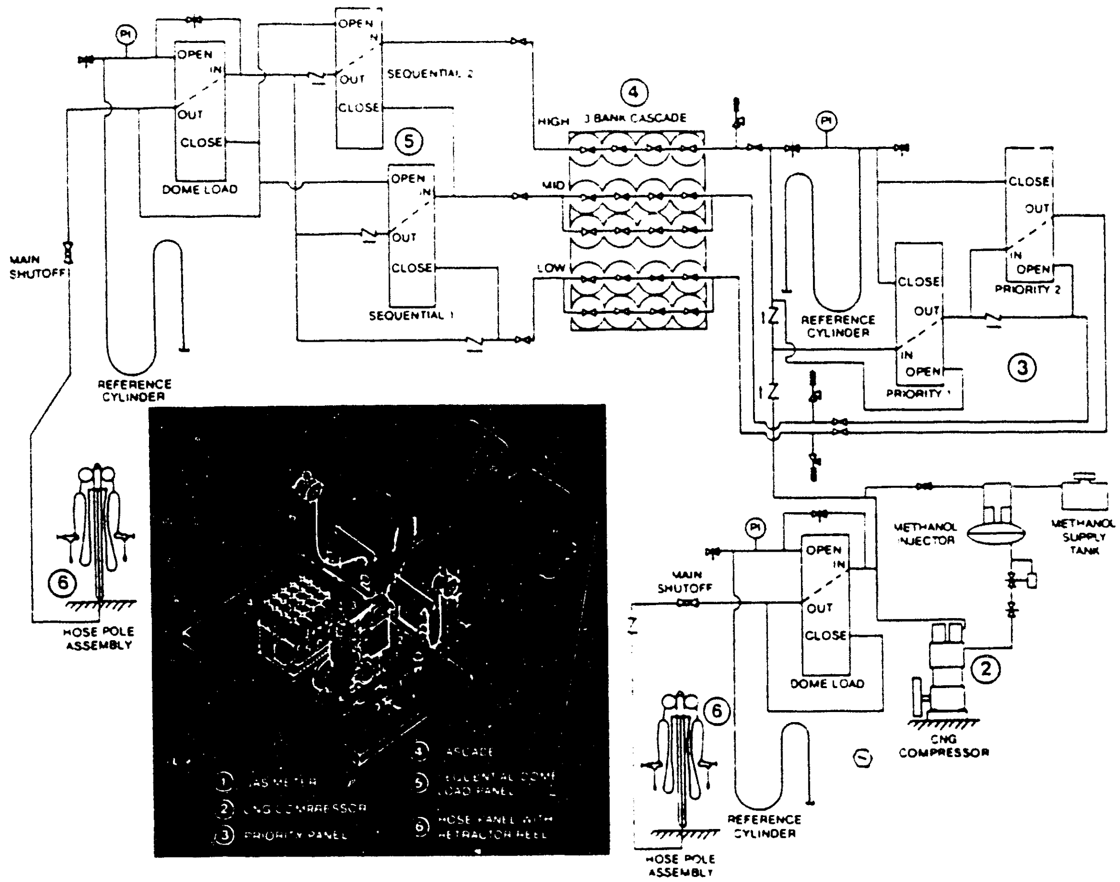

Figure 1. TYPICAL CNG REFUELING STATION LAYOUT

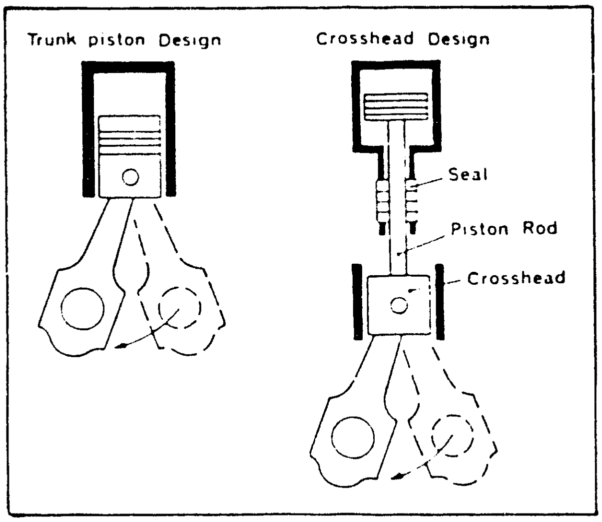

Figure 2. TRUNK PISTON AND CROSSHEAD DESIGN COMPRESSORS

Table 2. Typical NGV Refueling Station Components.

- Compressor(s)
- Drive(s), Electric or Gas IC Engine
- Fast-Fill Dispenser and Slow-Fill Dispensers
  - Fast-Fill Fully Metered
- Pipe, Valves & Fittings
- Ancillary vessels
- Instrumentation
- Electrical Interconnect
- Lightning / Static Protection
- Pressure Regulators (Dome Load)
- Storage Cascades (Both DOT and ASME)
- Flow Limiters
- Fire Detection System
- Electrical Requirements
  - General
  - Electric Equipment
  - Lighting & Appliance Panel
  - Compressor Motor
  - Control Panel
  - Annunciator Panel
  - Junction Boxes
  - Conduits
  - Conductors
  - Grounding
  - Lighting Fixtures

Design specifications requirements in the U.S. must also take into consideration all applicable codes and standards from organizations such as NFPA, DOT, ASME, ANSI, NEC, NEMA, and FM for refueling stations.

COMPRESSORS

Compressors are the largest single cost item in the refueling system. Compressors used for high pressure ratio service are almost exclusively of the reciprocating type. The basic reciprocating compressor is a single cylinder compressing gas on only one side of the piston, referred to as single-acting. Double-acting reciprocating compressors use both sides (strokes) of the piston to perform alternating compressions in the same cylinder per crankshaft revolution. Reciprocating compressors used for high pressure natural gas service can be defined further as crosshead or trunk-piston compressors. The trunk piston design, as shown in Figure 2, relies solely on the piston rings to prevent the escape of high pressure gas to the crankshaft/connecting rod casing. In a crosshead design as presented in Figure 2, a separate crosshead linked to the connecting rod is used with a piston rod linked to the piston.

This provides a straight-line motion to the piston rod and simplifies sealing. This arrangement minimizes the likelihood of combustible gas leakage to the crankshaft/connecting rod housing. Other design characteristics of reciprocating compressors include lubricated and non-lubricated designs, as well as air-cooled and water-cooled designs. At high output pressures (above 3000 psig) lubricated compressors are typically specified.

For reciprocating units designed for high pressure service, multiple stages are required. The compression ratio per stage is generally limited to 4, although small-sized units are designed with compression ratios of 8 or higher. Compressors designed for compressed natural gas service (< 3,600 psig) typically have 4 or 5 stages. In some machines, double-acting pistons are used in the first stages and single-acting in the higher pressure stages.

Compressors are also classified in terms of duty cycle. Typically, only moderate and heavy duty machines would be used for CNG refueling station service. Moderate duty machines are designed for reliable service over a reasonable service life where continuous, full-load, long-duration service is not required. Although moderate duty machines may be capable of operating under these conditions, their maintenance costs will increase dramatically over time, compared to use in their intended duty. Moderate duty machines can be of the trunk piston or crosshead design. Vertical or "Y" type trunk piston units are most often lubricated from the crankcase, air cooled, and operate at higher speeds than heavy duty machines. These factors contribute to higher operating temperatures and more rapid wear and deposit formations on valves and other parts. Larger moderate duty machines are typically of the crosshead variety. The principle distinguishing factor between these and heavy duty machines is that they operate at higher speeds. Heavy duty machines are typically of the crosshead type with entirely separate and well-controlled cylinder lubrication, water-cooled cylinders, and low operating speeds.

Distinguishing between moderate and heavy duty machines is an important factor in determining station compressor life and operating and maintenance costs. For example, a heavy-duty, crosshead reciprocating compressor operating at low speed may have a rated capacity of 300 SCF/min. That same compressor operating at a higher speed could have a capacity of 500 SCF/min. However, in this application that same machine would have a reduced service life and higher operating costs and would as such be rated a moderate duty machine.

Specifying a compressor for refueling station application is much more difficult than just specifying the input and output pressures, type and service rating. A typical partial detailed compressor specification as prepared by the Brooklyn Union Gas Co. is presented below.[3]

"Vendor shall furnish a natural gas compressor capable of compressing natural gas from an inlet pressure of 5 psig to a discharge pressure of 3600 psig at 70°F. Compression shall take place in various stages and after each stage gas shall be cooled and condensate removed prior to delivery to the next stage or final discharge.

Vendor shall specify method of cooling the gas after each compression stage. For a water cooled compressor, the coolant system shall be of a closed loop design, since no continuous water supply will be available.

Compressor shall operate in an environment whose design temperature is 0°F to 100°F. The system will be installed outdoors with suitable weather protection and shall be unmanned.

Each cylinder shall be protected for overpressure by means of a pressure relief valve set at no more than 10% above the design pressure of the cylinder. The discharge of the relief valve shall be piped to a common vent stack. Each relief valve shall be tagged with its rated setting. The vent stack shall conform to NFPA Std #68 latest edition Guide for Explosive Venting.

As a minimum, the compressor shall be equipped with check valves for the discharge, inlet solenoid-operated shut off valve, hand operated valve, pulsation cylinder suction with a pressure relief valve, low pressure drop filters and an approved stainless steel braided flexible connector between the inlet gas piping and the compressor inlet pulsation cylinder. The solenoid valve shall be of explosion-proof design rated for service intended. All solenoid valves shall be UL approved.

The compressor shall also be equipped with a condensate collection tank capable of collecting all condensate removed after each compression stage. The condensate tank shall be equipped, as a minimum, with a level indicator, drain valve, regulator, solenoid valves, and relief valves. The tank contents shall also be protected against freezing of condensed liquid.

Condensate blowdown shall be of a closed loop design. The compressor package shall be equipped with a methanol injection system (or approved equivalent), including but not limited to storage tank with sight glass, tubing, valves, and drip injector to prevent formation of hydrates in the gas.

All drive belts shall be of the antistatic design and shall be equipped with OSHA approved belt guards. The compressor shall be equipped with inlet pressure and temperature gauges and gauges to indicate the suction pressure and final discharge pressure gauge. The pressure gauges used shall be oil-filled, calibrated in pounds per square inch gauge and equipped with a pulsation damper and a valve to facilitate removal for calibration. The gauge valve shall be rated for the applicable pressure service. The temperature gauges shall be calibrated in degrees Fahrenheit.

The compressor shall also be equipped with a crankcase oil pressure switch to prevent overpressurization of the crankcase. The pressure switch shall be set to automatically shut down the system in the event that pressure in the crankcase exceeds the design pressure.

The compressor shall also be equipped with the following automatic shut down features:

Low suction pressure	High suction pressure
High oil temperature	Low oil pressure
High motor temperature	High discharge pressure
High discharge temperature	High crankcase pressure

Vendor shall specify in the proposal the limits of the aforementioned settings. Local visual shutdown fault indications for each shall be provided in the central panel. Contacts for remote indications shall also be provided.

Compressor shall also be equipped with a "run time" hour meter on the control panel. Control panel shall include all local indications including all gauges.

Vendor shall hydrostatically proof test the compressor at one and one half times the maximum operating pressure for a period of not less than thirty (30) minutes. If feasible, an engineer designated by the Utility shall witness this test. Vendor shall submit to the Utility a notarized affidavit attesting to such a satisfactory proof test. All electrical components shall be as specified in the Electrical Section of this specification."

Table 3 presents a partial listing of manufacturers offering compressors for NGV refueling station applications. In addition to compressor manufacturers, a number of "packagers" exist which sell complete refueling stations using various manufacturer's compressors. A partial listing of packagers is presented in Table 4.

Refueling station capital costs can vary widely depending on the delivery capacity, delivery rate, redundancy of equipment, and service rating to name a few. Typically, the compressor and drive unit represents the most expensive single component within the refueling station. Figure 3 presents

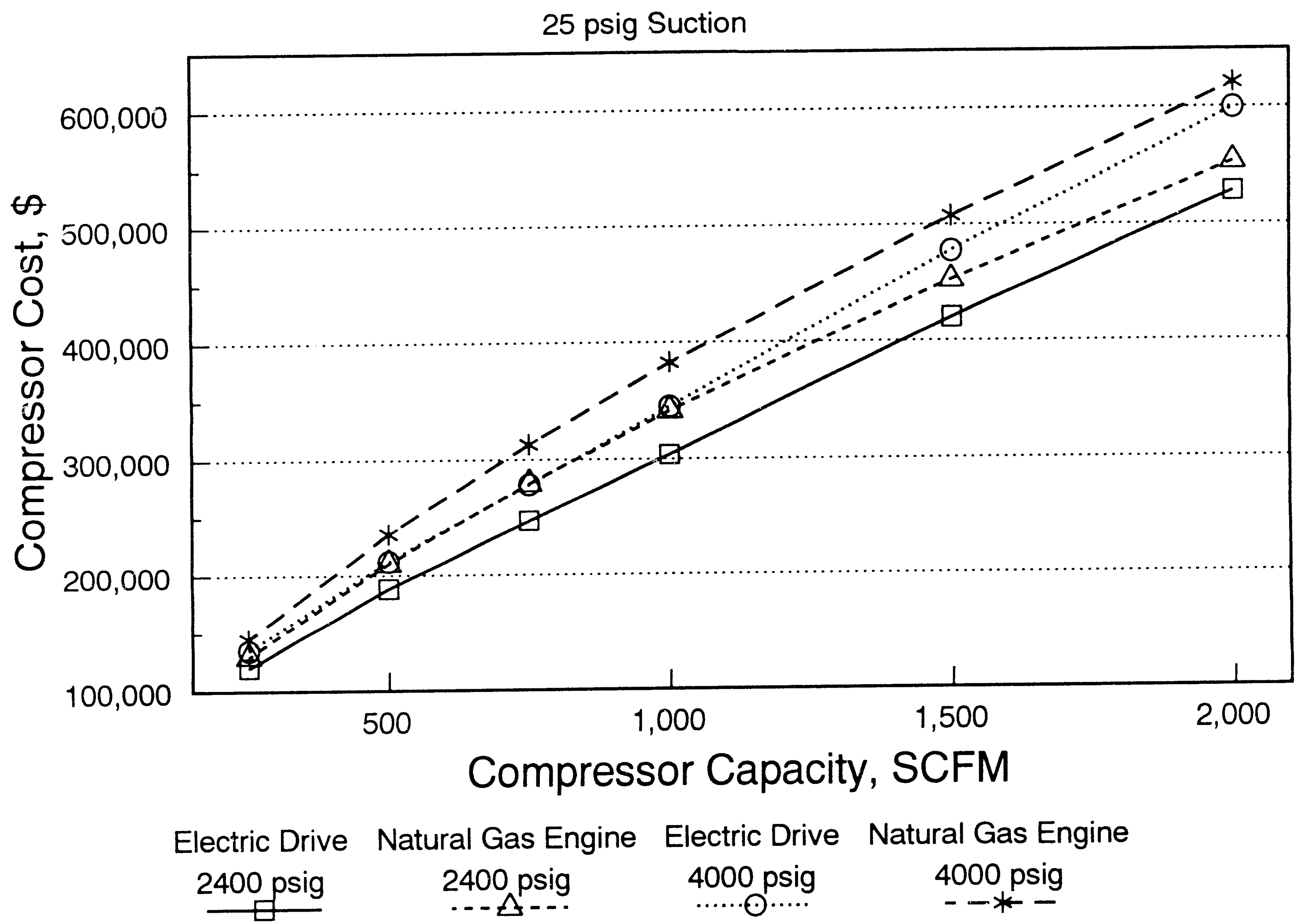

Figure 3. RECIPROCATING COMPRESSOR CAPITAL COSTS

compressor capital cost estimates for units in the 250 to 2000 SCF/min size range. This size range is representative of the largest compressor stations which would service heavy duty applications such as large urban bus fleets. Natural gas engines used to drive compressors are generally two to three times more costly than equivalently sized electric motors. Capital costs for natural gas engines become more competitive with electric motors as horsepower requirements increase, while lower horsepower applications strongly favor electric motors. Depending on local electric and gas rates as well as environmental factors, gas engine drives would become competitive in applications requiring more than 100 HP.

Table 3. Partial Listing of CNG Refueling Station Compressor Manufacturers.

Bauer	Rix
Norwalk	Corken
Ariel	LMF
Williams & James	Sulzer/Sulzer Burckhardt
Nuovo Pignone	Ingersoll Rand
Atlas Copco	Bowers
Compair	Haskell
Mako	J-Mar
Volvo	Pennsylvania Processors
Grimmer Schmidt	Knox Western

Table 4. Partial Listing of CNG Refueling Station Package Equipment Vendors

Automotive Natural Gas Inc.
CNG Fuel Systems
Challenger Energy Products
Hamworthy USA
National Energy Service Company
Joy Manufacturing
National Fuelcorp Ltd.
Wilson Gas Equipment
Wiljay

GROUND STORAGE

Refueling stations which utilize ground storage of compressed gas often do so in a cascade manner. Storage operation by cascade involves individually-actuated storage vessels controlled by valves switched in sequence. Cascade storage works on the principle that multiple independent banks of vessels can more efficiently fill a vehicle than bulk storage, or operation of total storage capacity as a unit at a common pressure. In cascade storage operation the compressor fills the ground storage vessels, which in turn fill the vehicle storage cylinders, drawing in order from the lowest to the highest pressure ground storage vessels, as the pressures vary with time. A single maximum pressure can be set for the storage facility, or each bank's maximum pressure can be individually defined.

Refueling station storage of compressed gas is an option for fleets that wish to reduce compression requirements. Ground storage vessels can be constructed to either DOT or ASME code. DOT ground storage vessels typically have a 500 SCF capacity at 3600 psig. Typical large ASME type storage vessels as manufactured by CP Industries of McKeesport, Pennsylvania have storage capacities of over 10,000 SCF each. CP storage vessels have been used in a number of NGV refueling station applications and are generally considered the most cost-effective means of storing large quantities of compressed gas at refueling stations. The CP storage vessels are built to ASME UPV Code, section VIII, Division 1, Appendix 22, Safety Factor 3. These seamless pressure vessels are designed for natural gas service and do not require any periodic recertification as would be the case for DOT type ground storage vessels. Approximate costs for this type of ground storage is presented in Table 5.

Table 5. Ground Storage Cost Factors

(1) * 20" OD x 22'4" L; 1.093" minimum wall thickness
* 35 cu.ft. water volume
* 4000 PSIG design pressure
* 10,500 SCF gas capacity @ 4000 PSIG
* approx. $10,000

(2) * Three vessel assembly [using (1)]
* Horizontally or vertically mounted in I-beams
* 105 cu.ft. water volume
* 31,500 SCF gas capacity @ 4000 PSIG
* approx. $30,000 per assembly

(3) * Three vessel assembly (2) with stainless steel manifold
* $35,000

DISPENSERS

Dispenser costs for NGV applications vary according to the number of hoses and the necessity for metering. For example, a two-position fill post assembly without metering is roughly $1,000. State-of-the-art in high pressure natural gas metering is represented by Micro Motion's Coriolis mass flow meters. A two-hose dispenser with mass flow metering approaches $20,000. This increases the total cost for a two-hose dispenser with mass flow metering and readouts for total quantity, unit price, and total sale amount, such as would be suitable for a public refueling station, to as much as $25,000.

OPERATING & MAINTENANCE COSTS

Preliminary operating and maintenance costs for small NGV refueling stations have been published by Northern Indiana Public Service Company (NIPSCO).[4] NIPSCO has operated NGVs since 1981 with a total current population of 682 vehicles. To service these vehicles NIPSCO has installed nearly 20 refueling stations. An analysis of 16 of these refueling stations for 1986 indicated that the compression costs per 100 SCF ranged from 6.26 cents to 13.95 cents. Electricity costs ranged from 4.5 cents per kWh to 12 cents per kWh during this period. In nearly all cases the cost of electricity for these electric-motor-driven compressors represented the majority of the compression costs.

As an example of NGV refueling station energy requirements, Figure 4 shows the horsepower needed to operate a compressor with suction pressure of 25 psig and discharge pressures of 500, 900, 2400, 3000, and 4000 psig. The figure shows that compression to 500 psig requires 55% of the horsepower for compression to 3000 psig, and only 53% of the horsepower required to compress to 4000 psig. To calculate actual compressor operating energy costs, information is required on the amount of fuel that will be consumed by the vehicles, which is determined by the annual mileage and fuel efficiency of the vehicles. From this information, the kWh of electricity or SCF of natural gas required to drive the compressor can be calculated. An example calculation of annual compressor operating costs for two cases, a 50 vehicle light/medium duty fleet and a 300 vehicle heavy duty bus fleet, is presented in Table 6. Costs are calculated for compressors using natural gas engines as well as electric motors for the heavy duty case, and only for electric motors for the light/medium duty case. Natural gas costs used were $4.50 per 1000 SCF, and electric costs used were $0.07 per kWh.

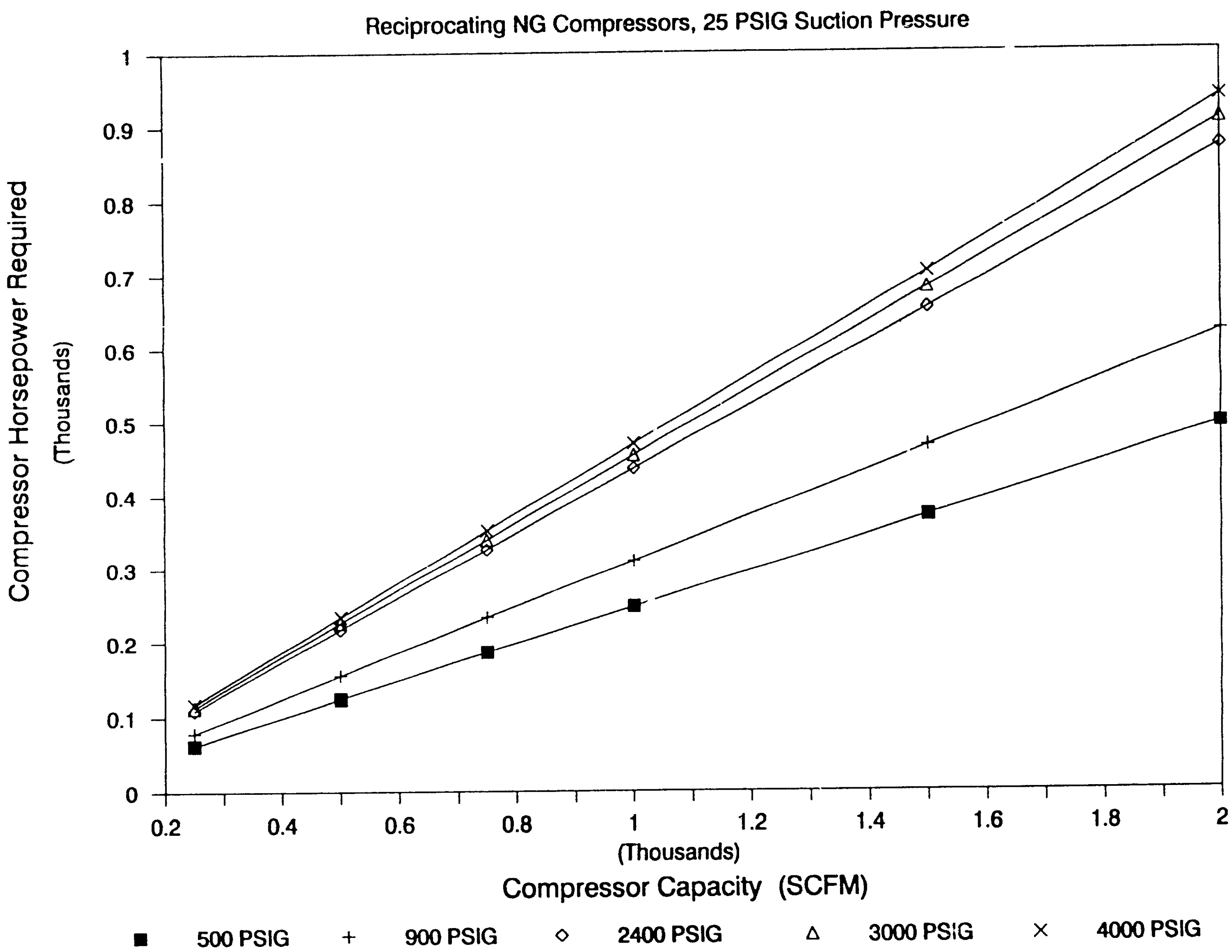

Figure 4. COMPRESSOR HORSEPOWER REQUIRED

Table 6. ANNUAL COMPRESSOR OPERATING COSTS

Discharge Pressure (PSIG)	Horse-power Required	Annual SCF Gas Required	Annual kWh Elec. Required	Annual NG Cost @ $4.50/ 1000 SCF	Annual Elec.Cost @ $0.07/ kWh
Light/Medium Duty Case: 50 Vehicle Fleet					
3000	159	-	125,912	-	$8,814
Heavy Duty Bus Case: 300 Vehicle Fleet					
3000	907	30,363,600	2,592,442	$136,636	$181,471

Table 6 illustrates the cost difference between natural gas and electric operation of the compressor. In the examples, compressor operating costs were nearly 25% higher using electric motors than using natural gas engine drives. However, it should be noted that electric motors can be easily cycled on and off to meet sporadic vehicle refueling demands while natural gas engines must idle and consume fuel during these off-load times. Thus, natural gas engines are normally used only at large facilities with constant refueling demand. Natural gas engines consume roughly 9,000 Btu's per horsepower-hour under load and about 4,000 Btu's per horsepower-hour at idle, so the cost of using natural gas should be adjusted upwards if the refueling station experiences periods of inactivity in which the NG engine would be idling. The fleet refueling station designer should carefully evaluate the actual utilization rate of the refueling station before selecting between an electric motor and a natural gas engine.

The cost for electricity may also deviate from the projected rate. The $0.07 per kWh cost is an *average* of peak and off-peak rates, so the actual cost experienced by the fleet refueling station would depend greatly upon the operating time of day and the prevailing electric rates for those times. Daytime electric rates will generally be above $0.07/kWh, while nighttime rates (such as for overnight slow-filling) will tend to be less. Also, these costs do not include any increase in demand charges resulting from installation of large electric motors at a fleet refueling station. Because these factors are impossible to quantify on a general scale, average electric rates were used.

REFUELING STATION OPTIMIZATION

The ability of a refueling station to deliver natural gas into a vehicle in compressed form is loosely termed the station delivery capacity. This capacity is determined by a variety of factors such as fleet size, refuel time per vehicle, vehicle fuel capacity, vehicle fuel efficiency, vehicle daily mileage, and operating time per day. The delivery capacity required for any given fleet can be calculated using this information. Refueling station delivery capacity can be met in one of two ways: through straight compression capacity, or compression assisted by ground storage of compressed natural gas. Figure 5 illustrates the required delivery capacity of a transit bus refueling station for fleets of 25 to 200 vehicles. Three curves are shown, representing the maximum allowable refueling time per vehicle (5 minutes, 10 minutes, and 15 minutes). The rather strange shape of the curves is attributable to the effect that imposition of maximum time limits has upon refueling practices. With a strict 5-minute time limit on refueling, fleets of less than 155 vehicles must design delivery capacity for 2000 SCF/min in order to ensure vehicle refilling within 5 minutes. With a less strict 15 minute time limit on refueling, fleets can refuel vehicles with as little as 667 SCF/min of delivery capacity or more depending upon the exact size of the fleet. However, fleets with greater than 77 vehicles must design delivery capacity for 10-minute refuels rather than 15-minute refuels in order to satisfy the restriction of servicing vehicles within the allotted 12-hour shift time. The line which describes this effect is the 45-degree line running from the lower left to the upper right areas of the graph, and is called the <u>fleet constraint</u> line. The horizontal lines to the left of the fleet constraint line describe the requirements of refueling vehicles within the time limits of 5-minutes, 10-minutes, and 15-minutes, respectively. These lines are referred to as the <u>vehicle constraint</u> lines. Thus, as fleet size grows, refilling one vehicle individually becomes less important than refilling the required number of fleet vehicles within the shift time period. This situation persists regardless of the number of dispensers and is only related to compression and storage capacity, as well as to the fleet factors mentioned above.

The manner in which delivery capacity is achieved will have a great impact upon refueling station economics. As mentioned earlier, refueling

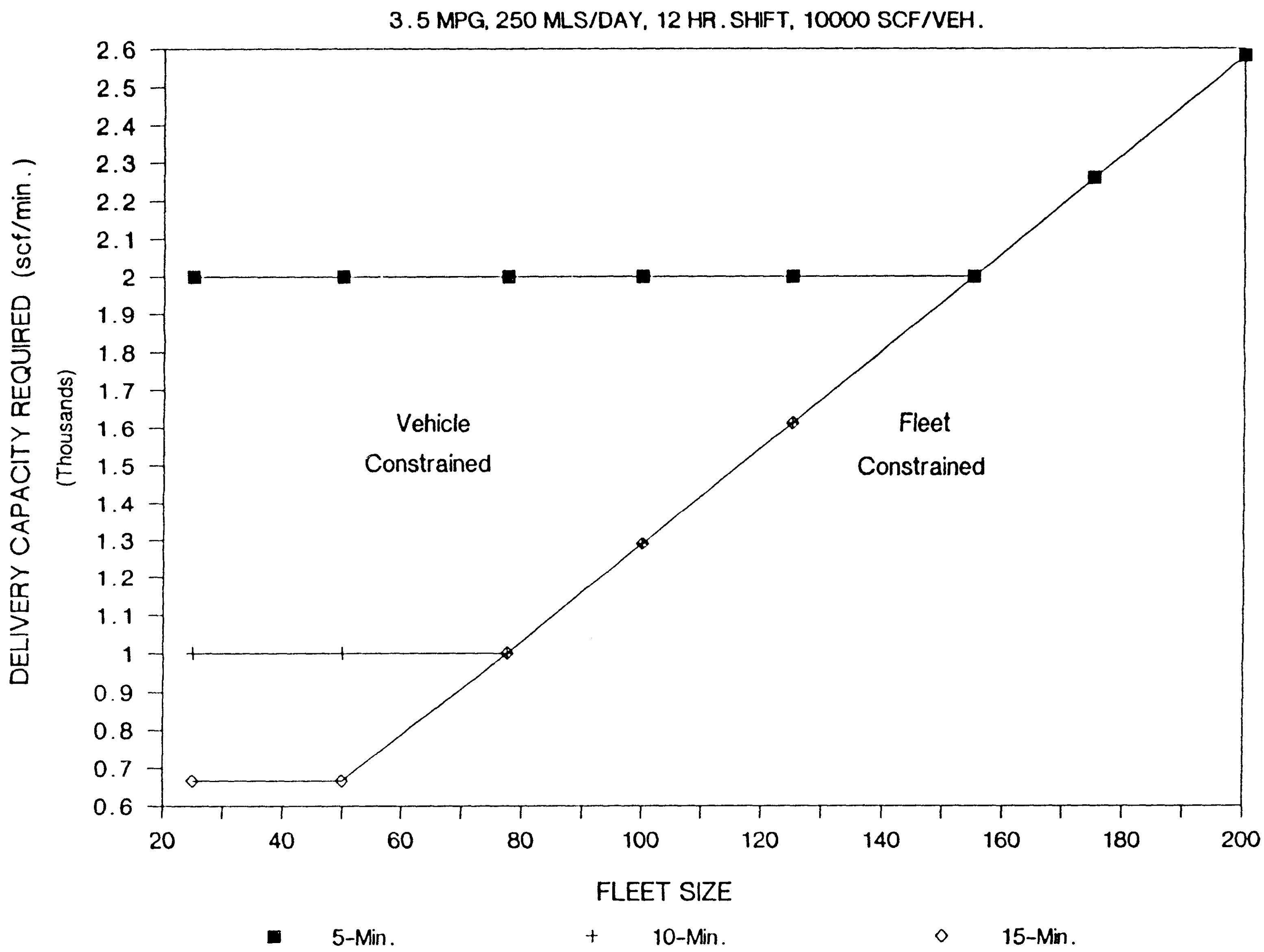

Figure 5. REFUELING STATION CAPACITY REQUIREMENTS

delivery capacity can be met with varying increments of compression and ground storage. Increments of storage may have a lower cost than increments of compression, so it is desirable to optimize the refueling component mix in order to achieve the most cost-effective configuration. Figure 5 again sheds light on the situation. The fleet constraint line depicts applications where individual vehicle time limits are not of overriding concern, but rather refueling of the required number of fleet vehicles within the shift period is the driving force. This line is obviously not affected by the presence of storage capacity because compressors would not have adequate time to refill storage cylinders, thereby quickly depleting any amount of storage capacity. On the other hand, the vehicle constraint lines would be greatly affected by the presence of storage capacity. Because these applications are not fleet constrained but rather are constrained by the time to refuel a single vehicle, sufficient opportunities would be available for compressors to refill storage cylinders throughout the course of a shift period. Some conclusions regarding refueling station design can be summarized in the following statements:

- A substantial penalty may be associated with requirements for maximum allowable refueling time per vehicle, although the magnitude of this penalty lessens as fleet size grows.

- A second dispenser is only required when a fleet refueling station is constrained by fleet refueling demands and not by individual vehicle refueling demands.

- Ground storage is an attractive alternative to compression in fleets which experience delays between refueling vehicles, such as smaller fleets or shorter refueling times. Storage also becomes more attractive in fleets with fewer vehicles, shorter required refueling times, longer operating shifts, higher vehicle fuel efficiencies, lower vehicle route mileage, or higher vehicle fuel capacities. Conversely, larger fleets, longer allowable refueling times, shorter operating shifts, lower vehicle fuel efficiencies, higher vehicle route mileage, or lower vehicle fuel capacities would tend to favor compression capacity.

- Ground storage operation by cascade increases the ability of a refueling station to fill vehicles. A larger number of individually-operated storage vessels will provide greater refueling efficiency than a smaller number. The number of vehicles capable of being successively refueled should be calculated and compared to the actual needs of the fleet.

The option of slow-filling all or a portion of fleet vehicles could also have an impact on refueling station costs. Because slow-filling reduces the required flow rate, a smaller compressor could be used to meet fleet vehicle demands. However, additional dispensers and piping would be required to accommodate the connections for overnight filling of fleet vehicles.

Ground storage complicates the analysis of a refueling station, especially in cases of cascade operation. Ground storage allows a smaller compressor to service a larger fleet by allowing it to run between vehicle refuels, thus lessening its burden during actual refuel times. However, one negative aspect to storage is its inability to operate satisfactorily after depletion, which occurs subsequent to a certain number of successive vehicle refuels. A storage system is considered to be depleted when its highest-pressure vessel or bank of vessels is no longer capable of completely filling vehicle storage cylinders to their maximum service pressure. The object of a refueling station designer is to match the ability of the storage/compression combination for successive vehicle refuels to the actual need for successive refuels in fleet operation.

One way of reducing refueling station cost is to carefully optimize the capacity of the refueling station. This can only be performed through the understanding of the relationships that exist between fleet refueling requirements, compression capacity, and the possible use and application of cascade ground storage of natural gas. Cascade storage is attractive for many fleet applications due to the lower incremental cost of ground storage as compared to compressor capacity. In order to analyze refueling station configurations using various combinations of compression and ground storage, the Institute of Gas Technology (IGT) created a computerized analytical tool. The "Natural Gas Vehicle Refueling Station Analysis Program" was developed to analyze the performance of fast-fill refueling station configurations for various fleet vehicle conditions. The necessity of a computer program arose due to the difficulty in assessing the operating performance of cascade-type ground storage systems. The program is most effectively used as a tool to determine the performance of different refueling station configurations and in the identification of system "bottlenecks". By setting all fleet parameters at a constant value and changing only the number of ground storage vessels and/or compressor size, the user can easily observe the performance of the station at varying increments of compression and storage capacity. This allows the refueling station designer to minimize compression requirements while still attaining the necessary refueling performance.

IGT's Refueling Station Demonstration Program was developed to analyze the performance of refueling station configurations for any set of average fleet vehicle conditions. Cascade storage works on the principle that multiple banks of storage more efficiently fill a vehicle than one bulk storage tank, or operation of the total storage capacity as a unit at a common pressure. In cascade storage operation the compressor fills the ground storage vessels, which in turn fill the vehicles' storage. Because of this ability of the vehicle and compressor to switch between cascade banks, the study of a cascade refueling station's capacity is one that must take into account its time-dependency. Since the solution to the question of the number of vehicles that can be continuously filled is not a state function, but relies on the order in which banks are selected for discharge to the vehicle and filling by the compressor, the computer simulation addressed this difficulty in assessing a cascade-based ground storage system by including the time-varying nature of its operation.

The simulation, called CASCADE, assumes that a general fleet of vehicles is described, with a general description applicable for each vehicle. The operation of CASCADE is based on a description of the fleet and compressor/cascade fueling system as presented in Figure 6, with sample input values. The fleet is defined by the average vehicle fuel efficiency, daily route mileage per vehicle, and the number of vehicles in the fleet. These parameters sufficiently specify the fleet to determine the amount of natural gas that must be delivered to the fleet by the refueling station at the end of each average day.

The storage capability of each vehicle is next defined by its total storage volume and maximum storage pressure. The total volume and maximum pressure determine the maximum amount of natural gas that can be carried by the vehicle and the end-of-day pressure when combined with the natural gas consumption per day. The simulation checks for exhaustion of the vehicle's storage by comparing the daily use with the storage capacity. If the capacity is exceeded, the program displays an error message and will not proceed with the simulation because the conditions would result in the vehicle being stranded in the real world. A flag for bi-fuel operation overrides this, allowing the program to simulate operation for complete natural gas utilization (under the assumption that the alternate fuel would be used to return the vehicle to the fueling station, if needed).

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Vehicle/Fleet Characteristics
Vehicle Fuel Efficiency: 10.0 MPG - equivalent
Daily Vehicle Route Mileage: 250 miles
Fleet Size:  15 vehicles              Dual Fuel? (Y/N) N

Vehicle Storage Characteristics
Vehicle Total Storage Volume:  30.00 cu.ft. (water volume)
Vehicle Maximum Storage Pressure: 3000 psig

Refueling Characteristics
Maximum Allowable Refueling Time:  5 minutes/vehicle
Time for Switching Between Vehicles:  2 minutes
Refueling Operation Time:  8 hours per day

Ground Storage Characteristics
Ground Storage Bank Volume:  30.00 cu.ft. (water volume)
Ground Maximum Storage Pressure: 3600 psig
Number of Storage Banks at Refuel Station: 5



Enter values, ending with <Enter>,   use ↑ to move to previous value
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Figure 6. FLEET AND STATION CHARACTERISTICS FOR CASCADE

The station's operating characteristics are identified by the maximum allowable refueling time per vehicle, the time required for switching or moving vehicles to the refueling dispensers, and shift operating time (number of hours per day the fleet will be refueled). Combining fueling and switching times with the number of vehicles determines whether the fleet could be refueled within the refueling shift period. The switching time recognizes that there is some finite amount of time in the real world when the station is not attached to a vehicle and the compressor can continue running to fill the cascade banks.

The ground storage is defined by the storage volume per bank, the maximum operating pressure, and the number of ground storage cylinders desired by the fleet operator. Each grouping of one or more physical cylinders that are manifolded together and switched as a unit is considered as one logical cylinder or bank, and the storage volume and number of cylinders refers to this bank.

Once given this information, the program then calculates a variety of intermediate measures such as capacity of the vehicle and ground storage cylinders, required refuel interval per vehicle, end-of-day gas supply and pressure for vehicles, average number of vehicles refueled per hour, average time between refuels, and total daily station demand. Two very important measures which are calculated include the "Minimum Required Flow Rate per Vehicle" and the "Average Required Flow Rate per Shift". These values give the required flow rate to meet the demands of refueling one vehicle within the allowable time, and refueling all fleet vehicles within the shift operating period, respectively. It should be noted that the required flow rates are adjusted for the amount of fuel remaining in the vehicle, so the assumption of daily refueling is made. The "Full Delivery Capacity" is the required vehicle flow rate and is the capacity that a compressor would need if it were fueling the vehicles directly, within the specified refueling time per vehicle. The user is then asked for the last entry, "Percentage of Full Delivery Capacity for Analysis". This determines the size of the compressor to be used in the analysis by multiplying the input percentage by the full delivery capacity. Thus, if the user wishes to analyze a compressor half as large as required with no storage, a value of 50% would be entered. Figure 7 shows intermediate calculated results and the input field for adjusting the compressor size.

```
Storage Capacity
Vehicle Storage Cylinder Capacity:     7773 scf
 Ground Storage Cylinder Capacity:     8884 scf
    Total Ground Storage Capacity:    44419 scf

Required Refuel Interval per Vehicle:  2.35 days
End of day gas supply:  4521 scf
End of day gas pressure:  1754 psig

Average number of vehicles refueled per hour:   1.88
Average time between refuels:  25.00 minutes
Total Daily Station Demand:    48788 scf
Minimum Required Flow per Vehicle:  650.5 scf/min
Average Required Flow per Shift:   101.6 scf/min


Full delivery capacity:   650.5 scf/min
Percentage of full-delivery capacity for analysis:  40



Enter value, ending with <Enter>
<F1> to display a help window
```

Figure 7. INTERMEDIATE CALCULATIONS OF CASCADE

After confirming that the user wants to continue with the analysis, CASCADE begins running, demonstrating the operation of the cascade natural gas refueling station. Because of the complexity of the switching operation, CASCADE has a graphical display of the compressor / banks / vehicle operation. The starting point is shown in Figure 8, with vehicle and storage bank values for the first vehicle just after it has been connected. An intermediate display is shown in Figure 9, after the storage banks have been partially depleted and vehicle 9 has been filled. The middle row of boxes represents the five cascade storage banks, with the volume of natural gas contained in each on the top line and the pressure on the bottom line. The vehicle display is similar, with the amount of natural gas on board and its pressure displayed. The lines connecting the compressor to banks and banks to vehicle are redrawn to reflect the changing connections. During the simulation, if the storage cannot completely fill a vehicle, the program backs up the time and pressure/volume values to that just before the vehicle and simulates the compressor filling each of the storage banks, until the system is recharged, when fueling begins again.

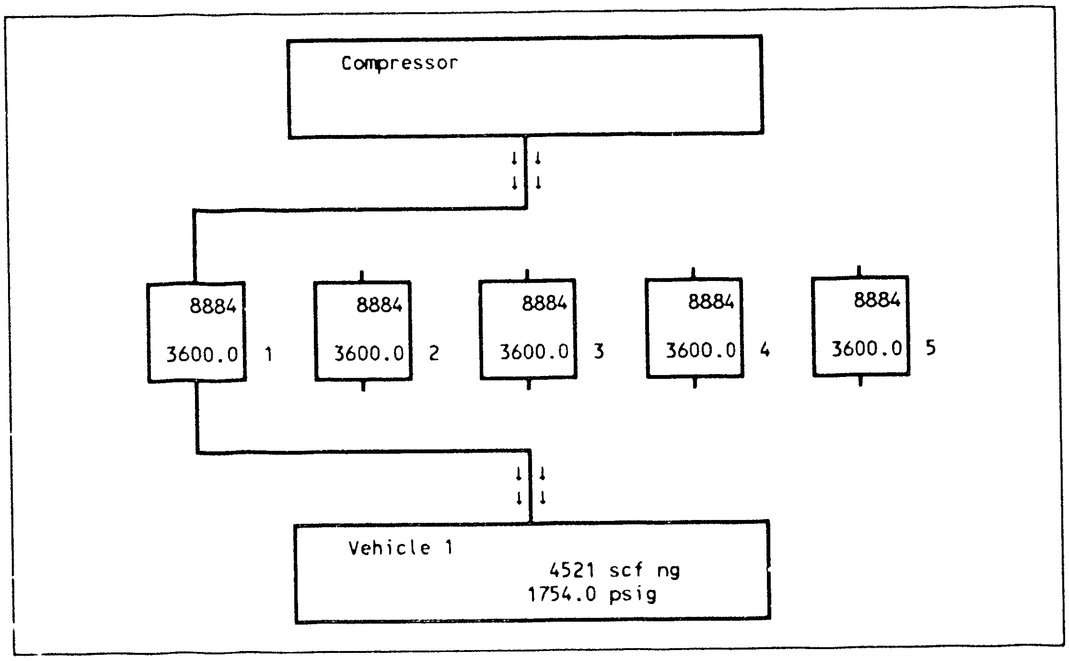

Figure 8. STARTING POINT FOR CASCADE SIMULATION

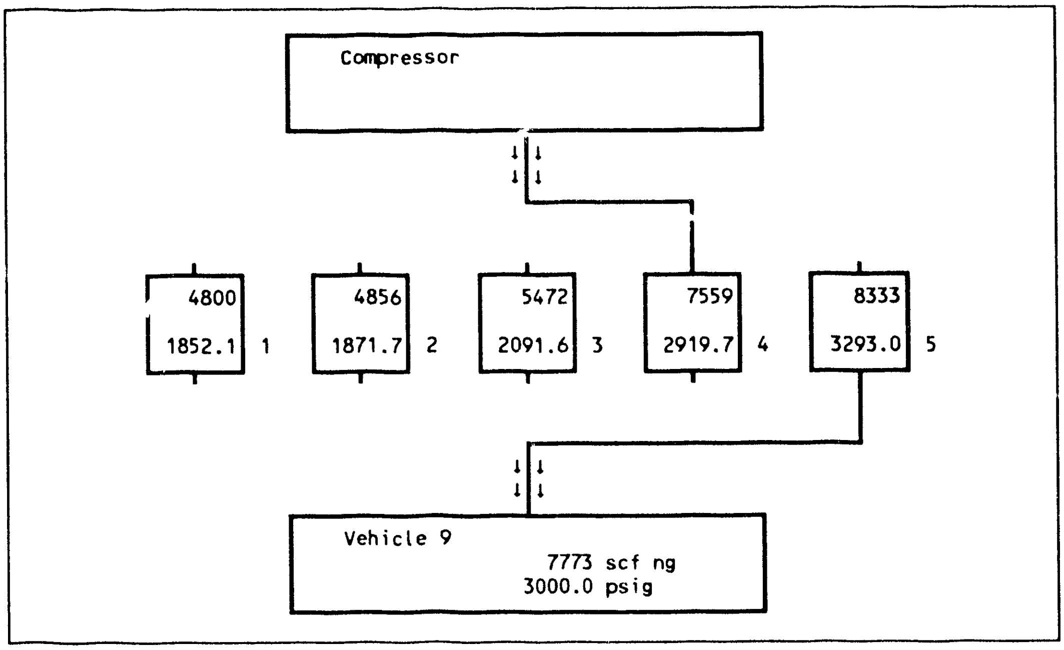

Figure 9. INTERMEDIATE DISPLAY OF CASCADE SIMULATION

The primary output of the program is the number of vehicles which can be refueled continuously. The program also calculates the continuous refueling time, total fleet refueling time, and time required for recharging after depletion of the cascade. The program is most effectively used as a tool to determine the performance of different refueling configurations. By setting all fleet parameters at a constant value and changing only the number of ground storage vessels and the compressor size, the user can easily observe the performance of the station at varying increments of compression and storage capacity. Figure 10 shows the summary results of the operation demonstration. Reports can be optionally printed for a permanent record of this information.

When applied to the light/medium duty fleet case, the program sheds some light on the possible reduction in compressor capacity through utilization of ground storage. Storage vessels chosen were 35 cubic foot water volume, 4000 psig steel vessels by CP Industries, which were discussed previously. For

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     Cascade Operation Analysis

Number of vehicles fueled continuously:   9
Time to fuel vehicles continuously: 01:03:00
Time for recharging cascade after depletion: 00:49:29
Time compressor spent idle during refueling: 00:00:00
Total time for refueling fleet: 02:34:29




    Print: Summary page / Detail pages / Both / Nothing (S/D/B/N)  « »
```

Figure 10. SUMMARY RESULTS OF CASCADE SIMULATION

example, if a given fleet operator wished to refuel 10 vehicles in a row, possible options include:

* 70% compressor (243 SCFM), 1 storage vessel
* 50% compressor (174 SCFM), 2 storage vessels
* 30% compressor (104 SCFM), 3 storage vessels
* 10% compressor (38 SCFM), 4 storage vessels

The reduction in required compressor capacity as a result of ground storage is significant in this instance. Required compression capacity was reduced from 347 SCFM without ground storage to 174 SCFM with 2 vessels, 104 SCFM with 3 vessels, or 38 SCFM using 4 vessels. Ground storage using only one vessel generally does not perform well because it does not benefit from the cascade effect provided by multiple banks of vessels.

To assess the cost of these configurations, the refueling station designer would determine the cost of each compressor size, and add to it the total cost of storage vessels for that configuration. An optimum configuration can be reached which provides the lowest refueling station cost yet still achieves the required refueling performance.

A quick analysis of the 30% compression/3 storage vessel case would be as follows. Compressor capital costs are reduced from $169,700 (350 SCFM) to $87,000 (100 SCFM), for a compressor savings of $82,700. Storage vessel costs of approximately $30,000 (3 vessels @ $10,000 per vessel) are subtracted from the compressor capital cost savings, for a net savings of $52,700. This methodology can be applied to any fleet using the refueling station program and the costs for compressors and storage vessels contained in this paper.

REFERENCES

1. Directory of Natural Gas Vehicle Refueling Stations - Products and Services, American Gas Association, February, 1991.

2. Norwalk Compressor brochure.

3. Personal communications with Brooklyn Union Gas Co., June 1990.

4. V. L. Elms, Northern Indiana Public Service Co., Natural Gas Vehicle Conference - The Drive for Clean Air, Sponsored by the American Gas Association and the Natural Gas Vehicle Association, pp 257-263, September 17-19, 1990, Washington D.C.

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